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Observing Dark Energy through CMB anisotropies

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Abstract. It is still unclear if the recent acceleration of the universe is fueled by a cosmological constant (whose energy density is constant and acts as a simple parameter in the Einstein equations) or by a new dynamical component (which fluctuates in time and space). While both of these possibilities are not completely satisfactory theoretically, a cosmological constant plus cold dark matter (ΛCDM model) provide the best fit to CMB anisotropies data. Here we present the signatures of dark energy perturbations on the CMB anisotropy pattern, as a possibility to discriminate between a new dynamical component (uncoupled to the rest of matter) and a cosmological constant or to test if the dark sector can be unified.

Key words. Cosmology - dark energy - CMB anisotropies

1. Introduction

Evidence for a recent acceleration of the universe has been independently found in the SNIa data by two groups (Perlmutter et al. 1996; Riess et al. 1996). Such possibility was also favored by other observational data, leading to a cosmic concordance model.

A positive cosmological constant Λ would be the simplest way to model this acceleration, but its value is completely unexplained on theoretical grounds. Λ is indeed related to the zero-point energy of quantum fluctuations: already with one of the lowest scales in particle physics, the QCD scale, the magnitude of the vacuum energy is $\Lambda \sim 10^{-41}\mathrm{GeV}^2$, which is much larger than the observed value $\sim 10^{-94}\mathrm{GeV}^2$. Anthropic arguments have then been advocated to explain such a small value (Weinberg 1989).

However, a cosmological constant Λ does not exhaust all the possibilities in explaining the recent acceleration of the universe (see Sahni & Starobinsky 2000; Peebles & Ratra 2003 for reviews). A component with a sufficiently negative equation of state ($w_X \equiv p_X/\rho_X \leq -1/3$) goes under the generic name of Dark Energy (DE henceforth). If DE is not a parameter in the Einstein equations, it may affect cosmological observations not only through its imprint in the expansion rate, but also by its fluctuations. In this latter case, a host of cosmological observations - CMB anisotropies, LSS, ... - may result complementary and, sometimes, more important with respect to SNIa data, as we shall see. This observational chance to reveal DE shoud be taken very seriously, given the enormous difficulty to directly detect DE quanta.

In this contribution we give the details for the treatment of DE perturbations and their imprint on CMB anisotropies. These imprints are on top of the DE background evolution, which alters the position of the peaks and produce a non-negligible Integrated Sachs-Wolfe (ISW henceforth) effect. In the ΛCDM case, this latter effect (first studied by Kofman & Starobinsky 1985) is due to the damping of gravitational fluctuations induced by a non-vanishing Λ and enhances the value of the observed temperature anisotropies in the low-multipole tails up to a factor 2 with respect to the sCDM case.

2. DE perturbations

By considering DE uncoupled to the rest of matter and isotropic DE pressure perturbations, the equations of motion for DE perturbations are similar to the ones for the other degrees of freedom (CDM, baryons, photons, see Ma & Bertschinger 1995):

$$\begin{aligned}\delta'_X &= -(1+w_X)\left(\theta_X - \frac{h'}{2}\right) \\ &\quad +3\mathcal{H}(w_X\delta_X - \frac{\delta p_X}{\rho_X}) \\ \theta'_X &= -\mathcal{H}(1-3c_X^2)\,\theta_X + \frac{c_X^2}{1+w_X}k^2\delta_X \qquad (1)\end{aligned}$$

where $\delta_X \equiv \delta\rho_X/\rho_X$ is the density contrast, θ_X is the velocity potential, $\mathcal{H} = a'/a$ is the conformal Hubble parameter and h is the trace of metric perturbations in the synchronous gauge. The isotropic pressure perturbation δp_X can be written as (Abramo et al. 2004):

$$\begin{aligned}\delta p_X &= c_X^2\delta\rho_X \\ &\quad + 3\mathcal{H}(1+w_X)\frac{\theta_X\rho_X}{k^2}\left(c_X^2 - \frac{\dot{p}_X}{\dot{\rho}_X}\right) \qquad (2)\end{aligned}$$

where the last piece vanishes if p_X is just a function of ρ_X. From the above equations we understand how it is not sufficient to specify $w_X(t)$ (and Ω_X at the present time) to study DE in the context of structure formation, but it is also necessary to specify its pressure perturbations (and therefore the speed of sound c_X^2). The present contribution is devoted to briefly illustrate the impact of DE perturbations on the CMB power spectrum.

3. DE models

The most popular idea is to model dark energy as a scalar field with a small effective mass (Ratra & Peebles 1988) - dubbed *quintessence* (Caldwell et al. 1998). The standard scenario (a canonical scalar field described by a Klein-Gordon (KG) Lagrangian for which $c_X^2 = 1$ in Eqs. (1,2)) is a minimal modification to ΛCDM because of the relative unimportance of scalar field perturbations on scales smaller than the Hubble radius. All the information contained in the scalar potential $V(\varphi)$ is encoded in w_X in that case. The low-ℓ tail is however different from a ΛCDM scenario because of the importance of quintessence perturbation on large scales (Abramo & Finelli 2001).

