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ON THE PATHWAY TO THE SKA
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The integrated Sachs-Wolfe effect and the SKA

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Abstract. An important probe of dark energy is the integrated Sachs-Wolfe effect, where cosmic microwave background anisotropies are generated at late times once the dark energy becomes important dynamically. This contribution briefly describes the effect and summarises the present observational evidence for it. A potential survey by the Square Kilometre Array (SKA) covering a large fraction of the sky could improve our understanding of the effect greatly.

1. Introduction

One major goal of future surveys like the Square Kilometre Array (SKA) will be to help us better understand what is responsible for the late time acceleration of the Universe. Whether this acceleration is due to some strange type of 'dark energy' or arises because the laws of gravity are modified on large scales, future surveys will enable us to better understand its origin.

If some kind of dark energy is the cause, there is much we would like to know: How much of it is there? How did evolve? Is it uniform everywhere, or does it cluster? Because it is dark, our knowledge of dark energy is necessarily indirect. Constraints on its present mass require measuring well the densities of the other cosmological ingredients: dark matter, baryons, neutrinos, photons, etc. The dark energy evolution is detected through measurements of the past expansion rate such as type IA supernovae, or the distance to the CMB last scattering surface.

We can also hope to learn about dark energy through its affect on the clustering matter. The rate that structures form will not only be affected by the changing the background expansion rate, but they will also be influenced by any inhomogeneities in the dark energy. These can be studied most directly through observations like gravitational lensing, and through the gravitational anisotropies they produce in the microwave background. The latter, which is known as the integrated Sachs-Wolfe (ISW) effect will be the subject of this contribution.

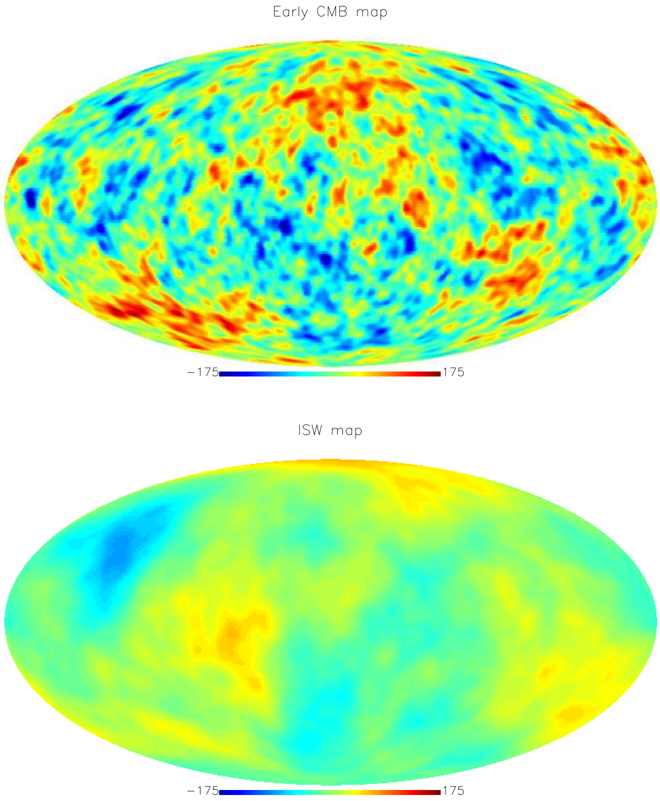

Fig. 1. Large scale CMB anisotropies arising in the early and late universe. Only the late contributions from the ISW effect on large scales are shown; non-linear effects like the Sunyaev-Zeldovich effect and the Rees-Sciama effect will arise on smaller scales.

