Scalar Field Condensate Baryogenesis Model in Different Inflationary Scenarios

Daniela Kirilova\textsuperscript{1,a)} and Mariana Panayotova\textsuperscript{1,b)}

\textsuperscript{1}Institute of Astronomy with NAO Rozhen, Bulgarian Academy of Sciences, 72 Tsarigradsko shose Blvd., Sofia, Bulgaria

\textsuperscript{a)}Corresponding author: dani@astro.bas.bg
\textsuperscript{b)}mariana@astro.bas.bg

Abstract. We calculate the baryon asymmetry value generated in the Scalar Field Condensate (SCF) baryogenesis model obtained in several inflationary scenarios and different reheating models. We provide analysis of the baryon asymmetry value obtained for more than 70 sets of parameters of the SCF model and the following inflationary scenarios, namely: new inflation, chaotic inflation, Starobinsky inflation, MSSM inflation, quintessential inflation. We considered both cases of efficient thermalization after inflation and also delayed thermalization.

We have found that SFC baryogenesis model produces baryon asymmetry by orders of magnitude bigger than the observed one for the following inflationary models: new inflation, new inflation model by Shafi and Vilenkin, MSSM inflation, chaotic inflation with high reheating temperature and the simplest Shafi-Vilenkin chaotic inflationary model. For these models strong diluting mechanisms are needed to reduce the resultant baryon excess at low energies to its observational value today.

We have found that a successful generation of the observed baryon asymmetry is possible by SCF baryogenesis model in Modified Starobinsky inflation, chaotic inflation with low reheating temperature, chaotic inflation in SUGRA and Quintessential inflation.

1. Introduction

The inflationary paradigm for the description of the very early Universe is already more than 30 years old, however, there still exist numerous models of inflation \cite{1}. Moreover, the reheating process at the end of inflation, that is believed to have provided the transfer of the energy stored in the inflaton to other fields and thus enabled the beginning of the radiation dominated stage of the Universe, could have also proceeded through different mechanisms (perturbative \cite{2}, nonperturbative \cite{3} (see also the discussion of different reheating mechanisms in ref. \cite{4})). Also different decay channels and different decay rates of the inflaton and other particles, and different thermalization (instant or delayed) are possible \cite{5}. Therefore, it is interesting to consider the possibility for production of the observed baryon asymmetry $\beta = 6 \times 10^{-10}$ for different reheating temperatures in different inflationary models.

In this work we analyze the baryon asymmetry generation according to the Scalar Field Condensate (SCF) baryogenesis model for several inflationary scenarios and different reheating models.

1.1 Baryon Asymmetry of the Universe

The generation of the baryon asymmetry of the Universe is one of the open cosmological issues. Both cosmic ray data and gamma ray data indicate that there are no significant quantities of antimatter in the local vicinity up to galaxy cluster scales of 10-20 Mpc \cite{6, 7, 8, 9, 10}. It is most probable that our Universe is made of matter.

The baryon asymmetry is usually described by:

$$\beta = (N_b - N_{\bar{b}})/N_\gamma \sim N_b/N_\gamma = \eta,$$  \hspace{1cm} (1)

where $N_b$ is the number of baryons, $N_{\bar{b}}$ is the number of anti-baryons, $N_\gamma$ - the number of photons.
The baryon-to-photon ratio $\eta$ is precisely measured today, namely:
\[ \eta \sim 6 \times 10^{-10}, \]  
(2)
the best baryometers being BBN and CMB measurements. Among the light elements produced during BBN Deuterium is the most sensitive to $\eta$, thus the most precisely obtained $\eta$, based on BBN theory and D observations is [11]:
\[ \eta_D = 6 \pm 0.3 \times 10^{-10} \text{ at } 95\% \text{ C.L.} \]
The CMB anisotropy data measures $\eta$ with comparative accuracy, namely (see ref.[12]):
\[ \eta_{\text{CMB}} = 6.11 \pm 0.04 \times 10^{-10} \text{ at } 68\% \text{ C.L.} \]

Though these independent measurements correspond to quite different epochs, namely BBN proceeds at $z \sim 10^9$, while CMB to $z \sim 1000$ they are in excellent agreement, i.e. there was no change in this ratio between the two epochs.

At present there exist many baryogenesis models, which successfully generate this number at quite different epochs, in the wide range between the end of inflation and before BBN. Just to mention the most popular ones: GUT baryogenesis [13, 14], SUSSY baryogenesis, baryogenesis through leptogenesis [15], Afleck and Dine baryogenesis [16], Scalar Field Condensate baryogenesis (SFC) [2, 17], etc.

