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PROBING THE DARK ENERGY THROUGH THE INTEGRATED SACHS-WOLFE EFFECT

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Abstract.

We investigate the detection of the integrated Sachs-Wolfe (iSW) effect through the impact of single superstructures on the cosmic microwave background (CMB) temperature, and its measurement using the stacking of CMB patches. We revisit the analysis of Granett et al. (2008a, Gr08) using our own robust protocol, and extend the study to the two most recent and largest catalogues of voids publicly available. We obtain the radial temperature and photometry profiles from the stacked images. Using a Monte Carlo approach, we computed their statistical significance and identified the angular scale at which the signal-to-noise ratio (S/N) is maximum. We essentially confirm the signal detection reported by Gr08, but for the other two catalogues, a rescaling of the voids to the same size on the stacked image is needed to find any significant signal (with a maximum at $\sim 2.4\,\sigma$). This procedure reveals that the photometry peaks at unexpectedly large angles in the case of the Gr08 voids, in contrast to voids from other catalogues. We also stress the importance of a posteriori selection effects that might arise when intending to increase the S/N, and we discuss the possible impact of void overlap and alignment effects. We argue that the interpretation in terms of an iSW effect of any detected signal via the stacking method is far from obvious.

Keywords: cosmology, cosmic microwave background, dark energy, large scale structures

1 Introduction

The discovery of the acceleration of the expansion of the Universe, made through supernovæ observations at the end of the last century, led us to hypothesize the existence of an unknown "Dark Energy", contributing $\sim 70\%$ to the energy budget of our Universe. In this presentation, we focus on a specific probe of the Dark Energy, namely the integrated Sachs-Wolfe (iSW) effect : This effect of gravitational origin induces secondary anisotropies in the CMB and is due to large-scale structures. The gravitational potentials of the latter are slowly decaying in a Λ-dominated Universe, and therefore give a net difference in energy to the CMB photons that travel across them. This effect shows in the power spectrum of the Cosmic Microwave Background (CMB) temperature anisotropies at large angular scales but its small amplitude and the cosmic variance at those ℓ make its direct detection very challenging, if not impossible, when using only the CMB itself. To circumvent this limitation, cosmologists have devised a way to exploit the link between this imprint on the CMB and the large-scale structures causing it, first by simply cross-correlating the CMB with matter density maps (galaxy maps in practice) and then comparing the results to a null hypothesis and to what is expected from theory. During the last decade or so, a growing interest has risen in this field thanks to the development of large galaxy surveys in many wavelengths. However, this method has yet to produce a definitive and conclusive detection of the ISW effect from current surveys, with significances ranging so far from negligible up to more than 4σ, and with sometimes conflicting results throughout the literature.

We make here a short report of our work presented in Ilić et al. (2013) and Planck Collaboration (2013), where we consider an alternative method of measuring the iSW effect, namely through the impact of individual superstructures in the CMB temperature. Unfortunately, the amplitude of such effect with respect to the primary CMB anisotropies does not allow us to detect it structure by structure. However, stacking techniques can be profitably adopted to enhance the signal-to-noise ratio (S/N). With the help of the Wilkinson Microwave

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Anisotropy Probe (WMAP) five year maps, such a technique has been applied by Granett et al. (2008) (Gr08 thereafter) to the supervoids and superclusters they identified in the catalogue of luminous red galaxies (LRGs) in the Data Release 6 (DR6) of the Sloan Digital Sky Survey (SDSS). Focusing on the most significant (in terms of the density contrast) 50 supervoids and 50 superclusters, Gr08 report a combined mean temperature deviation of 9.6 μK, at a significance just above $4\,\sigma$, which they interpret as a signature of the iSW effect. Using the Millennium simulation and measuring the iSW effect that is expected in a standard ΛCDM universe, Gr08 find that it is $\sim 2\,\sigma$ lower (at 4.2 μK) than what they obtained from the WMAP data. Other studies have also measured a somewhat higher iSW effect than expected, although with small statistical significance. The high significance and the stronger-than-expected amplitude of the iSW effect detected through stacking have also stimulated a number of investigations, which yielded mixed conclusions (cf. Ilić et al. 2013, and references therein).