2. What is the ISW effect?

The integrated Sachs-Wolfe effect results from the line of sight integral in the Sachs-Wolfe equation (Sachs & Wolfe 1967):

$$\frac{\Delta T}{T} = -2 \int d\tau \, \dot{\Phi} \qquad (1)$$

CMB photons pass through peaks and wells of the gravitational potential along their way to us. As they fall into a potential well, photons gain energy; if the well is not evolving, the photons lose the same energy when they climb out, leaving no net change. However, if the gravitational potentials decay while the photons pass through, then the energy that they lose climbing out is less that what they gained falling in, leaving a net shift in the photon temperature.

Both the ISW and Rees-Sciama effect arise in this way; the ISW effect is generally taken to be the contribution from the linear evolution of the gravitational potential, while the Rees-Sciama effect arises from the non-linear evolution of the potential in clusters (Rees & Sciama 1968). While the non-linear effect is inevitable, the linear effect depends on the cosmological model and requires that the background equation of state changes. This happens at early times as the universe goes from being radiation dominated to matter dominated, and can also occur at late times as the dark energy (or curvature) takes over from the matter.

The evolution of the gravitational potential can be related to the linear density perturbation via Poisson's equation in Fourier space,

$$\Phi = -\frac{4\pi G a^2}{k^2}\bar{\rho}_m \delta_m \tag{2}$$

where k is the comoving wave number. Since the matter density is proportional to $\bar{\rho}_m \propto a^{-3}$, we see that the gravitational potential evolves as $\Phi \propto \delta_m / a$. In the matter dominated regime, the growth of the perturbations is given by $\delta_m \propto a$, meaning the gravitational potential is constant in time: the collapse of the perturbations is exactly balanced by the dilution of the matter. However, when dark energy or curvature begins to dominate, the growth of perturbations is slowed, and the gravitational potentials begin to decay, giving rise to the late time ISW effect.

Unlike the ISW perturbations generated at the earlier radiation-matter transition, the ISW anisotropies generated at late times are virtually uncorrelated with the CMB fluctuations generated at the last scattering surface. Thus, the CMB sky we see is effectively composed of two independent maps, those fluctuations created at last scattering or soon afterwards, and those created at low redshifts when dark energy or curvature has become dynamically important (see Fig. 1.)

The spectrum of the temperature anisotropies generated by the late-time ISW effect is shown in Fig. 2. It is predominantly on very large scales, and for typical models, it is not as large as the anisotropies from the last scattering surface. It is dominated by modes which are of the horizon size, because it is these modes which will have the most time for the potential to change as the photons pass through. For smaller scale perturbations, photons can get many positive and negative smaller amplitude contributions which will tend to cancel out.

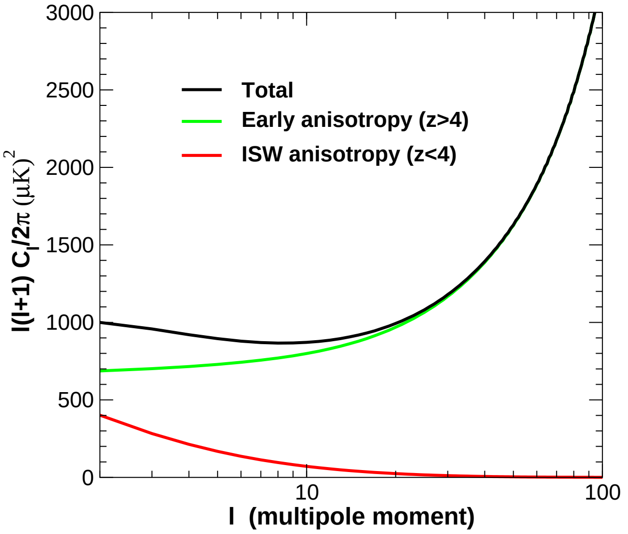

Fig. 2. Typical auto correlation function for the ISW effect in a cosmological constant model. The late ISW adds a small amount of large scale power to the temperature maps, largely uncorrelated with the anisotropy arising from early times.

