RevMexAA (Serie de Conferencias), **24**, 40–44 (2005)

DARK ENERGY FROM THE MILIMETER SKY

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RESUMEN

Presentamos una breve introducción al problema de la energía oscura en universos planos y la posibilidad de medirla combinando mapas ópticos/infrarrojos con mapas milimétricos. La correlación cruzada de mapas de galaxias y mapas de anisotropías en la temperatura de la Radiación Cósmica de Fondo puede usarse para acotar el ritmo de crecimiento lineal de estructuras y, por tanto, los parámetros cosmológicos. Presentamos una combinación de tales medidas de correlación cruzada y mostramos como, bajo ciertas hipótesis, los datos revelan la cantidad de energía oscura en el universo.

ABSTRACT

We present a brief introduction to dark energy in flat universes and the possibility to measure it with a combination of optical/infrared and millimeter surveys. The cross-correlation of galaxy maps with Cosmic Microwave Background radiation (CMB) temperature anisotropies can be used to constrain the rate of linear growth of structures and therefore the cosmic parameters. We present a combination of such cross-correlation measurements and show that, under certain assumptions, these data reveal the amount of dark energy in the universe.

Key Words: **COSMOLOGY — LARGE SCALE STRUCTURE**

1. INTRODUCTION

On scales larger than few arcminutes, the millimeter sky is dominated by Cosmic Microwave Background radiation (CMB) temperature fluctuations. A significant fraction of these CMB photons encode a wealth of information about its interaction with the local matter distribution, e.g. lensing, SZ, Integrated Sachs Wolfe (ISW) effect (Sachs & Wolfe 1967) or Rees-Sciama effects. On smaller scales, the millimeter sky is dominated by high redshift star forming galaxies (see the contribution by D.H.Hughes in these proceedings). This is illustrated in Fig. 1. Altogether, the millimeter sky provides a complementary tool to optical/IR view of the universe. This complementarity can be used to elaborate on the collaboration between the GTM (Gran Telescopio Milimétrico, http://www.lmtgtm.org/) and the GTC (Gran Telescopio de Canarias, http://www.iac.es/gabinete/grante/gtc1.html) projects.

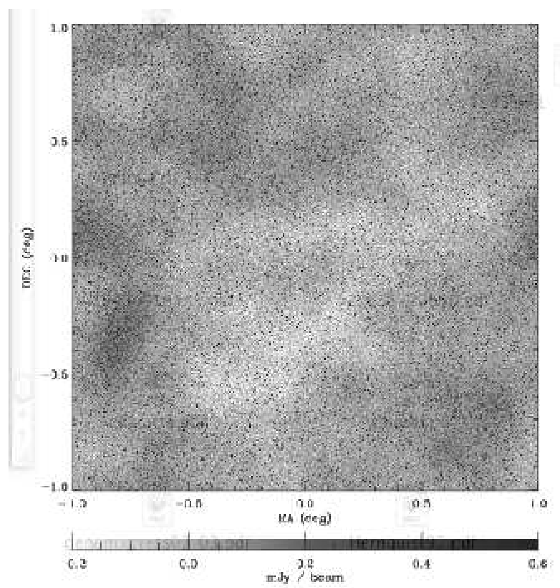

Fig. 1. Realistic $1^\circ \times 1^\circ$ map of what the GMT would detect at 1.4mm in $\simeq$ 2000 hr integration. The largest scales show smoothed CMB anisotropies, while point sources (dust from high-z forming galaxies) dominates at the smaller scales (Montaña 2003).

Here, we will review how it is possible to measure properties of the Dark Energy with optical/millimeter complementary observations. This can be done by cross-correlating (e.g. optically/IR selected) galaxy catalogues with CMB temperature anisotropies over the same region of the Sky. We first give a brief introduction to dark energy and how it can impact the growth of structure in the universe. This follows by a description fo the ISW effect and the cross-correlation measurements, to end with a section on conclusions.

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2. DARK ENERGY

The first fundamental (unsolved) problem in cosmology is to find the metric of our universe. At very large scales, for a homogeneous and isotropic space (we restrict ourselves here to the flat geometry), we have:

$$ds^2 = c^2dt^2 - a^2\left(dr^2 + r^2 d\Omega^2\right) \qquad (1)$$

where the scale factor, a, is the only unknown. Observational evidence for the Hubble-law ($\dot{a} \neq 0$) requires a to be a function of time $a = a(t)$ (the universe is not static). The function $a(t)$ will give us the metric as a function of cosmic time.

