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Astrophysical and cosmological applications of modified theories of gravity

PhD. In Physics

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Introduction

Cosmology has entered a ‘golden age’, in which the rapid development of increasingly high precision data has turned it from a speculative to an observationally based science. Recent experiments call upon state of the art technology to provide detailed information about the contents and history of the universe. These experiments include the Hubble Space Telescope, the NASA WMAP satellite instrument, that measures the temperature and polarization of the microwave cosmic background radiation (CMB), and the Sloan Digital Sky Survey (SDSS), that is automatically mapping the properties and distribution of 1 million galaxies. High-precision cosmology has allowed us to tie down the parameters that describe our universe with growing accuracy.

The standard model of cosmology is remarkably successful in accounting for the observed features of the universe. However, there remain a number of fundamental open questions at the foundations of the standard model. In particular, we lack a fundamental understanding of the acceleration of the late universe. Observations of supernovae, together with the WMAP and SDSS data, lead to the remarkable conclusion that our universe is not just expanding, but has begun to accelerate [1,2]. What is the dark energy that is driving the acceleration of the universe? Is it a vacuum energy in the guise of a cosmological constant or a dynamical field like a quintessence field? Or is the acceleration due to infrared modifications of Einstein’s general theory of relativity? How is structure formation affected in these alternative scenarios? What will the outcome be of this acceleration for the future fate of the universe?

The proposed research aims to address aspects of these fundamental questions whose resolution is so important for theoretical cosmology, looking beyond the standard theory of gravity. It is clear that these questions involve not only gravity, but also particle physics. String theory provides a synthesis of these two parts of physics and is widely believed to be moving towards a viable quantum gravity theory. One of the key predictions of string theory is the existence of extra spatial dimensions. In the brane-world scenario, motivated by developments in string theory, the observed 3-dimensional universe is embedded in a higher-dimensional spacetime [3]. Thus, the proposed research aims to use ideas from braneworld cosmology to study various models of dark energy. Relatively to the construction of quintessential dark energy models, recent fits to observational data indicate that an evolving equation of state crossing the phantom divide is mildly favoured [4]. In a cosmological setting, it has also been shown that the transition into the phantom regime, a mixture of various interacting non-ideal fluids is necessary [5]. If confirmed in the future, this behaviour holds important implications to the model construction of dark energy.

Hybrid metric-Palatini gravity

One of the modified theories of gravity being studied is the so called hybrid metric-Palatini gravity. More specifically, this hybrid metric-Palatini theory consists of adding to the Einstein-Hilbert Lagrangian an f(R) term constructed à la Palatini [6]. Using the respective dynamically equivalent scalar-tensor representation, it was shown that the theory can pass the Solar System observational constraints even if the scalar field is very light. This implies the existence of a longrange scalar field, which is able to modify the cosmological and galactic dynamics, but leaves the Solar System unaffected.

The absence of instabilities in perturbations were also verified [7], and it was also shown that the initial value problem can always be well-formulated and be well-posed depending on the adopted matter sources [8]. The theory was further generalized to depend on a general function of both the metric and Palatini curvature scalars [9]. Therefore the model predicts the existence of a long-range scalar field, modifying the cosmological and galactic dynamics [10].

The cosmological applications of the hybrid metric-Palatini gravitational theory were extensively explored [11, 12], and cosmological solutions coming from the scalar-tensor representation were presented. In particular, considering linear homogeneous perturbations, the stability regions of the Einstein static universe were analysed, and it was shown that a large class of stable solutions exists [13]. Furthermore, the cosmological perturbation equations were derived and applied to uncover the nature of the propagating scalar degree of freedom and the signatures these models predict in the large-scale structure [14]. More specifically, the full set of linearized evolution equations for the perturbed potentials, in the Newtonian and synchronous gauges, were derived. It was concluded that the main deviations from general relativity arise in the distant past, with an oscillatory signature in the ratio between the Newtonian potentials. Furthermore, using specific models and a combination of cosmic microwave background, supernovae and baryonic accoustic oscillations background data, it was shown that the models’ free parameters are in agreement with the observational constraints [15].

Results

In the area of cosmology, some analytical solutions for the scalar fields and for the scale factor have been obtained for flat FLRW universes without matter for a constant value of the deceleration parameter. We have shown that the solutions for the scalar fields decrease as the scale factor increases, as expected. The scale factor in these cases follows a power-law (or na exponential growth for the particular case q=-1). For an apropriate choice of the initial conditions, it is possible to derive a scale-factor expression that features na instant where it vanishes (a Big Bang) and/or na instant where it diverges (a Big Rip).

On the other hand, solutions for transversable wormholes have also been studied. We have shown that this theory allows for the existence of spherically symmetric asymptotically flat wormhole solutions with matter described by a perfect fluid with different radial and transverse pressures. Two classes of solutions were obtained, the first imposing a suitable potential to simplify the equations of motion for the scalar fields and computing the shape function and stress-energy tensor; and the second imposing a particular shape for the shape and redshift functions and leaving the potential as an unknown quantity.

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PhD. in Physics