In the next section we provide a short description of the SFC baryogenesis model. In the third section we present our results for the calculated baryon asymmetry $\beta$ in different inflationary scenarios and different reheating models. In the conclusion we list the main results and present a short discussion.

2. **SFC short description**

First ideas on SFC baryogenesis model and analytical construction of that model were presented in refs. [2, 17]. In following publications an inhomogeneous SFC baryogenesis model was explored semi-analytically, and was applied to explain the very large scale structure in the universe and the quasi-periodicity found at very large scales with typical period of 128 $h^{-2}$ Mpc [18, 19, 20]. Since first analytical considerations [2] it is known that particle creation processes play important role for the determination of the baryon asymmetry generation in that model. Recently, more precise numerical account for particle creation processes and their role in SFC baryogenesis was provided in refs. [21, 22, 23]. According to SCF baryogenesis model at the inflationary stage there existed the inflaton $\phi$ and a complex scalar field $\varphi$, carrying baryon charge. During inflation, as a result of the rise of quantum fluctuations of $\phi$, a condensate $<\varphi>$ $\neq$ 0 with a nonzero baryon charge $B$ is formed [24, 25, 26]. $B$ is not conserved at large $\varphi$ due to the presence of B non-conserving (BV) self-interaction terms in the potential $V(\varphi)$.

The equation of motion of $\varphi$ is:
\[ \ddot{\varphi} + 3H\dot{\varphi} + \frac{1}{4}\Gamma_2\varphi + U_\varphi = 0, \]  
(3)
where $a(t)$ is the scale factor, $H$ is the Hubble parameter $H = \dot{a}/a$, $\Gamma_2 = \alpha\Omega$ is the rate of particle creation, $\Omega = 2\pi/T$, where $T$ is the period of the field oscillations. The analytically estimated value: $\Omega_0 = \lambda^{1/2}\varphi_0$, is used as an initial condition of the frequency.

The potential is chosen of the form:
\[ U(\varphi) = m^2\varphi^2 + \frac{\lambda_1}{4}|\varphi|^4 + \frac{\lambda_2}{4}(\varphi^4 + \varphi'^4) + \frac{\lambda_3}{4}|\varphi|^2(\varphi^2 + \varphi'^2). \]  
(5)

The following natural assumptions are made: the mass parameters of the potential are small in comparison with the Hubble parameter during inflation $m \ll H_I$, the self-coupling constants $\lambda_i$ are of the order of the gauge coupling constant $\alpha$ and $m$ is in the range $10^2 - 10^4$ GeV. The energy density of $\varphi$ at the inflationary stage is of the order $H_I^4$, hence
\[ \varphi_0^{\text{max}} \sim H_I \lambda^{1/4}, \quad \varphi_0 = (H_I)^2, \quad B_0 = H_I^3. \]  
(6)
At the end of inflationary stage $\varphi$ starts to oscillate around its equilibrium and its amplitude decreases due to the Universe expansion and the particle creation processes, resultant from the coupling of the scalar field to fermions.
In SFC baryogenesis model $B$, contained in the condensate, can be considerably reduced due to particle creation at the BV stage [17, 27]. Therefore, at the high energy stage, where baryon violation is considerable, $B$, contained in $\varphi$ condensate, is reduced due to particle production.

Here we provide numerical account for the particle creation processes of $\varphi$.

BV becomes negligible at small $\varphi$. $B$ which survives until $B$-conservation epoch $t_b$, is transferred to fermions and the excess of matter is produced.

We have provided numerical analysis [27, 28, 21, 22] of the evolution of $\varphi(t) = x + iy$ and $B(t)$ from the inflationary stage until $t_f$. We developed a computer program in Fortran 77 using Runge-Kutta 4th order method. The system of ordinary differential equations, corresponding to the equation of motion for the real and imaginary part of $\varphi$ and $B$ contained in it was solved calculating $\Omega$ at each step. The numerical analysis included around 100 sets of parameters in their natural ranges of values: $\alpha = 10^{-3} - 5 \times 10^{-2}$, $H_I = 10^7 - 10^{12}$ GeV, $m = 100 - 1000$ GeV, $\lambda_1 = 10^{-3} - 5 \times 10^{-2}$, $\lambda_{2,3} = 10^{-4} - 5 \times 10^{-2}$. All considered in our calculations $H_I$ values are in agreement with the observational constraint from Planck data, namely: $H_I < 3.710^{-5} M_{pl}/(8\pi)^{1/2}$.