For a flat cosmological model, the rate of expansion in the universe, $H \equiv \dot{a}/a$, is given by:

$$H^2 = \frac{8\pi G}{3}\ \rho \qquad (2)$$

This is the second fundamental equation in cosmology, relating the energy-matter contend in the universe, $\rho(t)$, with its evolution, given by the scale factor $a = a(t)$. This equation is a direct consequence of Einstein field equations for General Relativity (e.g. see Weinberg 1972). If (dark) matter dominates ρ in the universe, the continuity equation (matter is not created or destroy) requires: $\rho = \rho_0 a^{-3}$ and $H^2 = H_0^2\ a^{-3}$, with $H_0^2 = 8\pi G/3\ \rho_0$ (note that H_0 and ρ_0 refer to the values evaluated at our current cosmic time). This model results in a constant dimensionless deceleration:

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = 1/2 \qquad (3)$$

which seems at odds with Supernova Ia (SNIa) data (Riess, Filippenko, Challis et al. 1998, Perlmutter, Aldering, Goldhaber et al. 1999) and other cosmic indicators.

In general, **dark energy** could be defined as an effective contribution to ρ which evolves less rapidly with a than (dark) matter, i.e. $\rho \sim a^{\alpha}$, with $\alpha > -2$, such that produces cosmic acceleration: $q < 0$. In our case we will take dark energy to be a constant, $\alpha = 0$, the so called **cosmological constant** Λ, introduced by Einstein in his field equations to force a static universe. This constant shift to the expansion rate, H^2, can be interpreted as a new energy component to the universe or as an effective change in the laws of gravity (i.e. modified Einstein field equation of General Relativity). We do not understand what makes the expansion rate accelerate, but nevertheless chose to call our ignorance by the name of **dark energy**, which also provides some physical insight to the problem (i.e. vacuum energy). There are, of course, many other ways in which we could parametrize or name our ignorance.

In a universe with a such cosmological constant, we can write the Hubble ratio $H \equiv \dot{a}/a$ as:

$$H^2 = H_0^2\ \left[\Omega_m\ a^{-3} + \Omega_\Lambda\right] \qquad (4)$$

with $\Omega_\Lambda + \Omega_m = 1$, where Ω_Λ and Ω_m are the dark energy and dark matter densities today in units of the critical density $\rho_c \equiv 3\ H^2/(8\pi G)$. It is straightforward to check that the Ω_m term produces negative acceleration: $\ddot{a} < 0$, while the cosmological constant Ω_Λ contributes to positive acceleration: $\ddot{a} > 0$. In the general case:

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2} = \Omega_m/2 - \Omega_\Lambda. \qquad (5)$$

Thus measurements of q typically provides degenerate information on Ω_m and Ω_Λ, although this degeneracy is broken with the flat prior ($\Omega_m + \Omega_\Lambda = 1$).

3. GROWTH OF STRUCTURE

The gravitational evolution of matter fluctuations, $\delta = \rho/\bar{\rho} - 1$, depends on the cosmological model via the evolution of the scale factor $a = a(t)$. Compared to a static background, a rapidly expanding background will slow down the collapse of an overdense region. In the linear regime, a small initial perturbation δ_0 grows according to the growth factor $D(t)$:

$$\delta(t) = D(t)\ \delta_0, \qquad (6)$$

which, under quite generic assumptions (e.g. see Peebles 1980; Gaztañaga & Lobo 2001; Multalmaki, Gaztañaga & Manera 2003; Lue, Scoccimarro & Starkman 2004) follows a simple harmonic equation:

$$D'' + \left(2 + \frac{\dot{H}}{H^2}\right) D' + 3c_1\ D = 0. \qquad (7)$$

where derivatives are over conformal time $\eta = \ln(a)$ and $H = H(\bar{\rho})$ is the background Hubble rate. For Eq.[4], $c_1 = -(1/2)\ \Omega_m/(\Omega_m + \Omega_\Lambda a^3)$. A flat universe with only matter (the so called Einstein-de Sitter Universe, hereafter EdS) corresponds to setting $\Omega_\Lambda = 0$, $\Omega_m = 1$, in which case the solution to Eq.(7) is $D \propto a$. This means that fluctuations grow linearly with the scale factor, $\delta \propto a$, while the corresponding gravitational potential fluctuation, $\Phi \sim \delta/r$, remains constant as the universe expands ($r \propto a$).

4. THE ISW EFFECT

The ISW effect is a direct probe for the (linear) rate of structure formation in the universe. Secondary anisotropies in the CMB appear because of the net gravitational redshifts affecting CMB photons that travel through an evolving gravitational potential Φ:

$$\triangle_T^{ISW}(\hat{n}) = -2\int dz\ \frac{d\Phi}{dz}(\hat{n},z) \tag{8}$$

where Φ is the Newtonian gravitational potential at redshift z (or conmoving radial distance $r = r(z)$) and angular position $\hat{n}$.