Should we conclude that the large CMB temperature deviations measured in association with superstructures signal a tension with the ΛCDM model? Here, we would like to take a further step towards answering that question. Since the study of Gr08, new CMB maps have been released and other superstructure catalogues have been published. We do the stacking analysis with the new data and look for the iSW signal that could be associated with the large scale structure. We pay particular attention to the bias introduced into the results by selection effects and illustrate it with an explicit example.

2 The data used

The first and foremost way to improve stacking studies was to use the latest CMB data to improve and validate our stacking studies. We conducted two separate works on the topic: one that used WMAP 7-year data (the latest at the time of the study) which led to the publication of a paper (Ilić et al. 2013), and another inside the Planck collaboration itself by leading the stacking section in the iSW-dedicated cosmological paper (Planck Collaboration 2013). Although the CMB data is different, the protocol that we devised is largely the same for both new studies and the catalogues of structures used are identical. The impact of foregrounds and the associated possibility of false signals is often a source of uncertainty in iSW studies. We therefore consider and assess their possible influence by redoing our analyses on the foreground reduced maps released by both teams in the same frequency channels.

The first catalogue of superstructures (clusters and voids) that we considered was created and studied by Gr08. Since it was already explored with WMAP 5-year data, it will serve us as a “fiducial” set when testing all the steps of our own stacking procedure. This will also be the opportunity to revisit the work of Gr08 with the newer seven-year data from WMAP. Pan et al. (2012) (Pan12) published a catalogue of cosmic voids and void galaxies identified in the seventh data release (DR7) of the SDSS. Using the VoidFinder algorithm as described by Hoyle & Vogeley (2002), they identified and catalogued 1055 voids with redshifts lower than $z = 0.1$. Finally, the most recent catalogue considered in the present study was released by Sutter et al. (2012) (Sut12). Using their own modified version of the void finding algorithm ZOBOV, Sut12 also built a void catalogue from the SDSS DR7, taking particular care to account for the effects of the survey boundary and masks. In the latest version of their catalogue, they found a total of 1495 voids, which they divided into six distinct subsamples of increasing redshift, spanning $z \sim [0, 0.4]$. This catalogue stands out by the large amount of information provided about its voids.

3 Stacking protocol

The analysis of these three different catalogues requires us to have a robust and well defined procedure for a systematic analysis of all the structures considered. First, the standard stacking procedure that we apply in this study consists in the following steps, for each superstructure sample or subsample: we retrieve the galactic longitudes and latitudes of the structures considered, and use a custom code based on the HEALPix package to cut a patch in the considered CMB map centred on each structure. The final stacked image is then constructed as the average image of all CMB patches weighted by their corresponding weight patches. Two main products are then extracted from the stacked image. Firstly, the radial temperature profile starting from the centre of the image, by computing the mean temperature of the pixels in rings of fixed width and increasing angular radius. Then, the aperture photometry profile, using a compensated filter approach. At each angle θ, we compute the photometry as the difference between the mean temperature of the pixels inside the disk of angular radius θ and the temperature of the pixels in the surrounding ring of same area, i.e. the ring enclosed between circles of radii θ and $\theta\sqrt{2}$. We mainly focus on the analysis of these two profiles (the image itself is useful for illustration purposes only), where we look for any remarkable signal whose significance we need to assess (as described later section).

Each of the different CMB maps that we use inherently has a different resolution and contains different types and levels of foregrounds that may contaminate them. Before progressing any further, we assessed the impact of the properties of each map, using our fiducial stacking (i.e. using the Gr08 void positions) as a basis. First, to have a consistent stacking analysis through all the considered frequencies, we need to "standardise" those maps by first smoothing them at the lowest resolution in order to lose as little information as possible. The stacks at each frequency, both raw and smoothed, give roughly the same results with only percent-level differences especially for the photometry profiles – the most useful products here. One other source of concern comes from the influence of foregrounds present in the CMB maps, because they might mimic the expected iSW signal in the stacked images. To assess their possible impact, we performed the stacking of the Gr08 voids first on raw and then on foreground cleaned CMB maps at all frequencies. We obtained systematic offsets of a few micro-kelvins in the radial temperature profiles and less in the photometry profiles. This indicates that we mainly remove an almost uniform background, which does not influence the aperture photometry of the stacked image much.