For each set of SFC baryogenesis model parameters we have calculated the final $B$ contained in the condensate $\varphi(t)$ before its decay. The dependence of the produced $B$ on the parameters of the models (namely $m$, $H_I$, $\lambda$, and $\alpha$) were revealed.

The produced baryon asymmetry $\beta = (N_B - N_\bar{B})/N_\gamma$ in SFC baryogenesis model depends on the generated baryon excess $B$, the reheating temperature of the Universe $T_R$ and the value of the Hubble parameter at the end of inflation $H_I$. Namely:

$$\beta \sim N_B / T_R^3 \sim B T_R / H_I,$$

(7)

$T_R$ and $H_I$ values depend on the kind of inflation and reheating.

Hence, in the present work we calculated the baryon asymmetry of the Universe produced in the SFC baryogenesis model using the available results on $B$ for all studied range of model's parameters from ref. [22] and considered different models of inflation and reheating. In the next section we present the results of our analysis for the generated baryon asymmetry $\beta$ in several inflationary models and different reheating scenarios.

### 3. Baryon Asymmetry in Different Inflationary Models

#### 3.1. Notes on Inflation and Reheating

The idea of an exponential inflationary stage in the early evolution of the Universe has been established as an extension to the standard cosmological model in order to resolve several conceptional problems of the standard cosmological model, among which homogeneity, isotropy, flatness of the Universe and the predicted over abundance of magnetic monopoles.

Now there exist hundreds models of inflation (see for example the Encyclopaedia Inflationaris collection [29]). Recently the inflation models were probed by the Planck data. Planck 2013, 2015, and 2018 releases have put strong constraints on several types of inflationary models.

Chronologically, the first realistic inflationary model was created by Starobinsky in 1980 [30]. The Starobinsky $R^2$ inflation model has a potential as follows:

$$V(\psi) = \Lambda^4 \left(1 - e^{-\sqrt{\Lambda M_{pl}}/M_{pl}}\right)^2$$

(8)

The model is in a good agreement with Planck18 data.

In 1981 Linde [31] and Albrecht and Steinhardt [32] independently proposed a new inflation or slow-roll inflation model, where inflation occurred by a scalar field rolling down a potential energy hill, instead of tunneling out of a false vacuum state, as in ref. [33].

In 1983 the chaotic inflationary model was proposed, which does not require an initial state of thermal equilibrium, supercooling and tunneling from the false vacuum. This class of inflationary models has a single monomial potential [34]:

$$V(\psi) = \lambda M^4 \left(\frac{\psi}{M^4}\right)^p,$$

(9)

where inflation occurs at $\psi > M^4$. Planck18 data disfavors potentials with $p \geq 2$ but models with simple linear potentials $p = 1$ or $p = 2/3$ and fractional power monomials are more compatible.
Other popular inflationary model is the model of \textit{quintessential inflation} of Peebles and Vilenkin [35], which provides a unified description for both the inflationary stage and the current acceleration stage of the Universe using a single scalar field potential:

\begin{equation}
V = \lambda \psi^4 + M^4, \quad \psi < 0, \quad (10)
\end{equation}
\begin{equation}
V = \frac{\lambda M^8}{\psi^4 + M^4}, \quad \psi \geq 0. \quad (11)
\end{equation}

At $-\psi > M$ this is a “chaotic” inflation potential [34], at $\psi > M$ it is a “quintessence” form, $\lambda = 1 \times 10^{-14}$. Some model improvements were proposed lately to obtain agreement with the recent Planck18 observational data [36].

Planck CMB anisotropy measurements [37] put constraints on inflationary models.

We have considered here the following inflationary models: the new inflation [31, 32], Shafi-Vilenkin model of new inflation, chaotic inflation [34, 38], Shafi-Vilenkin model of chaotic inflation, chaotic inflation in SUGRA, Starobinsky inflation [39], MSSM inflation and quintessential inflation.

Besides the great variety of inflationary models, there exist also different possibilities for reheating realizations after inflation. During reheating the inflaton energy is transferred to other dynamical degrees of freedom, which results in radiation dominated stage of the Universe. However, there exist different reheating mechanisms [40]. The resultant $T_R$ depends on the way reheating proceeds: namely reheating by perturbative decay of the inflaton $\psi$ and by non-perturbative decay of the inflaton $\psi$, it depends also on the inflaton decay rate, on the spectrum of inflaton decay particles, on the thermalization after inflation (instantaneous or delayed) reheating, etc. [41].

