The Predictive Power of Computational Astrophysics as a Discovery Tool
Proceedings IAU Symposium No. 362, 2023
D. Bisikalo, D. Wiebe & C. Boily, eds.
doi:10.1017/S174392132200151X

Favoured Inflationary Models by SFC Baryogenesis

Mariana Panayotova[1] **and Daniela Kirilova**[2]

[1]Institute of Astronomy with National Astronomical Observatory,
Bulgarian Academy of Sciences
email: mariana@astro.bas.bg

[2]Institute of Astronomy with National Astronomical Observatory,
Bulgarian Academy of Sciences
email: dani@astro.bas.bg

Abstract. We provide analysis of the baryon asymmetry generated in the Scalar Field Condensate (SFC) baryogenesis model obtained in new inflation, chaotic inflation, Starobinsky inflation, MSSM inflation, quintessential inflation, considering both cases of efficient thermalization after inflation and also delayed thermalization. We have found that baryon asymmetry generated in SFC baryogenesis model is considerably bigger than the observed one for the 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. Therefore, strong diluting mechanisms are needed to reduce the baryon excess to its observational value today for these models. We have shown that for the SFC baryogenesis model a successful generation of the observed baryon asymmetry is possible in Modified Starobinsky inflation, chaotic inflation with low reheating temperature, chaotic inflation in SUGRA and quintessential inflationary model.

Keywords. early univese

1. Introduction

Here we present shortly the results of our study of SFC baryogenesis models in different inflationary scenarios, published in Kirilova&Panayotova (2021).

Cosmic and gamma-ray data indicate that there is no significant antimatter quantity up to galaxy cluster scales of 10-20 Mpc Steigman (1976), Steigman (2008), Stecker (1985), Ballmoos (2014), Dolgov (2015)†. Hence, a generation of the observed baryon asymmetry from initially matter-antimatter symmetric state of the very early Universe must have happened in the period after inflation, but before Big Bang Nucleosynthesis (BBN) epoch.

Baryon asymmetry is usually described by the baryon density or the baryon to photon ratio:

$$\beta = (N_b - N_{\bar{b}})/N_\gamma \sim N_b/N_\gamma = \eta, \tag{1.1}$$

† However, small quantities of antimatter, even in our Galaxy have been observed, see refs. Dolgov (2021), Dolgov (2022), where indications about the presence of 14 anti-stars in our Galaxy are presented. The fractional density of compact anti-stars in the universe up to 10% does not contradict the existing observational bounds, see for instance ref. Blinnikov, Dolgov&Postnov (2015) and references there in. The observational limits on anti-stars are less constraining than on gas clouds of antimatter because surface annihilation on the stars is not as efficient as the volume annihilation ref. Steigman (1976).

and is known with high precision from BBN and Cosmic Microwave Background (CMB) measurements. Namely, $\eta \sim 6 \times 10^{-10}$.

1.1. *SFC baryogenesis model short description*

There exist various baryogenesis models which generate successfully this number at different epochs before BBN - GUT baryogenesis, SUSSY baryogenesis, baryogenesis through leptogenesis, warm baryogenesis, etc. Here we discuss the SFC baryogenesis Dolgov&Kirilova (1990), Dolgov&Kirilova (1991) based on the Affleck and Dine baryogenesis scenario Affleck&Dine (1985).

According to SFC baryogenesis model at the end of inflation besides the inflaton ψ, there existed a complex scalar field φ, carrying baryon charge. B is not conserved at large φ due to the presence of B non-conserving (BV) self-interaction terms in the potential V(φ), while at small φ BV is negligible. During inflation because of the rise of quantum fluctuations of φ, a condensate $<\varphi>\neq 0$ with a nonzero baryon charge B was formed Vilenkin&Ford (1982), Bunch&Davies (1978), Starobinsky (1982).

At the end of inflation φ starts to oscillate around its equilibrium and its amplitude decreases due to the universe expansion and particle creation processes of scalar field to fermions Dolgov&Kirilova (1990), Kirilova&Panayotova (2007). B which survives until B-conservation epoch t_B, is transferred to fermions. For more details about SFC baryogenesis model see Kirilova&Panayotova (2015) and Kirilova&Panayotova (2021).