When taken alone, the stacked images and their associated profiles are not enough to conclude anything about a possible detection of the iSW effect. Any peculiar feature that seems to stand out could very well be a random event well within statistical fluctuations. As a consequence, we have to take great care in assessing the significance of our results. We have devised a systematic way to compute the significance adopting a Monte Carlo approach. We consider the stack of N_v voids, identified in the data, whose significance we try to estimate. We pick many sets (at least 10000) of N_v random positions on the sky confined within the area covered by the SDSS. For each random set, we perform the same analyses as for the data voids; i.e., we produce a stacked image of the N_v patches extracted from the same CMB maps, and compute its radial temperature and photometry profiles. We store all these profiles in memory and end up with thousands of temperature profiles and photometry profiles. After this, for each angular size of the profiles, we compare the results from the stack of data voids to the statistical distribution of results from the random stacks. In practical terms, we calculate the S/N of the data temperature or photometry profiles, at each angle θ considered. Applying this procedure to the fiducial stacking of the Gr08 voids, we found that this estimation of the significance was robust and used it in the remainder of our study for all our results.

4 Results

The work of Gr08 reported a $3.7\,\sigma$ signal ($-11.3\,\mu$K) in the stacking of their voids on a scale of 4°. With the same dataset we find a reasonable agreement with a preferred scale of $\sim 3.7°$ with an S/N ~ 3.3 ($-10.8\,\mu$K). These differences can be imputed to our use of WMAP 7 maps instead of the WMAP 5 ILC map for Gr08 and, to a lesser extent, to light differences in the stacking procedure, profile calculations, or significance estimation. While we can argue about its cosmological origin, the signal seems to be persisting and is essentially identical across frequencies as expected for the iSW effect. However, we found an important feature in the temperature profile of the stacked image and its significance. Indeed, the central cold spot of the signal (below 3.5°) does not particularly stand out compared to random stacks ($1\,\sigma$ significance only). On the other hand, we measure a wide hot ring with around the spot a higher significance (up to $2\,\sigma$) on scales between 3.5° and 10°. Interpreting it in the light of the iSW effect, this would imply the presence of much higher overdensities surrounding the already large supervoids. Considering the filamentary structure of our Universe, this situation is unlikely, and the source of this hot ring remains unknown. This peculiarity leads us to question whether the measured central cold spot – physically interpreted as an iSW signal – is really remarkable. It might as well be due to random fluctuations of the CMB, of which the significance in the photometry profile is coincidentally strengthened by a surrounding hot region in the stacked image.

The two other catalogues used in our analysis, when taken as such, yield mixed results, with no significance on the same level as the Gr08 catalogue. While discouraging, one has to remember that according to current theoretical predictions, we expect this iSW signal to be difficult to detect. Preliminary analysis strongly suggested that we needed to take the size of each individual void into account in the stacking procedure to improve the significance of the results. We therefore kept each subsample in its entirety and did the stacking analysis again, but this time rescaling the voids according to their effective radii. Beginning with the fiducial stacking of the voids of Gr08, the signal identified before still appears after rescaling, with the best significance around scales between 0.7 and 0.9 times the void effective radii. The significance of the signal is also found to be lower (S/N~ 2.8 versus ~ 3.3). This is partly due to the increased variance of the signal induced by the rescaling. But it is also a consequence of the lower amplitude measured for the signal, at odds with our expectations of the rescaling procedure and a possible further hint of a contribution from random CMB fluctuations. On the other hand, the temperature profile of the rescaled stack is closer to expectations, with a higher significance cold spot in the centre. Again, no signal of particular importance arises from this new analysis of Pan12 voids (except at very small angular sizes, most likely due to random fluctuations and not in relation to any underlying structure). Concerning the Sut12 catalogue, signals seem to arise in several of the rescaled profiles, especially on a scale equal to 0.5-0.55 times the voids effective radii, with a clear departure from the previous (without rescaling) results for some of the subsamples. However, some other subsamples do not benefit from the rescaling procedure. A possible explanation may come from the presence in these particular subsample of some of the largest voids in the whole Sut12 catalogue, which are supposed to yield the strongest iSW effect.