There exist CMB and BBN constraints on the inflationary reheating temperature. Reheating should proceed before BBN and $T_R > 5$ MeV, so that low reheating temperature would not effect strongly the properties of neutrino and consequently BBN He production and CMB [42, 43].

On the other hand, reheating should proceed at low enough energy so that GUT symmetry is not restored and thus monopole problem is evaded. Besides in SUSY models in order to avoid gravitino overproduction, which can destroy BBN predictions the reheating temperature should be $T_R < 10^7 - 10^9$ GeV. This is a constraint in case gravitinos are in the mass range (100 GeV - 1 TeV) [44]. When gravitino mass is $> 10$ TeV, another constraint holds: $T_R < 10^{11}$ GeV, following from the constraints on gravitino number from overclosure bound [45].

In the 90ies of the previous century the preheating by perturbative decay of the inflaton $\psi$ into fermions was considered. See the pioneer works of refs. [2, 46]. Reheating takes place when $H$ drops to the value of $\Gamma$, the total decay rate of the inflaton, and inflaton decay becomes effective. Using the Friedmann equation and assuming an \textit{instantaneous} conversion of the inflaton energy at the end of inflation into radiation $\rho_r = g_* \pi^2 / 30 T^4 = \rho_\psi$ and \textit{fast thermalization}, the reheating temperature is given by:

\begin{equation}
T_R = \left( \frac{90}{8 \pi^3 g_*} \right)^{1/4} (M_P H)^{1/2}. \quad (12)
\end{equation}

Reheating completes when $H$ becomes less than $\Gamma/2$. Then an upper bound is obtained for $\Gamma = 2H$ in case of efficient thermalization, namely:

\begin{equation}
T_R = \left( \frac{90}{32 \pi^3 g_*} \right)^{1/4} (M_P \Gamma)^{1/2}, \quad (13)
\end{equation}

where $g_*$ is of the order $10^2$, $T_R \sim 0.1 (M_P \Gamma)^{1/2}$. Then the typical $T_R$ is less than $10^9$ GeV [47, 48].

However, $\psi$ may decay into other bosons due to broad resonance [47, 48, 49]. In this case $T_R$ may be $\sim 10^{12}$ GeV, i.e. much higher than $T_R$ estimated in eq.13. Non-perturbative preheating was discussed for example in refs. [50, 51, 52, 53].

On the other hand, $T_R$ may be much smaller than these estimations in case of \textit{slow thermalization} when local thermodynamical equilibrium is not reached until the beginning of the RD epoch. This is usually the case for small inflaton couplings and very big inflaton masses. The conditions for efficient or inefficient thermalization were discussed in ref. [5].

Thus, there is a large range of the allowed values of $T_R$. We have used in our analysis $T_R$ in the range $[10^5, 10^{14}]$ GeV.

\section*{3.2 Baryon Asymmetry in Different Inflationary Models - Results}

Here we present our results of the baryon asymmetry value calculated for different reheating possibilities and different inflationary scenarios. First consideration of SFC baryogenesis model in different inflationary scenarios and preliminary results were reported in ref. [54, 55]. In the present work we considered all $B$-excess values in the whole range of studied parameter sets of the SFC baryogenesis model.
The results of our analysis on the calculated $\beta$ for certain $T_R$ values corresponding to different inflationary scenarios and different types of thermalization are presented below:

3.2.1 Inflationary models with overproduction of baryon asymmetry

In case of new inflation [56, 32] for $H_I = 10^{10}$ GeV and $T_R = 10^{14}$ GeV we have found that the calculated baryon asymmetry for all sets of model’s parameters is several orders of magnitudes bigger than the observational value $\beta_{obs}$. (The same holds if one varies $H_I$ within the range $[5 \times 10^9, 5 \times 10^{10}]$ GeV.)

In the new inflation model by Shafi and Vilenkin [57] for $H_I = 3 \times 10^9$ GeV and $T_R = 3 \times 10^7$ GeV, the calculated baryon asymmetry again is much bigger than $\beta_{obs}$, namely $\beta > 10^{-7}$. (We have calculated $\beta$ for all sets of the SFC model parameters and for $H_I$ in the range $[10^8 - 10^{10}]$ GeV.)

In case of chaotic inflation, for $H_I \in [10^{11}, 10^{12}]$ GeV, and $T_R < 3 \times 10^{14}$ GeV, namely we have used $T_R \in [10^{12}, 10^{14}]$ GeV, the calculated asymmetry is $\beta > 10^{-3}$.

