Extended Quintessence: imprints on the cosmic microwave background spectra

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We describe the observable features of the recently proposed Extended Quintessence scenarios on the Cosmic Microwave Background (CMB) anisotropy spectra. In this class of models a scalar field $\phi$, assumed to provide most of the cosmic energy density today, is non-minimally coupled to the Ricci curvature scalar $R$. We implement the linear theory of cosmological perturbations in scalar tensor gravitational theories to compute CMB temperature and polarization spectra. All the interesting spectral features are affected: on sub-degree angular scales, the acoustic peaks change both in amplitude and position; on larger scales the low redshift dynamics enhances the Integrated Sachs Wolfe effect. These results show how the future CMB experiments could give information on the vacuum energy as well as on the structure of the gravitational Lagrangian term.

1 Introduction

One of the most interesting novelty in modern cosmology is the observational trend for an accelerating Universe, as suggested by distance measurements to type Ia Supernovae. These results astonishingly indicate that almost two thirds of the energy density today is vacuum energy.

It has been thought that this vacuum energy could be mimicked by a minimally-coupled scalar field, considered as a "Quintessence" (Q). The main features of such a vacuum energy component, that could also allow to distinguish it from a cosmological constant, are its time-dependence as well as its capability to develop spatial perturbations.

Theoretically, Quintessence models are attractive, since they offer a valid alternative explanation of the smallness of the present vacuum energy density instead of the cosmological constant; indeed, we must have $|\rho_{\text{vac}}| < 10^{-47}$ GeV$^4$ today, while quantum field theories would predict a value for the cosmological constant which is larger by more than 100 orders of magnitude. Instead, the vacuum energy associated to the Quintessence is dynamically evolving towards zero driven by the evolution of the scalar field. Furthermore, in the Quintessence scenarios one can select a subclass of models, which
admit "tracking solutions" here a given amount of scalar field energy density today can be reached starting from a wide set of initial conditions.

The effects of possible couplings of this new cosmological component with the other species have been explored in recent works, both for what regards matter and gravity. Here we review some of the results obtained in a recent paper for what concerns the effects on the Cosmic Microwave Background (CMB) anisotropy: this scenario has been named ‘Extended Quintessence’ (EQ), by meaning that the scalar field coupled with the Ricci scalar $R$ has been proposed as the Quintessence candidate, in analogy with Extended Inflation models.

2 Cosmological dynamics in scalar-tensor theories of gravity

The action $S = \int d^4x \sqrt{-g} [F(\phi)R - \phi^\mu \phi_{,\mu} - 2V(\phi) + L_{\text{fluid}}]$ represents scalar-tensor theories of gravity, where $R$ is the Ricci scalar and $L_{\text{fluid}}$ includes matter and radiation.

We assume a standard Friedman-Robertson-Walker (FRW) form for the unperturbed background metric, with signature $(-,+,+,+)$, and we restrict ourselves to a spatially flat universe. The FRW and Klein Gordon equations are

$$H^2 = \frac{a^2 \rho_{\text{fluid}}}{3F} + \frac{\dot{\phi}^2}{6F} + \frac{a^2 V}{3F} - \frac{\mathcal{H} \dot{F}}{F}, \quad \dot{\phi} + 2\mathcal{H} \phi = \frac{a^2 F}{2} \rho_{\phi} R - a^2 \ddot{V}_{\phi},$$

where the overdot denotes differentiation with respect to the conformal time $\tau$ and $\mathcal{H} = \dot{a}/a$. Furthermore, the continuity equations for the individual fluid components are $\dot{\rho}_i = -3\mathcal{H} (\rho_i + p_i)$.

For what concerns our treatment of the perturbations, we give here only the very basic concepts. A scalar-type metric perturbation in the synchronous gauge is parameterized as

$$ds^2 = a^2 [-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j];$$

by linearly perturbing the Einstein and Klein Gordon equations above, the equation for the metric perturbing quantities can be derived; these equations are linked to the fluid perturbed quantities, from any species including $\phi$, obeying the perturbed continuity equations.

Let us define now the gravitational sector of the Lagrangian. We require that $F$ has the correct physical dimensions of $1/G$. Note that all this fixes the link between the value of $F$ today and the Newtonian gravitational constant $G$: $F_0 = F(\phi_0) = 1/8\pi G$. Different forms of $F(\phi)$ can be considered. In Induced Gravity (IG) models, that we treat here, the gravitational constant is
directly linked to the scalar field itself, as originally proposed in the context of the Brans-Dicke theory:

$$F(\phi) = \xi \phi^2,$$

where $\xi$ is the IG coupling constant. Note that solar system experiments already offer constraints to the viable values of $\xi$, that may be easily obtained by integrating the background equations. The dynamics of $\phi$ is determined by its coupling with $R$, as well as by its potential, that is responsible for the vacuum energy today; we take the simplest inverse power potential, $V(\phi) = M^5/\phi$, where the mass-scale $M$ is fixed by the level of energy contribution today from the Quintessence. In our integrations, we adopt adiabatic initial conditions. We require that the present value of $\Omega_\phi$ is 0.6, with Cold Dark Matter at $\Omega_{CDM} = 0.35$, three families of massless neutrinos, baryon content $\Omega_b = 0.05$ and Hubble constant $H_0 = 50$ Km/sec/Mpc; the initial kinetic energy of $\phi$ is taken equal to the potential one at the initial time $\tau = 0$.

3 Effects on the CMB

The phenomenology of CMB anisotropies in EQ models is rich and possesses distinctive features. In Fig. 3, the effect of increasing $\xi$ on the power spectrum of COBE-normalized CMB anisotropies is shown. The rise of $\xi$ makes substantially three effects: the low $\ell$’s region is enhanced, the oscillating one attenuated, and the location of the peaks shifted to higher multipoles. Let us now explain these effects. The first one is due to the integrated Sachs-Wolfe effect, arising from the change from matter to Quintessence dominated era occurred at low redshifts. This occurs also in ordinary Q models, but in EQ this effect is enhanced. Indeed, in ordinary Q models the dynamics of $\phi$ is governed by its potential; in the present model, one more independent dynamical source
is the coupling between the Q-field and the Ricci curvature $R$. The dynamics of $\phi$ is boosted by $R$ together with its potential $V$. As a consequence, part of the COBE normalization at $\ell = 10$ is due to the Integrated Sachs-Wolfe effect; thus the actual amplitude of the underlying scale-invariant perturbation spectrum gets reduced. In addition, it can be seen that the Hubble length was smaller in the past in EQ than in Q models. This has the immediate consequence that the horizon crossing of a given cosmological scale is delayed, making the amplitude the acoustic oscillations slightly decreasing since the matter content at decoupling is increased.

Finally, note how the location of the acoustic peaks in term of the multipole $\ell$ at which the oscillation occurs, is shifted to the right. Again, the reason is the time dependence of the Hubble length, which at decoupling subtended a smaller angle on the sky. It can indeed verified that the ratio of the peak multipoles in Fig. coincides numerically with the the ratio of the values of the Hubble lengths at decoupling in EQ and Q models.

We have used here values of $\xi$ large in order to clearly show the CMB effects. It can be seen these values do not satisfy the solar system experimental constraints; however, a smaller $\xi$ produces the same spectral features, reduced but still detectable by the future generation of CMB experiments, able to bring the accuracy on the CMB power spectrum at percent level up to $\ell \simeq 1000$.

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