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Intrinsic problems of the gravitational baryogenesis

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ABSTRACT

Modification of gravity due to the curvature dependent term in the gravitational baryogenesis scenario is considered. It is shown that this term leads to the fourth order differential equation of motion for the curvature scalar instead of the algebraic one of General Relativity (GR). The fourth order gravitational equations are generically unstable with respect to small perturbations. Non-linear in curvature terms may stabilize the solution but the magnitude of the stabilized curvature scalar would be much larger than that dictated by GR, so the standard cosmology would be strongly distorted.

1. Introduction

Different scenarios of baryogenesis are based, as a rule, on three well known Sakharov principles [1]:

1. Non-conservation of baryonic number.
2. Breaking of symmetry between particles and antiparticles.
3. Deviation from thermal equilibrium.

For details see e.g. reviews [2,3].

However, as is mentioned in review [2], none of these conditions is obligatory. There are versions of baryogenesis scenarios which can be successfully realized even if baryonic number, B, is strictly conserved. For example, if there exists a hidden or sterile baryon, the baryon asymmetry in the sector of our visible baryons would be exactly equal to the asymmetry in the invisible (or slightly visible) sector consisting of hidden baryons. In particular, such new baryons could form cosmological dark matter. Another example of baryogenesis with conserved B is the model of generation of baryon asymmetry in the process of black hole evaporation. In this case the compensating antibaryon asymmetry would be hidden inside the evaporating black holes.

Out of the three Sakharov principles only non-conservation of baryons is necessary for spontaneous baryogenesis (SBG) in its classical version [4], but this mechanism does not demand an explicit C and CP violation and can proceed in thermal equilibrium. Moreover, it is usually most efficient in thermal equilibrium.

The statement that the cosmological baryon asymmetry can be created by SBG in thermal equilibrium was mentioned in the original papers [4]. The reaction rate may be very high, such that all essential processes are forced to equilibrium, so the particle distributions do not deviate from the canonical equilibrium form. Nevertheless in this thermal equilibrium state an asymmetry between particles and antiparticles happened to be non-vanishing. Temporal evolution of the (pseudo)goldstone field $\theta(t)$, see below, in a sense mimics the non-equilibrium situation but this has nothing to do with thermal equilibrium, it is simply induced by a deviation from the mechanical equilibrium point of $\theta(t)$.

As for C or CP violation, they are effectively present in SBG due to the external field $\theta(t)$, which acts differently on particles and antiparticles but this field ultimately disappears and thus does not lead to C and CP violation in particles physics in our laboratories. It may be a matter of terminology, but we do not say e.g. that the different scattering of particles and antiparticles on a positively charged nucleus means C or CP violation.

The term "spontaneous" is related to spontaneous breaking of a global $U(1)$-symmetry, which ensures the conservation of the total baryonic number in the unbroken phase. When the symmetry is broken, the baryonic current becomes non-conserved and the Lagrangian density acquires the term

$$\mathcal{L}_{SB} = (\partial_\mu \theta) J^\mu_B , \tag{1.1}$$

where θ is the Goldstone (or pseudo Goldstone) field and J^μ_B is the baryonic current of matter fields.

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For a spatially homogeneous field $\theta = \theta(t)$ the Lagrangian (1.1) is reduced to $\mathcal{L}_{SB} = \dot\theta n_B$, where $n_B \equiv J^0_B$ is the baryonic number density of matter, so it is tempting to identify $(-\dot\theta)$ with the baryonic chemical potential, μ_B, of the corresponding system. The identification of $\dot\theta$ with chemical potential is questionable and depends upon the representation chosen for the fermionic fields, as is argued in refs. [5,6], but still the scenario is operative and presents a beautiful possibility to create an excess of particles over antiparticles in the universe.

Subsequently the idea of gravitational baryogenesis (GBG) was put forward [7], where the scenario of SBG was modified by the introduction of the coupling of the baryonic current to the derivative of the curvature scalar R:

$$\mathcal{L}_{GBG} = \frac{1}{M^2}(\partial_\mu R) J^\mu_B\,, \tag{1.2}$$

where M is a constant parameter with the dimension of mass. More references on GBG can be found in [8].

In this work we demonstrate that the addition of the curvature dependent term (1.2) to the Hilbert–Einstein Lagrangian of GR leads to higher order gravitational equations of motion which are strongly unstable with respect to small perturbations. A similar gravitational instability in $F(R)$ gravity, which also leads to higher order equations of motion, has been found in refs. [9].

2. Equations of motion

Let us start from the model where baryonic number is carried by scalar field ϕ with potential $U(\phi,\phi^*)$. An example with baryonic current of fermions will be considered elsewhere.

The action of the scalar model has the form:

$$A = \int d^4x \sqrt{-g}\left[\frac{m_{Pl}^2}{16\pi} R + \frac{1}{M^2}(\partial_\mu R) J^\mu - g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi^* + U(\phi,\phi^*)\right] - A_m\,, \tag{2.1}$$

where $m_{Pl} = 1.22 \cdot 10^{19}$ GeV is the Planck mass, A_m is the matter action, $J^\mu = g^{\mu\nu} J_\nu$, and $g^{\mu\nu}$ is the metric tensor of the background space–time. We assume that initially the metric has the usual GR form and study the emergence of the corrections due to the instability described below.