For the simplest Shafi-Vilenkin model in chaotic inflation $T_R = 10^{12} - 10^{13}$ GeV again $\beta > 10^{-7}$. We have provided the analysis for $H_I \in [5 \times 10^9, 10^{12}]$ GeV.

However, depending on the inflaton decay rate, decay channels, couplings, $T_R$ may be lower, namely $T_R \in [10^{9}, 10^{11}]$ GeV. $T_R$ may be lower, thus allowing successful baryogenesis in these chaotic inflationary models, i.e. even in case of big $H_I \sim 10^{12}$ GeV $\beta_{obs}$ can be obtained (as will be discussed in the next subsection).

In MSSM inflation model [60, 61] with $H_I = 1$ GeV, $T_R = 2 \times 10^8$ GeV, SCF baryogenesis model does not work, $\beta >> \beta_{obs}$. This inflationary model also has severe problems with gravitino overproduction, violating BBN and observed DM abundance.

3.2.1 Inflationary models with successful production of the observed baryon asymmetry

We have used the values of $T_R$ and $m_\phi$ for $\alpha_\phi = 10^{-11}$ from ref. [5] to calculate the baryon asymmetry for the different cases, different $T_R$. (Assuming $\Gamma = \alpha_\phi m_\phi$ the authors have calculated $T_R(m_\phi)$ from ref. [58] for different $\alpha_\phi$ and for delayed and efficient thermalization.)

In case of efficient thermalization we have found that the production of the observed value of $\beta$ is possible for $H_I = 10^{12}$ GeV, $T_R = 6.2 \times 10^9$ GeV and specific sets of SFC model’s parameters, namely: $\lambda_1 = 5 \times 10^{-2}$, $\alpha = [3 \times 10^{-2}, 5 \times 10^{-2}], \lambda_2 = \lambda_3 = [10^{-3}, 10^{-2}], m = 350$ GeV. For $H_I = 10^{11}$ GeV and $T_R = 1.9 \times 10^9$ GeV the production of the observed value of $\beta$ is possible when $\lambda_1 = 5 \times 10^{-2}, \lambda_2 = \lambda_3 = 10^{-2}$ and $m = 100, 200$ and 350 GeV.

In case of delayed thermalization there appear possibilities for the production of $\beta_{obs}$ corresponding to $H_I = 10^{12}$ GeV, $T_R = 4.5 \times 10^8$ GeV and several different sets of model’s parameters in the following ranges $\lambda_1 \in [5 \times 10^{-2}, 10^{-2}]; \alpha \in [5 \times 10^{-2}, 10^{-2}], \lambda_2 = \lambda_3 = 10^{-3}$ and $m = 350 - 500$ GeV. It could be easily seen that the strongest influence comes from $\alpha$ parameter of the model and then from $m$. For fine tuning $\lambda_1$ can be used and then $\lambda_2 = \lambda_3$ parameters of the SCF model. (We have studied $H_I$ in the range $[5 \times 10^9 - 10^{12}]$ GeV.)

In case of modified Starobinsky inflation [30] $T_R = 0.1(TM_{Pl})^{1/2} = 10^9$ GeV, $H_I = 10^{11}$ GeV, successful baryogenesis is possible for the efficient thermalization as well. Namely $\beta = \beta_{obs}$ was found possible for several sets of model’s parameters. (We have studied $H_I$ in the range $[5 \times 10^9, 10^{12}]$ GeV.) For the simplest extension of the Starobinsky inflation see ref. [59].

For monomial potential of eqn. 8 we have calculated $\beta$ for $p = 2/3$ and $T_R \in [10^9, 10^{11}]$ GeV. For $T_R = 10^9$ GeV and $H_I \sim 10^{11}$ GeV $\beta_{obs}$ can be produced.

For chaotic inflation in SUGRA [62] $T_R > 10^9$ GeV it is possible to generate $\beta_{obs}$.

In quintessential inflation with $T_R = 2 \times 10^5$ GeV and decay into massless particles, the production of the baryon asymmetry is successful for $H_I = 10^{12}$ GeV and several sets of SCF model parameters as well. When $m = 350$ GeV, the favored value of $\alpha$ parameter is $\alpha = 10^{-3}$ with wider range of $\lambda_1 \in [10^{-3}, 5 \times 10^{-2}]$ and $\lambda_2 = \lambda_3 \in [10^{-4}, 5 \times 10^{-3}]$. Again, strong dependence of $\alpha$ parameter may be mentioned since $\alpha$ reflects on the time of the scalar field decay and therefore it has influence on the baryon excess and baryon asymmetry values.