2. Baryon asymmetry production in different inflationary models and different reheating scenarios

2.1. *Description of the numerical analysis*

We have provided numerical analysis of the SFC baryogenesis model. We have used the following equation of motion describing the evolution of φ:

$$\ddot{\varphi} + 3H\dot{\varphi} + \frac{1}{4}\Gamma_\varphi \dot{\varphi} + U'_\varphi = 0, \tag{2.1}$$

where $a(t)$ is the scale factor, H is the Hubble parameter $H = \dot{a}/a$. $\Gamma_\varphi = \alpha\Omega$ 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 in the numerical analysis.

The field potential was chosen of the form:

$$U(\varphi) = m^2\varphi^2 + \frac{\lambda_1}{2}|\varphi|^4 + \frac{\lambda_2}{4}(\varphi^4 + \varphi^{*4}) + \frac{\lambda_3}{4}|\varphi|^2(\varphi^2 + \varphi^{*2}). \tag{2.2}$$

The following assumptions were made: the mass is $m \ll H_I$ and $m = 10^2 - 10^4$ GeV, the self-coupling constants λ_i are of the order of the gauge coupling constant α. The energy density of φ at the inflationary stage is of the order H_I^4, hence

$$\varphi_o^{max} \sim H_I \lambda^{-1/4}, \quad \dot{\varphi}_o = (H_I)^2, \quad B_0 = H_I^3. \tag{2.3}$$

We have developed a program in fortran 77 using 4th order Runge-Kutta method to solve the system of ordinary differential equations, corresponding to the equation of motion for the real and imaginary part of φ and B. We have provided a numerical analysis Kirilova&Panayotova (2007), Kirilova&Panayotova (2012), Kirilova&Panayotova (2014), Kirilova&Panayotova (2015) of the evolution of φ,

$$\varphi(t) = x + iy \quad and \quad B(t) = -i(\dot{\varphi}^*\varphi - \dot{\varphi}\varphi^*) \tag{2.4}$$

from the inflationary stage until B conservation epoch for about 100 sets of parameters of SFC baryogenesis model.

The parameters ranges studied are: $\alpha = 10^{-3} - 5\times10^{-2}$, $H_I = 10^7 - 10^{12}$ GeV, $m = 100 - 1000$ GeV, $\lambda_1 = 10^{-3} - 5\times10^{-2}$, $\lambda_{2,3} = 10^{-4} - 5\times10^{-2}$.

The produced baryon asymmetry β in SFC baryogenesis model depends on the generated baryon excess B at the epoch t_B, the reheating temperature of the Universe T_R and the value of the Hubble parameter at the end of inflation H_I. Namely:

$$\beta \sim N_B/T_R^3 \sim BT_R/H_I. \tag{2.5}$$

T_R and H_I values depend on the type of inflation and reheating. First consideration of the SFC baryogenesis model in different inflationary scenarios and preliminary results were reported in refs. Kirilova&Panayotova (2019), Kirilova&Panayotova (2020). In the work Kirilova&Panayotova (2021) we considered all B-excess values in the whole range of the studied parameter sets of the SFC baryogenesis model and different values of T_R and H_I corresponding to the studied inflationary models and reheating scenarios.

We have considered the following inflationary models: the new inflation Linde (1982), Albrecht&Steinhardt (1982), Shafi-Vilenkin model of new inflation, chaotic inflation Linde (1985), Linde (1990), Shafi-Vilenkin model of chaotic inflation, chaotic inflation in SUGRA, Starobinsky inflation Kofman, Linde&Starobinsky (1985), MSSM inflation and quintessential inflation.

We have discussed different possibilities for reheating. Reheating temperature T_R depends on the model of reheating, perturbative or non-perturbative decay of the inflaton, inflaton decay rate, spectrum of the decay particles, thermalization after inflation (efficient or delayed) Marko et.al. (2020).

2.2. *Production of the baryon asymmetry – results and discussion*

Our calculations show that for the new inflation model Linde (1982), Albrecht&Steinhardt (1982) for $H_I = 10^{10}$ GeV and $T_R = 10^{14}$ GeV, the obtained baryon asymmetry β is by order of magnitude bigger than the observed for all sets of parameters. We calculated baryon asymmetry also for new inflation by Shafi and Vilenkin for $H_I = 3\times10^9$ GeV and $T_R = 3\times10^7$ GeV, Chaotic inflation for $H_I \in [10^{11}, 10^{12}]$ GeV and $T_R \in [10^{12}, 10^{14}]$ GeV, Shafi and Vilenkin Chaotic inflation for $T_R = 10^{12} - 10^{13}$ GeV and $H_I \in [5\times10^9, 10^{12}]$ GeV and MSSM inflation for $H_I = 1$ GeV, $T_R = 2\times10^8$ GeV. In these models, values orders of magnitude bigger than the observed baryon asymmetry are generated. Hence, for these inflationary models strong diluting mechanisms are necessary to reduce the resultant baryon excess to the value observed today.