These secondary temperature anisotropies are therefore correlated with local (evolving) structures on large scales. The correlation is negative when structures grow (increasing potential leaves a cold spot in the CMB sky) and positive otherwise. In a flat universe without dark energy, the EdS universe, this cross-correlation is expected to be zero because the gravitational potential remains constant (despite the linear growth of the matter fluctuations).

One way to detect the ISW effect is to cross-correlate temperature fluctuations with galaxy density fluctuations projected on the sky (Crittenden & Turok 1996). On large (linear) scales, the projected galaxy density fluctuations can be modeled by:

$$\delta_G(\hat{n}) = \int dz\ \phi_G(z)\ b(z)\ \delta_m(\hat{n},z) \tag{9}$$

where ϕ_G is the survey galaxy selection function along the line of sight. We assume that galaxy and matter fluctuations are related through the linear bias factor $\delta_G(\hat{n},z) = b(z)\delta_m(\hat{n},z)$. The galaxy-CMB temperature cross-correlation is hence (Fosalba & Gaztañaga 2004):

$$\begin{aligned} w_{TG}^{ISW}(\theta) &= \frac{1}{2\pi}\int \frac{dk}{k} P(k) g(k\theta) \\ g(k\theta) &\equiv \int dz\, W_{ISW}(z) W_G(z) J_0(k\, r_A \theta) \\ W_{ISW}(z) &\equiv 3\Omega_m\ E(z)\ (H_0/c)^3 \frac{d[D(z)/a]}{dz} \\ W_G(z) &\equiv b(z)\phi_G(z)D(z), \end{aligned} \tag{10}$$

where $E(z) \equiv H(z)/H_0$, J_0 is the zero order Bessel function and $r_A = r_A(z)$ the comoving transverse distance (for a flat universe r_A equals the radial comoving distance $r_A = r(z)$). The linear growth factor, $D(z)$, can be computed from perturbation theory for a given cosmology, Eq. (7). In particular, in the EdS universe where there is no dark energy, $D = a$ so that the ISW effect vanishes and one expects no cross-correlation signal. For the ΛCDM case the ISW effect is non-zero, and can be well approximated by $W_{ISW}(z) = -3\Omega_m(H_0/c)^3 E(z)D(z)(f-1)$, where f is the relative growth factor, $f \simeq \Omega_m(z)^{6/11}(z)$. In ΛCDM models, the power spectrum $P(k)$ is $P(k) = A\ k^{n_s}\ T^2(k)$, where $n_s \simeq 1$ and $T(k) = T(k,\Gamma)$ is the ΛCDM transfer function (Sugiyama 1995), which is mostly a function of Ω_m and h.

Note how W_{ISW} decreases as a function of increasing redshift (as $\Omega_m(z) \to 1$) and goes to zero both for $\Omega_m \to 0$ and for $\Omega_m \to 1$. Thus, for flat universes, $\Omega_m + \Omega_\Lambda = 1$, W_{ISW} has a maximum at $\Omega_\Lambda \simeq 0.6$ and tends to zero both for $\Omega_\Lambda \to 1$ and also for $\Omega_\Lambda \to 0$. To first approximation the predictions depend only on Ω_m, but because of the different ingredients involved in the w_{TG} calculation (power spectrum shape and normalization and the geometry in the projection) w_{TG} is also sensitive to Ω_Λ. Of course, for a flat universe prior, both dependences merge into a strong $\Omega_\Lambda = 1 - \Omega_m$ determination.

4.1. *Biasing*

As with any tracer, the question of bias must be considered: that is, how well our observations are tracing the underlying statistics in the matter fluctuations. The linear bias prescription gives a good approximation because, on these very large scales, fluctuations are small and linear theory works well both for biasing and for gravity.

We can remove the effects of biasing in our parameter estimation by comparing the observed galaxy-galaxy auto correlation w_{GG} to the matter-matter auto correlation w_{mm} predicted by each model. The effects of bias are also redshift dependent, but for a galaxy selection function $\phi_G(z)$, picked at $z = \bar{z}$, we can approximate the bias with a constant $b = b(\bar{z})$ for that particular survey. Therefore, we have: $w_{TG} = b(\bar{z})w_{Tm}$ and $w_{GG} = b^2(\bar{z})w_{mm}$, so that an effective bias b can be estimated as the square root of the ratio of galaxy-galaxy and matter-matter correlation functions:

$$b = \sqrt{\frac{w_{GG}}{w_{mm}}} \tag{11}$$

The values of w_{mm} can be computed in a similar way to Eq.[10] by just replacing $P(k)$ by $k^2P(k)$ and $W_G\ W_{ISW}$ by $W_m^2 \equiv [D(z)\phi_G(z)]^2$.