In order to investigate the impact of the DE sound speed it is necessary to study a different class of models, based on a Born-Infeld (BI) Lagrangian, in which $c_X^2 = -w_X$ (Abramo & Finelli 2003, 2001; see also DeDeo et al. 2003). In Fig. 1 we show the comparison of two different theories for scalar fields. The impact of the sound speed is marginal for scalar field theories, but important at low multipoles. For the WMAP (Bennett et al. 2003) constraints on these two theories see Abramo et al. (2004).

The simplest DE model (even if it has not been historically the first to be analyzed) is a perfect fluid with pressure $p_X = -A/\rho_X^\alpha$ and speed of sound $c_X^2 = \dot{p}_X/\dot{\rho}_X = -\alpha w_X$ (called Generalized Chaplygin Gas, for brevity GCG, Kamenshchik et al. 2001). In absence of experimental evidence for scalar fields, this model is very important in order to check if DE might be described by a perfect fluid. In these GCG models DE is not a smooth component and therefore its perturbations are important also at larger multipoles (Carturan & Finelli 2003; Amendola et al. 2003). In Fig. 2 we show the

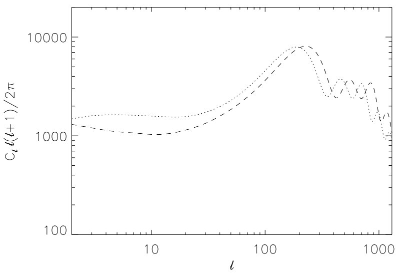

Fig. 1. Upper panel: background quantities for two similar BI (dashed lines) and KG (solid lines) dark energy models as a function of redshift. The upper curves denote Ω_r and Ω_M (= $\Omega_b + \Omega_{\rm CDM}$), and the lower w_X: for each curve another one is nearly superimposed to it, since the two models are designed to be very similar. The cosmological parameters are $\Omega_{b\,0} = 0.04$, $\Omega_{\rm CDM\,0} = 0.26$, $h = 0.72$ (in the radiation dominated era the sound speed for BI is zero). Lower panel: CMB TT power spectra for KG model (solid line), BI model (dashed line) and a fiducial ΛCDM (dotted line), all normalized at the amplitude of their first acoustic peak. Only for comparison we also show the (wrong) power spectrum of the BI model obtained without considering the scalar field perturbations (dot-dashed line). There are no appreciable differences in the power spectrum for the E-mode polarization.

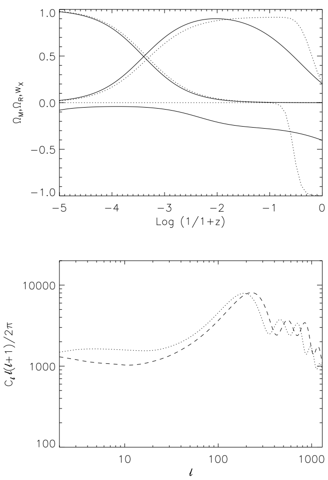

Fig. 2. A comparison of the GCG model (with $\alpha = 1$) and the BI model. As in Fig. 1, in the upper panel the background (BI solid, GCG dotted) and in the lower the CMB TT power spectrum (BI dotted, GCG dashed). The different equations of state explain the peaks position, but the different shape of the plateau is due to the different pressure in the two models (although $c_X^2 = -w_X$ in both).

difference between a GCG (perfect fluid) and a scalar field BI as a candidate for DE.

4. Unified Dark Models

The study of DE perturbations becomes decisive for a model in which dark energy and dark matter are described in a unified way. Different scenarios which aim at unifying the dark sector (96 % of the current total energy density) have been recently proposed: the GCG is one among these. In these unified dark models (UDM for brevity), the difficulty is not to have a (homogeneous) cosmological model which reproduce vacuum energy and dust; the real challenge is to obtain density perturbations which behave according to the data (and therefore similarly to CDM). In this sense, the comparison of the CMB and LSS predictions of UDM based on the GCG with observations has been much more selective than the SNIa test (Carturan & Finelli 2003; Amendola et al. 2003), as it can be seen from Fig. 3. It was found that the better agreement with WMAP data is in the region of parameters where the ΛCDM and a UDM are almost identical (Amendola et al. 2003).

5. Conclusions

Although the acceleration of the universe has been found in samples of SNIa data, the fundamental or effective degree of freedom responsible for such acceleration may fluctuate in space and time, if it is not simply a cosmological constant. In this case a detailed study of DE perturbations is needed in order to fully investigate the DE imprints on CMB anisotropies and structure formation. By taking this approach, we have studied and con-

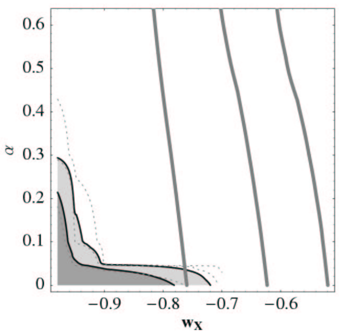

Fig. 3. The importance of CMB constraints for GCG models. The thick lines are the SNIa constraints and the three dashed lines are the CMB constraints from WMAP (in both cases 65% , 95% , 99% CL from left to right respectively). The combined constraints are the grey lines (65% , 95% CL respectively): as can be seen, the SNIa constraints add little information (Amendola et al. 2003).

strained the macroscopic properties of DE. This study is important in the perspective of better CMB data as those coming from PLANCK (http://astro.estec.esa.nl/ , see Burigana et al. *this issue*). With the same techniques the matter power spectrum may be studied and compared with LSS data.

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