This indicates that instead of considering each subsample separately, a better approach may be to combine them all and stack the voids starting from the largest ones. Indeed, in theory the noise should scale as usual roughly as the inverse square root of the number of stacked voids, but the stacked iSW signal is also expected to drop at some point due to the addition of smaller and less contributing voids. By starting from the largest voids, we intend to select the supposedly largest iSW contributions in order to keep the stacked signal from dropping too fast and effectively to boost the S/N of the detection. We carried out this analysis on the 1495 voids of Sut12, first focusing on the whole photometry profiles and increasing progressively the number of stacked voids. As expected, a negative signal consistently appears around an aperture of 0.54 times the voids effective radii. As intuited before, its amplitude gradually decreases as we include smaller and smaller voids in the stacking. To estimate the significance of this signal, we focus on the value of the photometry at this particular aperture scale. Similarly to the previous section, we estimate the significance of these values by repeating the analysis many times after randomly shifting the stacked positions. We note once again that the photometry is stable across frequencies and consistently negative for practically any number of stacked voids, but the shape of this curve and its significance are hard to interpret. The significance first rises up to $\sim 2.3\,\sigma$ for the first 200 stacked voids, a behaviour that would be expected from an ISW signal that progressively takes over the CMB noise. After this, the S/N quickly decreases and then oscillates between about $1\,\sigma$ and $2\,\sigma$ before dropping, after stacking more than 1300 voids. Although this significance appears to vary quite significantly, the stability of the signal itself (always negative and on the same scale) may indicate that this variability is due to random CMB fluctuations. In summary, the rescaling process had positive results on the much larger catalogue of Sut12, highlighting a particular scale around half the void sizes in all the tests performed, in apparent agreement with both intuitive arguments and theoretical works in the literature. Although the maximum observed significance only reaches around $2.3\,\sigma$ and the signal depends quite significantly on the number of stacked voids and their size, the persistent nature of the signal seems to bolster the case for iSW detection.

5 Conclusions

In this work, we revisited the stacking of voids in CMB maps as a potential probe of dark energy through the expected iSW effect from these structures. We devised a complete protocol for a stacking procedure from a careful choice of maps to a rigorous estimation of the significance. We first applied it to the catalogue of voids of Gr08 and did not find any significant difference, if not a little weaker signal and associated S/N (by $0.4\,\sigma$). We then extended the analysis to two new void catalogues by Pan et al. (2012) and Sutter et al. (2012). The first did not yield any significant result, most likely owing to the limited range of redshift and radii of the sample. The second new catalogue, however, hinted at more significant signals (although not nearly as strong as the Gr08 results) with a trend for the preferred scale in the signal, which seemed to point to half the mean size of the voids used in the stacking. This was not found with the Gr08 voids, for which the highest significance scale was close to the mean void size, but it is more coherent with our expectations because of the irregular geometry of the stacked voids. In any case, the rescaling of the CMB patches (according to the void sizes) prior to stacking proved to be a mandatory step toward obtaining a significant signal in the photometry profiles, especially in light of our results with the incremental stacking of the largest voids of the Sut12 catalogue.

Along with these results, we also addressed the risks of possible selection effects that could easily lead to an overestimation of the significance. We also stressed that the surface density of the voids within the SDSS area make them overlap significantly, making it even more difficult to formulate clear expectations about, and interpretations of, the measured signals. Finally, it is known that voids are actually difficult to identify with certainty and that one must proceed with caution when analysing such void samples. Another instance of this is that while being identified in the same SDSS DR7 set, two void subsamples of Sut12 lie within the same redshift range as the voids identified by Pan12, but they cover quite a different range in size and are distributed differently in redshift. We argue, therefore, that, combined with the unavoidable overlap of voids along a line of sight mentioned above, any claim of a detection of an iSW-like signal by the stacking of voids and/or claim of an oddity with respect to ΛCDM would be premature.

References

Granett, B. R., Neyrinck, M. C., & Szapudi, I. 2008, ApJ, 683, L99

Hoyle, F. & Vogeley, M. S. 2002, ApJ, 566, 641

Ilić, S., Langer, M., & Douspis, M. 2013, A&A, 556, A51

Pan, D. C., Vogeley, M. S., Hoyle, F., Choi, Y.-Y., & Park, C. 2012, MNRAS, 421, 926

Planck Collaboration. 2013, ArXiv:1303.5079

Sutter, P. M., Lavaux, G., Wandelt, B. D., & Weinberg, D. H. 2012, ApJ, 761, 44