The particular parameters sets of the SCF baryogenesis model and the inflationary models and the types of thermalization, for which successful production of the baryon asymmetry close to its observational value is possible, are listed in the table.

As it can be seen from the Table 1 in case of Starobinsky and chaotic inflationary scenarios with successful production of the baryon asymmetry value for $T_R \in [4.5 \times 10^8, 6.2 \times 10^9]$ GeV and $H_I \in [10^{11}, 10^{12}]$, the SFC
SFC baryogenesis may be achieved more easily in the chaotic inflationary models. Curiously enough these are also inflationary models: Modified Starobinsky inflation, chaotic inflation with lower reheating temperature, chaotic inflation with high reheating temperature, the simplest Shafi-Vilenkin chaotic inflationary model and MSSM inflation.

For the following inflationary models: new inflation, new inflation model by Shafi and Vilenkin, chaotic inflation with different reheating temperatures, as given in Table 1.

| Inflation Model                      | $H_I = 10^{11}$ GeV; $T_R = 10^9$ GeV | $H_I = 10^{12}$ GeV; $T_R = 10^9$ GeV | $H_I = 10^{12}$ GeV; $T_R = 2 \times 10^5$ GeV | $H_I = 10^{12}$ GeV; $T_R = 6.2 \times 10^9$ GeV | $H_I = 10^{12}$ GeV; $T_R = 4.5 \times 10^8$ GeV |
|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Starobinsky Inflation               | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 100$ GeV, $\beta = 9.3 \times 10^{-10}$ | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 8.0 \times 10^{-10}$ | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 6.6 \times 10^{-10}$ | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 4.6 \times 10^{-10}$ | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 7.8 \times 10^{-10}$ |
| Quintessential Inflation            | $\lambda_1 = \alpha = 5 \times 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 6.6 \times 10^{-10}$ | $\lambda_1 = \alpha = 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 7.4 \times 10^{-10}$ | $\lambda_1 = \alpha = 10^{-3}$, $\lambda_2 = \lambda_3 = 10^{-4}$, $m = 350$ GeV, $\beta = 3.6 \times 10^{-10}$ |
| Chaotic Inflation, Efficient Thermalization | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-2}$, $m = 350$ GeV, $\beta = 4.6 \times 10^{-10}$ | $\lambda_1 = \alpha = 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 9.5 \times 10^{-10}$ | $\lambda_1 = \alpha = 5 \times 10^{-2}$, $\lambda_2 = \lambda_3 = 10^{-3}$, $m = 350$ GeV, $\beta = 3.6 \times 10^{-10}$ |

parameters can be approximately fixed - they lie within the following ranges: $m \sim 350$ GeV (with one exception) $\alpha \in [10^{-2}, 5 \times 10^{-2}]$, $\lambda_1 \sim 5 \times 10^{-2}$, $\lambda_{2,3} \in [10^{-3}, 10^{-2}]$.

In case of quintessential inflation, however, for $H_I \sim 10^{12}$ GeV and $m \sim 350$ GeV, the reheating temperature is much lower $T_R \sim 2 \times 10^5$ GeV and the rest of the SFC parameters - the coupling constants have lower values, namely $\alpha \sim 10^{-3}$, $\lambda_1 \in [5 \times 10^{-3}, 10^{-2}]$, $\lambda_{2,3} \in [10^{-4}, 5 \times 10^{-3}]$.

Quintessential inflationary models need the smallest $\lambda_1$ and $\alpha$, by order of magnitude smaller than the ones in other considered here inflationary models. If we impose the requirement for the value of $\alpha$ to be close to the $\alpha_{GUT}$, SFC baryogenesis cannot be realized in Quintessential inflation.

Vice versa, fixing the inflationary model we can fix the SFC model parameters.

In Figure 1 we present in the $\alpha$-$\lambda_{2,3}$ plane the inflationary models in which the closest to the observational baryon asymmetry value is generated. The other fixed values for model parameters are: $\lambda_1 = 5 \times 10^{-2}$, $m = 350$ GeV and $H_I = 10^{12}$ GeV. Mind that, however, the models correspond to different reheating temperatures, as given in Table 1.

We have also results for SUGRA inflationary model. In case of $T_R \sim 10^{12}$ GeV the obtained $\beta$ are bigger than the observational value independent of the $H_I$ value assumed. For $T_R = 10^9$ GeV, the results coincide with the ones for Starobinsky model.