The numerical analysis showed that baryon asymmetry equal to the observed one can be produced by the SFC baryogenesis model in the following inflationary models: Modified Starobinsky inflation with $T_R = 0.1(\Gamma M_{Pl})^{1/2} = 10^9$ GeV, $H_I = 10^{11}$ GeV; chaotic inflation with efficient thermalization for $H_I = 10^{12}$ GeV, $T_R = 6.2\times10^9$ GeV and for $H_I = 10^{11}$ GeV and $T_R = 1.9\times10^9$ GeV; chaotic inflation with delayed thermalization for $H_I = 10^{12}$ GeV, $T_R = 4.5\times10^8$ GeV; chaotic inflation with monomial potential with $p = 2/3$ and $T_R = 10^9$ GeV and $H_I \sim 10^{11}$ GeV; Chaotic inflation in SUGRA with $T_R > 10^9$ GeV; and Quintessential inflation with $T_R = 2\times10^5$ GeV and decay into massless particles, $H_I = 10^{12}$ GeV. The particular parameters sets of the SFC baryogenesis model are listed in Table 1. So, choosing the inflationary model, it is possible to fix the SFC baryogenesis model parameters.

In Figure 1 we present the successful inflationary models, corresponding to different reheating temperatures in the plane of α - $\lambda_{2,3}$ with fixed parameters for the SFC baryogenesis model, namely: $\lambda_1 = 5\times10^{-2}, m = 350$ GeV and $H_I = 10^{12}$ GeV. The models correspond to different reheating temperatures, see Table 1.

Table 1. Successful production of the observed baryon asymmetry β for particular sets of SFC model parameters in different inflationary scenarios. Table from ref. Kirilova&Panayotova (2021).

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

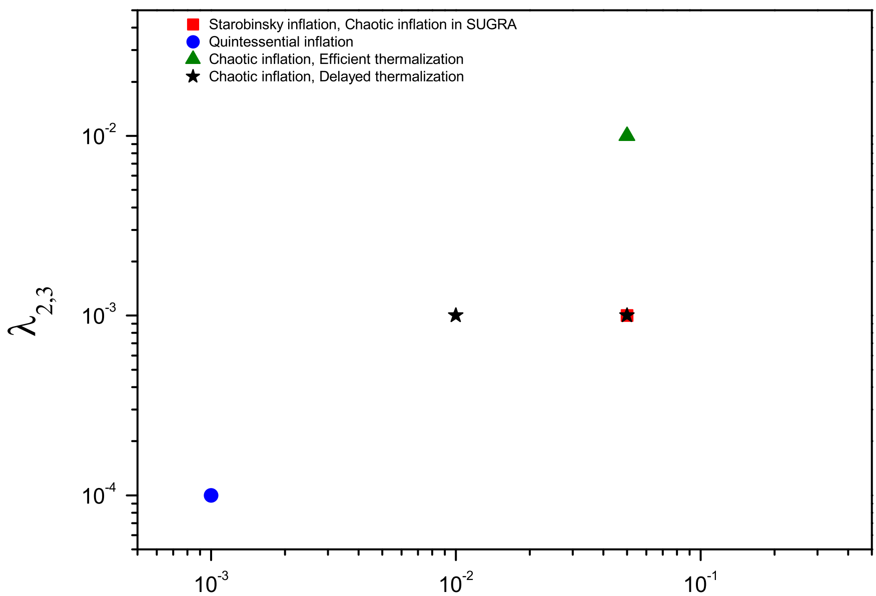

Figure 1. The figure presents different inflationary models in the α - $\lambda_{2,3}$ plane for which successful SFC baryogenesis is achieved for the following parameters: $\lambda_1 = 5 \times 10^{-2}, m = 350$ GeV and $H_I = 10^{12}$ GeV.