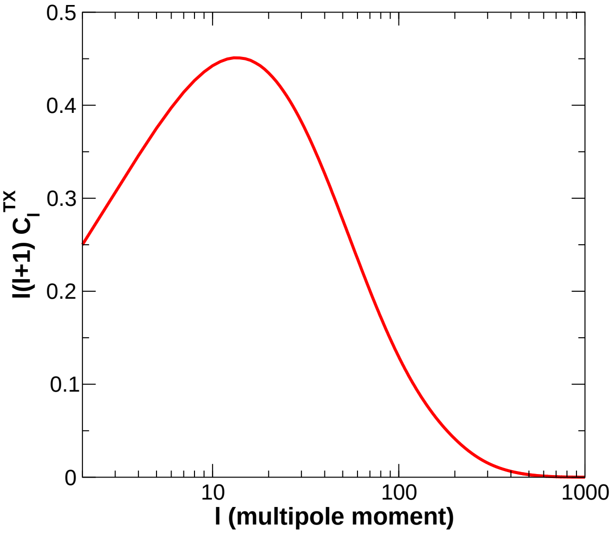

Fig. 3. Typical cross correlation function for the ISW effect in a cosmological constant model. The cross correlation (shown in arbitrary units) peaks on scales of a few degrees.

3. Detecting the ISW effect with cross correlations

How can we determine whether the CMB fluctuations we see are generated at early or late times? Unlike many foregrounds, the ISW fluctuations have the same frequency spectrum as the primordial anisotropies, so we cannot use different frequency observations to isolate them. We can attempt to look for the additional power in the CMB auto-correlation spectrum, but this is difficult because the ISW amplitude is small and where it is largest, cosmic variance is also large (Fig 2.) This makes direct detection difficult.

However, we do know that the ISW anisotropies will be produced by local ($z < 2$) fluctuations in the gravitational potential, and this we can determine if we know how the matter is distributed on large scales. While the gravitational potential is difficult to reconstruct, we can use the observed galaxy density as a way of tracing it. If the gravitational potential is decaying, statistically we expect over-densities of galaxies to align with temperature hot spots and under densities with temperature cold spots. Thus we can constrain our cosmological model by looking for cross correlations between the CMB maps and large scale distribution of matter (Crittenden & Turok 1995; Kinkhabwala & Kamionkowski 1999).The power spectrum of the cross correlations are shown in Fig. 3; while the cross correlations remain on relatively large scales, they are shifted somewhat smaller scales compared to the auto-correlation in Fig.2 because the galaxy surveys have a bluer spectrum.

Detecting the cross correlations is difficult, as it requires both a good map of the CMB on large scales and a map of the galaxy distribution which is both deep and covers a large fraction of the sky (Crittenden & Turok 1995; Peiris & Spergel 2000; Afshordi 2004). Large sky coverage is essential because the primordial fluctuations act effectively like noise when searching for anisotropies generated recently, and so the measurements are always 'noise' dominated. The first attempts of detecting the correlation using the COBE data and maps of the X-ray background (believed to trace AGN) or radio galaxy distribution produced no detections (Boughn et al. 1998; Boughn & Crittenden 2002).

However, the picture improved greatly with the WMAP observations (Bennett et al. 2003; Hinshaw et al. 2007). Correlations were quickly seen with the hard X-ray background (Boughn & Crittenden 2004), the NVSS radio galaxy survey (Boughn & Crittenden 2004; Nolta et al. 2004), the APM galaxy survey (Folsalba & Gaztanaga 2004), the SDSS (Fosalba et al. 2003; Scranton et al. 2003; Padmanabhan et al. 2005) and the 2MASS survey (Afshordi et al. 2003). While all the detections are at a low significance ($2-3\sigma$), it is encouraging that they are seen is such a broad range of surveys, from the radio and infrared to the optical and X-ray. More recent analyses have improved the significance of the detections using wavelet techniques (Vielva et al. 2006; McEwan et al. 2007), and seen correlations with new SDSS data (Cabre et al. 2006; Giannantonio et al. 2006).