5. CROSS-CORRELATION

Recent studies by a number of independent collaborations, have cross-correlated the cosmic microwave background anisotropies measured by WMAP (Bennett, Halpen, Hinshaw et al. 2003) with different galaxy surveys (Boughn & Crittenden 2004, Nolta, Wright, Page et al. 2004, Fosalba & Gaztañaga 2004, Fosalba, Gaztañaga & Castander

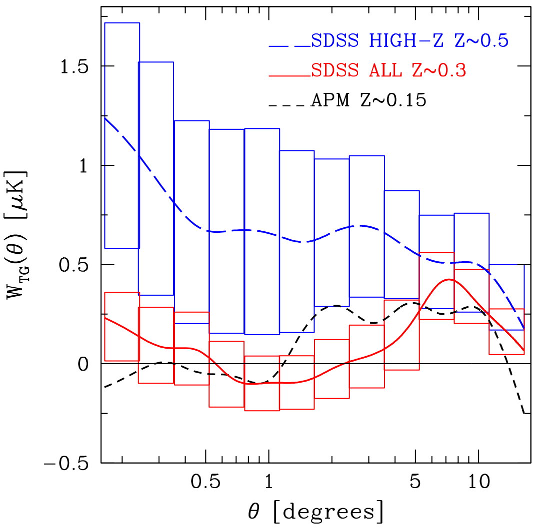

Fig. 2. Long dashed and solid lines show the WMAP-SDSS correlation measurement for the *SDSS HIGH-Z* ($\bar{z} \simeq 0.5$) and *SDSS ALL* sample ($\bar{z} \simeq 0.3$). Short-dashed correspond to the WMAP-galaxy cross-correlation for the APM ($\bar{z} \simeq 0.15$). Boxes show 1-σ error-bars. (From Fosalba et al. 2003).

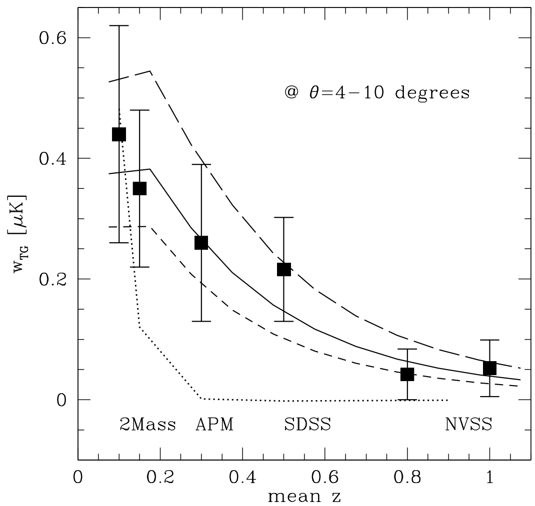

Fig. 3. Symbols with errorbars correspond to the different cross-correlation measurements w_{TG}. The dashed and continuous lines show predictions for three values of $\Omega_\Lambda = 0.6, 0.7, 0.8$ in the flat ΛCDM model (at $\theta = 6$ deg), encompassing the 2-sigma confidence level region ($\Delta\chi^2 \simeq 4.6$) of agreement between data and theory. The dotted line shows the prediction for dust galaxy emission.

2003, Scranton, Connolly, Nichol et al. 2004, Afshordi, Loh & Strauss 2004). An example of the signal measured is shown in Fig. 2.

The different cross-correlation data (where the linear bias $b(z)$ is known) is summarized as points with error-bars in Fig. 3, which shows the mean values on fixed angular scales around $\theta = 5°$. This corresponds to (proper) distances of $\simeq 25 - 100$Mpc/h for $\bar{z} \simeq 0.1 - 1.0$ and avoids possible contamination from the small scale SZ and lensing effects (eg see Fig.3 in Fosalba, Gaztañaga & Castander 2003).

We have computed the expected ISW effect and compared it with the observational data within the flat ΛCDM family of models, where Ω_Λ is the only free parameter (we fixed $h = 0.7$, $n_s \simeq 1$, $\Omega_m = 1 - \Omega_\Lambda$, $\Omega_B \simeq 0.04$ and $\Gamma \simeq \Omega_m h$). The amplitude of fluctuations of the predictions are normalized to $\sigma_8 \simeq 1$ (more details and other constraints will be presented elsewhere).