For successful production of β, the parameters α and λ have the same values in Starobynsky and Chaotic inflation. In case of chaotic inflation in SUGRA, our analysis has shown that for $T_R = 10^9$ GeV, the results coincide with these for Starobynsky inflation.

Quintessential inflationary model, however, needs an order of magnitude smaller parameters values to produce the observed baryon asymmetry.

https://doi.org/10.1017/S174392132200151X Published online by Cambridge University Press

3. Conclusion

The numerical analysis of the SFC baryogenesis model with different reheating temperatures of several inflationary scenarios has shown that:

(i) SFC baryogenesis model overproduces baryon asymmetry 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 strong diluting mechanisms are needed to reduce the baryon excess to its observational value.

(ii) SFC baryogenesis model produces close to the observed baryon asymmetry value 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, a successful SFC baryogenesis may be achieved in the chaotic inflationary models.

(iii) However, choosing for the value of α a value close to α_{GUT}, SFC baryogenesis cannot be realized in Quintessential inflation. Thus, in this case, SFC baryogenesis favors Starobynsky and Chaotic inflation.

4. Acknowledgements

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

Kirilova, D., Panayotova, M. 2021, *Galaxies*, 9, 49
Steigman, G. 1976 *Ann. Rev. Astron. Astrophys.*, 14, 339
Steigman, G. 2008, *J. Cosmol. Astropart. Phys.*, 0910, 001
Stecker, F. 1985, *Nucl. Phys. B*, 252, 25
Ballmoos, P. 2014, *Hyperfine Interact.*, 228, 91
Dolgov, A. 2015, *EPJ Web of Conferences*, 95, 03007
Dolgov, A. 2021, *Proceedings of 20th Lomonosov Conference on Elementary Particle Physics, ICNFP 2021* e-Print:2112.15255
Dolgov, A. 2021, *20th Lomonosov Conference on Elementary Particle Physics* e-Print:2201.04529
Blinnikov S., Dolgov A., Postnov K. 2015, *Phys.Rev.D* 92 2, 023516
Pettini, M., Cooke, R. 2012, *Mon. Not. Roy. Astron. Soc.*, 425, 2477
Ade, P., et.al. [Planck Collaboration] 2016, *Astron. Astrophys.*, 594, A13
Dolgov, A., Kirilova, D. 1990, *Sov. J. Nucl. Phys.*, 51, 172
Dolgov, A., Kirilova, D. 1991, *J. Moscow Phys. Soc.*, 1, 217
Affleck, I., Dine, M. 1985, *Nucl. Phys. B*, 249, 361
Vilenkin, A., Ford, L. 1982, *Phys. Rev. D*, 26, 1231
Bunch, T., Davies, P. 1978, *Proc. R. Soc. London, Ser. A*, 360, 117
Starobinsky, A. 1982, *Phys. Lett. B*,117, 175
Kirilova, D., Panayotova, M. 2007, *Bulg. J. Phys.*, 34 s2, 330
Kirilova, D., Panayotova, M. 2012, *Proc. 8th Serbian-Bulgarian Astronomical Conference (VIII SBGAC), Leskovac, Serbia 8-12 May*
Kirilova, D., Panayotova, M. 2014, *BAJ*, 20, 45
Kirilova, D., Panayotova, M. 2015, *Advances in Astronomy*, 465
Linde, A. 1982, *Phys. Lett. B*, 108, 389
Albrecht, A., Steinhardt, P. 1982, *Phys. Rev. Lett.*, 48, 1220
Linde, A. 1985, *Phys. Lett. B*, 129, 177, (1983); *Phys. Lett. B*, 162, 281
Linde, A. 1990, *Particle Physics and Inflationary Cosmology, Harwood, Chur, Switzerland*
Kofman, L., Linde, A., Starobinsky, A. 1985, *Phys. Lett. B*, 157, 36
Marko, A., Gasperis, G., Paradis, G., Cabella, P. 2020, *arXiv:1907.06084*
Kirilova, D., Panayotova, M. 2019, *AIP Conf. Proc.*, 2075, 090017
Kirilova, D., Panayotova, M. 2020, *Publ. Astron. Soc. "Rudjer Bockovic", Proc. XII SB Astronomical Conference, 25–29 September 2020, Sokobanja, Serbia*, 20, 39