### Conclusions

On the basis of the numerical analysis of the evolution of baryon charge $B(t)$ produced in the SFC baryogenesis model and the estimation of the produced baryon asymmetry for different sets of models parameters and different reheating temperatures of several inflationary scenarios we have shown that:

(i) SFC baryogenesis model produces baryon asymmetry by orders of magnitude bigger than the observed one for the following inflationary models: new inflation, new inflation model by Shafi and Vilenkin, chaotic inflation with high reheating temperature, the simplest Shafi-Vilenkin chaotic inflationary model and MSSM inflation.

For these models SCF baryogenesis needs strong diluting mechanisms in order to reduce the resultant baryon excess at low energies to its observational value today.

(ii) SFC baryogenesis model produces similar to the observed value of the baryon asymmetry in the following inflationary models: Modified Starobinsky inflation, chaotic inflation with lower reheating temperature, chaotic inflation in SUGRA and Quintessential inflation. In case of delayed thermalization, when $T_R$ is much lower, a successful SFC baryogenesis may be achieved more easily in the chaotic inflationary models. Curiously enough these are also
FIGURE 1. The figure presents different inflationary models in the $\alpha$-$\lambda_{2,3}$ plane for which successful SFC baryogenesis is achieved for the following parameters: $\lambda_1 = 5 \times 10^{-2}$, $m = 350$ GeV and $H_I = 10^{12}$ GeV.

models preferred by the Planck CMB data analysis.

However, choosing for the value of $\alpha$ the value closest to the $\alpha_{GUT}$, it is possible to conclude that SFC baryogenesis cannot be realized in Quintessential inflation.

Vice versa, fixing the inflationary model we can fix the SFC model parameters.

Encouraged by the numerous possibilities of successful $\beta$ generation found for the discussed in this work inflationary models, we consider it interesting to continue the study SFC baryogenesis model in other inflationary models and also to expand the numerical analysis towards higher values of $m$ and $H_I$. The latter is necessary because there exist models, like power law inflation, braneworld inflation, quintessential power law inflation, etc. which require higher than the upper bound used in our analysis values of $H_I$, i.e. higher than $H_I \sim 10^{12}$ GeV.

ACKNOWLEDGMENTS

We acknowledge the partial financial support by project DN18/13-12.12.2017 of the Bulgarian National Science Fund of the Bulgarian Ministry of Education and Science.

