Dynamics and Observational Constraints on a Scalar-tensor Model with Gauss-Bonnet Coupling

A. Banijamali [a] [1], **S. Bellucci** [b] [2], **B. Fazlpour** [c] [3] and **M. Solbi** [a]

[a] *Department of Basic Sciences, Babol Noshirvani University of Technology, Babol, Iran*

[b] *INFN - Laboratori Nazionali di Frascati, 1-00044, Frascati (Rome), Italy*

[c] *Department of Physics, Babol Branch, Islamic Azad University, Babol, Iran*

Abstract

In the current work we study the dynamics of a scalar-tensor model of dark energy in which scalar field that plays the role of dark energy, non-minimally coupled to the Gauss-Bonnet invariant in 4 dimensions. We utilize the dynamical system method to extract the critical points of the model. We find scaling attractor solutions with the property that the ratio of dark energy and dark matter density parameters are of order one. These solutions give the hope to alleviate the well-know coincidence problem in cosmology. We also obtain constraints on the free parameters by using different sources of cosmological data. The viability of the model is explored by combining the conditions imposed by the Type Ia supernova (SN Ia) and Baryon Acoustic Oscillations data.

1 Introduction

In 1974 Horndeski [1] found the most general class of scalar tensor theories which lead to the second order differential equations similar to the Einstein general relativity. Horndeski's gravity has been considered in many papers in the context of the inflationary cosmology [2, 3]. Furthermore, an interesting subclass of Horndeski theory is given by the non-minimal coupling of the scalar field with the Gauss-Bonnet invariant in four dimensions [4]. Such a non-minimal coupling originates from the string theory and the trace anomaly and may play an important role in cosmological context. It deserves mention that modifications of gravity from the Gauss-Bonnet invariant have been often considered as the result of quantum gravity effects [5]. In the present work, we will consider a model in which scalar field playing the role of dark energy is coupled to the Gauss-Bonnet invariant. Moreover, in recent years the dynamical system methods have been extensively used in cosmology. This method provides a general picture of dynamics of a given cosmological model and derives asymptotic solutions using a simple programmed algorithm. This feature requires introducing new set of auxiliary variables in which the initial system can be rewritten as a system of first order equations. In the following we are going to study our model utilizing dynamical system method.
Our model is described by the following action in which the scalar field coupled to the Gauss-Bonnet invariant through an arbitrary function $\eta(\varphi)$

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{2\,\kappa^2} - V(\varphi)\sqrt{1-\partial_\mu\varphi\,\partial^\mu\varphi} - \eta(\varphi)\,\mathcal{G} + \mathcal{L}_m \right]. \tag{1}$$

[1] a.banijamali@nit.ac.ir
[2] Stefano.Bellucci@lnf.infn.it
[3] b.fazlpour@umz.ac.ir

By assuming a homogeneous scalar field ϕ, the Friedmann and Raychaudhuri equations in a flat FRW background can be written in the form

$$H^2 = \frac{\kappa^2}{3}\big(\rho_\phi + \rho_m\big), \tag{2}$$

$$\dot{H} = -\frac{\kappa^2}{2}\big(\rho_\phi + P_\phi + \rho_m + P_m\big), \tag{3}$$

where the energy density and pressure of tachyon field read

$$\rho_\phi = \mu\, V\,(\phi) + 24H^3\, f(\phi)\,\dot{\phi}, \tag{4}$$

and

$$p_\phi = -\mu^{-1}\, V(\phi) - 8H^2\left(f_{,\phi}\,\dot{\phi}^2 + f(\phi)\,\ddot{\phi}\right) - 16\,H\,f(\phi)\,\dot{\phi}(\dot{H} + H^2), \tag{5}$$

Moreover, variation of the action (1) with respect to tachyon field yields to its evolution equation which in FRW background takes the form

$$\ddot{\phi} + 3\,\mu^{-2}\,H\,\dot{\phi} + \left(1 - \frac{3\,\dot{\phi}^2}{2V}\right) V_{,\phi} + 24\,H^2\,\left(\dot{H} + H^2\right) f(\phi) = 0. \tag{6}$$

By introducing the following new variables we will transform the evolution equations into an autonomous form which is needed to study the dynamics of the model :

$$x \equiv \frac{\kappa\sqrt{V}}{\sqrt{3}\,H}, \quad y \equiv \sqrt{8\sqrt{3}\,\kappa\, f}\,H, \quad z \equiv \frac{\dot{\phi}}{\sqrt{V}}, \quad \alpha \equiv \frac{f_{,\phi}}{\kappa f}, \quad \lambda \equiv -\frac{V_{,\phi}}{\kappa V}. \tag{7}$$

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