We built a standard χ^2-test with:

$$\chi^2 = \sum_i (O_i - T_i)^2/\sigma_i^2 \qquad (12)$$

where O_i and σ_i correspond to the different measurements and errors and T_i correspond to the model. The label i runs for $i = 1$ to $i = 6$ marking the different redshifts. The absolute value of χ^2 can be used to assess the significance of a given model. Here, we use the relative χ^2 values: $\Delta\chi^2 \equiv \chi^2 - \chi^2_{min}$ to define confidence levels in parameter estimation.

The best fit model has a significant dark energy contribution, with $\Omega_\Lambda \simeq 0.7 \pm 0.1$ at 2-sigma confidence level.

6. DISCUSSION

The constraining power of the ISW data comes from the simultaneous fitting of data at different redshifts, that is from the shape information in Fig. 3. Because of the uncertainties in the relative normalization (an relative bias) any given point does not constraint well the cosmological parameters.

The shape of the curve as a function of redshift also provides an important test for systematics. There are two important contaminants that can be shared by CMB and galaxy maps: galactic extinction and cold/warm dust in galaxies and clusters.

Although CMB and galaxy maps are both corrected for extinction there will always be some residual signal and therefore a cross-correlation. Absorption by our own galaxy produce patchy cold spots in the CMB maps and negative density fluctuations in the galaxy distribution. In principle, this should therefore result in a negative cross-correlation, but overcorrection of this effect can also result in a positive signal. This possibility have been tested for each of the samples, by comparing the cross-correlation to WMAP maps at different frequencies. Most analysis use the WMAP Kp0 mask, which excludes about 30% of sky on the basis of galactic or extra-galactic (e.g. radio sources) contamination. In all cases the contamination seems smaller than the errors (see Fig. 2 in Fosalba & Gaztañaga 2004). Moreover, one does not expect this effect to have any redshift dependence, contrary to the measurements in Fig. 3.

The second possibility, cold/warm dust in galaxies, will produce patchy hot spots in the CMB maps and positive density fluctuations in the galaxy distribution (depending on the galaxy selection, one could also imagine negative fluctuation because of internal extinction). This is clear in Fig. 1. If we smooth fluctuations over angular scales of $0.2° - 0.3°$, small scale point sources will contribute to the large scale primary CMB anisotropies. In cross-correlating with a galaxy sample of similar depth, this could result in an artificial cross-correlation signal, which will trace the galaxy-galaxy auto correlation function, w_{GG}. Note that this contamination will have a very different redshift dependence to the ISW effect. Dotted line in Fig. 2 shows the predicted shape dependence for w_{GG} contamination (with arbitrary normalization), which is clearly incompatible with the actual cross-correlation measurements.

7. CONCLUSION

We can summarize our results as follows:

- Detection of the cross-correlation of CMB anisotropies with very different galaxy surveys yield consistent results. Their combination gives a positive signal with a low probability of being a false detection.

- The redshift evolution is consistent with the ISW effect: a fast decline in the recent growth of large scale linear structures. The signal is incompatible with galactic extinction or with a contamination of dust traced by galaxies.

- The combined detection provides new, independent evidence for dark energy. For a flat universe (and fixing $h = 0.7$, $\Omega_b = 0.4$ and $n_s \simeq 1$), we find $\Omega_\Lambda \simeq 0.7 \pm 0.1$, at 2-sigma confidence level

Note how ISW secondary anisotropies are much smaller in amplitude (less than $1\mu K$) than primary anisotropies ($> 50\mu K$) and therefore have little impact on parameter determination from the angular power spectrum c_l in WMAP (Slosar & Seljak 2004).

It should also be emphasized that the ISW effect is a direct measurement for the rate of growth of linear fluctuations: $dD(z)/dz$ in Eq.(7), and as such it is strongly dependent on the value of Ω_m, and not on Ω_Λ, as sometimes claimed (see special issue, Breakthrough #1 of year 2003, in Science, Vol 302, 2038). The dependence on the Dark Energy content Ω_Λ comes about because of the flat universe prior, which is based on fitting the CMB power spectrum to primary WMAP anisotropies (Spergel, Verde, Peiris et al. 2003). Further details and interpretation are given in a separate analysis (Gaztañaga, Multalmäki & Manera 2004).

I acknowledge support of grants from IEEC/CSIC and the spanish Ministerio de Ciencia y Tecnologia, project AYA2002-00850 and EC FEDER funding.

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