REFERENCES

[1] Linde A., Phys. Scripta T117, 40, (2005).
[2] Dolgov A., Kirilova D., Sov. J. Nucl. Phys. 51, 172, (1990).
[3] Felder G., Kofman L., Linde A., JHEP 0002, 027, (2000).
[4] Moghaddam H., PhD thesis "Reheating in the Early Universe Cosmology", (2017).
[5] Mazumdar A., Zaldívar B., Nuclear Physics B886, 312, (2014).
[6] Steigman G., Ann. Rev. Astron. Astrophys., 14, 339, (1976).
[7] Steigman G., J. Cosmol. Astropart. Phys., 0910, 001, (2008).
[8] Stecker F., Nucl. Phys. B, 252, 25, (1985).
[9] Ballmoos P., Hyperfine Interact., 228, 91, (2014).
[10] Dolgov A., EPJ Web of Conferences, 95, 03007, (2015).
[11] Pettini M., Cooke R., Mon. Not. Roy. Astron. Soc., 425, 2477, (2012).
[12] Ade P., et al. [Planck Collaboration], Astron. Astrophys., 594, A13, (2016).
[13] Sakharov A., JETP, 5, 32, (1967).
[14] Kuzmin V., Rubakov V., Shaposhnikov M., Phys. Rev. Lett. 84, 3756, (1985).
[15] Fukugita M., Yanagida T., Phys. Lett. B174, 45, (1986).
[16] Affleck I., Dine M., Nucl. Phys. B, 249, 361, (1985).
[17] Dolgov A., Kirilova D., J. Moscow Phys. Soc. 1, 217, (1991).
[18] Chizhov M., Kirilova D., AATr. 10, 69, (1996).
[19] Kirilova D., Chizhov M., MNras, 314, 256, (2000).
[20] Kirilova D., Nucl. Phys. Proc. Suppl. 122, 404, (2003).
[21] Kirilova D., Panayotova M., BAJ 20, 45, (2014).
[22] Kirilova D., Panayotova M., Advances in Astronomy, 465, (2015).
[23] Panayotova M., Kirilova D., Bulg. J. Phys. 43, 327–333, (2016).
[24] Vilenkin A., Ford L., Phys. Rev. D26, 1231, (1982).
[25] Bunch T., Davies P., Proc. R. Soc. London, Ser. A 360, 117, (1978).
[26] Starobinsky A., Phys. Lett. B117, 175, (1982).
[27] Kirilova D., Panayotova M., Bulg. J. Phys. 34 s2, 330, (2007).
[28] Kirilova D., Panayotova M., Proc. 8th Serbian-Bulgarian Astronomical Conference (VIII SBGAC), Leskovac, Serbia 8-12 May, (2012).
[29] Martin J., Ringeval C., Vennin V., Phys. Dark Univ.5-6, 75, (2014); Martin J., Ringeval C., Trotta R., Vennin V., JCAP 1403, 039, (2014).
[30] Starobinsky A., Phys. Lett. B91, 99, (1980).
[31] Linde A., Phys. Lett. B108, 389, (1982).
[32] Albrecht A., Steinhardt P., Phys. Rev. Lett. 48, 1220, (1982).
[33] Guth A., Phys. Rev. D 23, 347, (1981).
[34] Linde A., Phys. Lett., 129B, 177, (1983); Phys. Lett., 162B, 281, (1985).
[35] Peebles P., Vilenkin A., Phys.Rev. D59, 063505 (1999).
[36] Haro J., Amoros J., Pan S., Eur. Phys. J. C79, 505 (2019).
[37] Akrami Y., et al. [Plank Collaboration], Astronomy & Astroph. 641, A10, (2020).
[38] Linde A., Particle Physics and Inflationary Cosmology, Harwood, Chur, Switzerland, (1990).
[39] Kofman L., Linde A., Starobinsky A., Phys. Lett. B157, 36, (1985).
[40] Moghaddam H., PhD Thesis "Reheating in Early Universe Cosmology".
[41] Marko A., Gasperis G., Paradis G., Cabella P., arXiv:1907.06084.
[42] Martin J., Ringeval C., Vennin V., Phys. Rev. Lett. 114, no.8, 081303, (2015); Kawasaki M., Kohri K., Sugiyama N., Phys. Rev. Lett. 82, 4168, (1999).
[43] Salas P., Lattanzi M., Mangano M., Miele G., Pastor S., Pisanti O., PRD 92, 12, 123534 (2015).
[44] Kawasaki M., Kohri K., Moroi T., PRD 53, 103502, (2001).
[45] Giudice G., Tkachev I., Riotto A., JHEP 9908, 009, (1999); Buchmuller W., NPB 606, 518, (2001).
[46] Traschen J., Brandenberger R., PRD 42, 2491, (1990).
[47] Kofman L., Linde A., Starobinsky A., Phys. Rev. Lett. 73, 3195, (1994).
[48] Kofman L., Linde A., Starobinsky A., Phys. Rev. D 56, 3258, (1997).
[49] Boyanovsky D., et. al., PRD 52, 6805, (1995); PRD 51, 4419, (1995).
[50] Allahverdi R., et. al., Phys. Rev. D83, 123507, (2011).
[51] Felder G., Kofman L., Linde A., Phys. Rev. D59, 123523, (1999).
[52] Fujisaki H., et. al., Phys. Rev. D53, 6805, (1996).
[53] Allahverdi R., Bastero-Gil M., Mazumdar A., Phys. Rev. D64, 023516, (2001).
[54] Kirilova D., Panayotova M., AIP Conf. Proc. 2075, 090017, (2019).
[55] Kirilova D., Panayotova M., Publ. Astron. Soc. "Rudjer Bockovic", Proc. XII SB Astronomical Conference, 25-29 September 2020, Sokobanja, Serbia (to be published).
[56] Dolgov A., Linde A., Phys. Lett. 116B, 329, (1982).
[57] Shafi O., Vilenkin A., Phys. Rev. Lett. 52, 691, (1984).
[58] Abbott L., Fahri E., Wise M., Phys. Lett. B117, 29, (1982).
[59] Van de Bruck C., Dansby P., Paduraru L., International Journal of Modern Physics D 26, 13, (2013).
[60] Allahverdi A., et. al., Phys. Rev. Lett 97, 191304, (2006).
[61] Ferrantelli A., Eur. Phys. J. C 77, 716, (2017).
[62] Nanopoulos D., Olive K., Srednicki M., Phys. Lett. B127, 30, (1983).