The observational evidence of the cross correlations between the CMB and large scale structure is shown in Fig. 4, where the correlations at a particular angle are shown as a function of the mean redshift of the survey. Despite the wide frequency range of the observations (from the radio to the X-ray) and the very different systematics in these surveys, the cross correlations are all consistent, and are consistent with the theoretical expectations for the ISW effect in a cosmological constant cosmology.

4. Prospects for the future and the SKA

The various cross correlation measurements have already been combined to give constraints on cosmological models (Gaztanaga et al. 2006; Corasaniti et al. 2005). While the limits are still relatively weak, the cross correlation measurements constitute direct physical evidence of dark energy, giving independent confirmation of our cosmological model. With improved large scale structure data, future observations will improve these measurements and may be able to break parameter degeneracies of the dark energy model (Garriga et al. 2004; Pogosian 2005; Pogosian et al. 2005). However, the 'noise' from the primordial anisotropies fundamentally limits how well cross correlations can ever be detected, with an ideal signal to noise of approximately 10 in the most optimistic models (Crittenden & Turok 1995; Afshordi 2004).

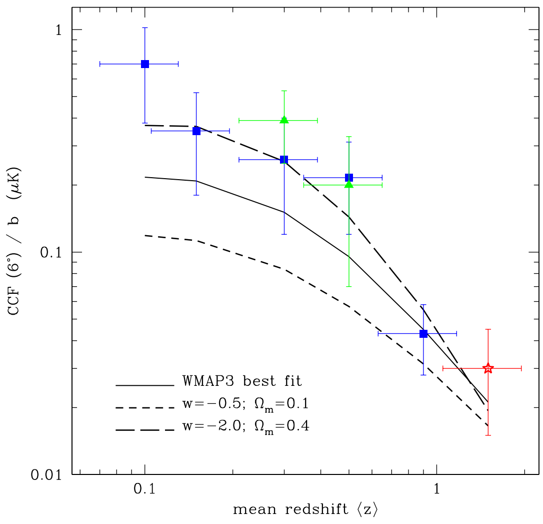

Fig. 4. A summary of the ISW cross correlation measurements to date (from Giannantonio et al. 2006). The lower redshift points represent the WMAP correlations with the APM and 2-MASS surveys, the median redshift points arise from the correlations with the SDSS galaxy and LRG surveys, and the highest redshift points come from radio galaxy, x-ray and SDSS quasar surveys. The results from all the various surveys are consistent with each other and the theoretical predictions of the standard concordance model.

The amplitude of the final signal will depend on the actual strength of the correlations and the data so far has shown slightly higher correlations than expected, but the significance of this excess is not great. Obtaining the best possible limits will require very good CMB and large scale structure data. While data from WMAP and Planck should be sufficient from the CMB side, much progress is needed in the large scale structure data, and here is where the SKA could play a vital role.

The present surveys are limited by a number of factors. Some, like the 2-MASS infrared survey, simply do not go deep enough in redshift to see the largest part of the effect. Others, like the NVSS radio galaxy survey, are deep enough but the exact redshift dependence and bias of the sample are uncertain. These surveys also suffer from having relatively few objects, leading to significant Poisson uncertainties. The biggest limiting factor in most surveys is sky coverage; the only way to beat down the noise of the uncorrelated early CMB map (Fig. 1) is to cover the largest fraction of sky available. The signal to noise is roughly proportional to the square root of the area of the survey, meaning that bigger is generally better.

Recently, cosmological surveys have been proposed for the SKA which could be ideal for the study of the ISW effect. For example, Blake et al. (2004) describe a survey with of order 10^9 HI emission line galaxies covering half of the sky, with full three dimensional information out to redshifts of order $z = 1.5$. Such a survey (were it only able to cover the whole sky) would be able to measure virtually the entire ISW signal, with sufficient number densities that Poisson errors would not be a problem.