In contrast to scalar electrodynamics, the baryonic current of scalars is not uniquely defined. In electrodynamics the form of the electric current is dictated by the conditions of gauge invariance and current conservation, which demand the addition to the current of the so called sea-gull term proportional to $e^2 A_\mu |\phi|^2$, where A_μ is the electromagnetic potential.

On the other hand, a local $U(1)$-symmetry is not imposed on the theory determined by action (2.1). It is invariant only with respect to $U(1)$ transformations with constant phase. As a result, the baryonic current of scalars is considerably less restricted. In particular, we can add to the current an analogue of the sea-gull term, $\sim (\partial_\mu R)\,|\phi|^2$, with an arbitrary coefficient. So we study the following two extreme possibilities, when the sea-gull term is absent and the current is not conserved (the case A below), or the sea-gull term is included with the coefficient ensuring current conservation (the case B). In both cases no baryon asymmetry can be generated without additional interactions. It is trivially true in the case B, when the current is conserved, but it is also true in the case A despite the current non-conservation, simply because the non-zero divergence $D_\mu J^\mu$ does not change the baryonic number of ϕ but only leads to redistribution of particles ϕ in the phase space. So to create any non-zero baryon asymmetry we have to introduce an interaction of ϕ with other particles which breaks conservation of B by making the potential U non-invariant with respect to the phase rotations of ϕ, as it is described below.

2.1. Current: version 1

If the potential $U(\phi)$ is not invariant with respect to the $U(1)$-rotation, $\phi \to \exp(i\beta)\phi$, the baryonic current defined in the usual way

$$J_{1\mu} = iq(\phi^*\partial_\mu\phi - \phi\partial_\mu\phi^*) \tag{2.2}$$

is not conserved. Here q is the baryonic number of ϕ and for brevity we omitted index B in current $J_{1\mu}$.

With this current and Lagrangian (1.2) the equations for the gravitational field take the form:

$$\begin{aligned}
&\frac{m_{Pl}^2}{16\pi}\left(R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R\right)\\
&\quad - \frac{1}{M^2}\left(\left[R_{\mu\nu} - (D_\mu D_\nu - g_{\mu\nu}D^2)\right] D_\alpha J^\alpha_1 + \frac{1}{2} g_{\mu\nu} J^\alpha_1 D_\alpha R\right.\\
&\quad \left.- \frac{1}{2}(J_{1\nu}D_\mu R + J_{1\mu}D_\nu R)\right) - \frac{1}{2}(D_\mu\phi\, D_\nu\phi^* + D_\nu\phi\, D_\mu\phi^*)\\
&\quad + \frac{1}{2}g_{\mu\nu}(D_\alpha\phi\, D^\alpha\phi^* - U(\phi)) = \frac{1}{2}T_{\mu\nu}\,,
\end{aligned} \tag{2.3}$$

where D_μ is the covariant derivative in metric $g_{\mu\nu}$ (of course, for scalars $D_\mu = \partial_\mu$) and $T_{\mu\nu}$ is the energy–momentum tensor of matter obtained from action A_m.

Taking the trace of equation (2.3) with respect to μ and ν we obtain:

$$\begin{aligned}
&\frac{m_{Pl}^2}{16\pi} R + \frac{1}{M^2}\left[(R + 3D^2)D_\alpha J^\alpha_1 + J^\alpha_1 D_\alpha R\right]\\
&\quad - D_\alpha\phi\, D^\alpha\phi^* + 2U(\phi) = -\frac{1}{2} T^\mu_\mu\,.
\end{aligned} \tag{2.4}$$

The equation of motion for field ϕ is:

$$D^2\phi + \frac{\partial U}{\partial\phi^*} = -\frac{iq}{M^2}(2D_\mu R\, D^\mu\phi + \phi D^2 R)\,. \tag{2.5}$$

According to definition (2.2), the current divergence is:

$$\begin{aligned}
D_\mu J^\mu_1 = &\frac{2q^2}{M^2}\left[D_\mu R\,(\phi^* D^\mu\phi + \phi D^\mu\phi^*) + |\phi|^2 D^2 R\right]\\
&+ iq\left(\phi\frac{\partial U}{\partial\phi} - \phi^*\frac{\partial U}{\partial\phi^*}\right)\,.
\end{aligned} \tag{2.6}$$

If the potential of U is invariant with respect to the phase rotation of ϕ, i.e. $U = U(|\phi|)$, the last term in this expression disappears. Still the current remains non-conserved, but this non-conservation does not lead to any cosmological baryon asymmetry. Indeed, the current non-conservation is proportional to the product $\phi^*\phi$, so it can produce or annihilate an equal number of baryons and antibaryons.

To create cosmological baryon asymmetry we need to introduce new types of interactions, for example, the term in the potential of the form: $U_4 = \lambda_4\phi^4 + \lambda_4^*\phi^{*4}$. This potential is surely non-invariant w.r.t. the phase rotation of ϕ and can induce the B-non-conserving process of transition of two scalar baryons into two antibaryons, $2\phi \to 2\bar\phi$. An additional B-nonconserving interaction may contain some other fields, e.g. $\phi\bar{q}q$, where q is a fermion, not necessarily a quark. Anyhow such new terms, or something more complicated, can be included into the potential U. Of course, because of them the invariance of the theory with respect to the phase rotation of ϕ would be broken.