However, even in such perfect conditions the cosmic variance would prevent the signal to noise from being too high. Despite this limitation, cross correlation studies are crucial as they offer an important window on the clustering of the dark energy. Few other probes are on sufficiently large scales to see this clustering, and including the dark energy perturbations makes a significant impact on the ISW anisotropies (Bean & Dore 2004; Weller & Lewis 2003). Given the uncertainties, the present constraints on the sound speed are fairly weak; however, ultimately cross correlation measurements should be able to discriminate between different sound speeds (Hu & Scranton 2004).

In addition, the ISW effect provides a means for distinguishing dark energy from modified gravity, even if the background expansion is identical (e.g. Lue et al. 2004; Song et al. 2006). The modified gravity models can change the rate of gravitational collapse at higher redshifts, generating additional correlations. Thus, it is vital that we continue looking for correlations in future surveys like the SKA and keep pushing the bounds to higher and higher redshifts.

References

Afshordi, N., Loh, Y. S., & Strauss, M. A., 2004, Phys. Rev. D, 69, 083524

Afshordi, N., 2004, Phys. Rev. D, 70, 083536

Bean, R. & Dore, O., 2004, Phys. Rev. D, 69, 083503

Bennett, C. L., et al., 2003, ApJS, 148, 1

Blake, C. A., Abdalla, F. B., Bridle, S. L., & Rawlings, S., 2004, New Astron. Rev., 48, 1063

Boughn, S. P., Crittenden, R. G., & Turok, N. G., 1998, New Astron., 3, 275

Boughn, S. P. & Crittenden, R. G., 2002, Phys. Rev. Lett., 88, 021302

Boughn, S. & Crittenden, R. G., 2004, Nature, 427, 45

Cabre, A., et al., 2006, MNRAS, 372, L23

Corasaniti, P. S., Giannantonio, T., & Melchiorri, A., 2005, Phys. Rev. D, 71, 123521

Crittenden, R. G. & Turok, N., 1996, Phys. Rev. Lett., 76, 575

Fosalba, P. & Gaztanaga, E., 2004, MNRAS, 350, L37

Fosalba, P., Gaztanaga, E. & Castander, F., 2003, ApJ, 597, L89

Garriga, J., Pogosian, L., & Vachaspati, T., 2004, Phys. Rev. D, 69, 063511

Gaztanaga, E., Manera, M., & Multamaki, T., 2006, MNRAS, 365, 171

Giannantonio, T., et al., 2006, Phys. Rev. D, 74, 063520

Hinshaw, G., et al., 2007, ApJS, 170, 288

Hu, W. & Scranton, R., 2004, Phys. Rev. D, 70, 123002

Kinkhabwala, A. & Kamionkowski, M., 1999, Phys. Rev. Lett., 82, 4172

Lue, A., Scoccimarro, R., & Starkman, G. D., 2004, Phys. Rev. D, 69, 124015

McEwen, J. D., et al., 2007, MNRAS, 373, 1211 arXiv:astro-ph/0602398.

Nolta, M. R., et al., 2004, ApJ, 608, 10

Padmanabhan, N., et al., 2005, Phys. Rev. D, 72, 043525

Peiris, H. V. & Spergel, D. N., 2000, ApJ, 540, 605

Pogosian, L., 2005, JCAP, 0504, 015

Pogosian, L., 2005, Phys. Rev. D, 72, 103519

Rees, M. J. & Sciama, D. W., 1968, Nature, 217, 511

Sachs, R. K. & Wolfe, A. M., 1967, ApJ, 147, 73

Scranton, R., et al., (SDSS Collaboration), 2003, (astro-ph/0307335)

Song, Y. S., Sawicki, I., & Hu, W., 2007, Phys. Rev. D, 75, 064003

Vielva, P., Martinez-Gonzalez, E., & Tucci, M., 2006, MNRAS, 365, 891

Weller, J. & Lewis, A. M., 2003, MNRAS, 346, 987