PROBING THE ORIGINS OF VOIDS WITH THE CMB

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In this talk presented at the 5th Rencontres du Vietnam 2004, we discuss our preliminary investigations into voids of primordial origin. We show that if voids in the cold dark matter distribution existed at the epoch of decoupling, they could contribute significantly to the apparent rise in cosmic microwave background (CMB) power on small scales detected by the Cosmic Background Imager (CBI) Deep Field. Here we present the preliminary results of our improved method for predicting the effects of primordial voids on the CMB in which we treat the voids as an external source in the cold dark matter (CDM) distribution, employing a Boltzmann solver. Our improved predictions include the effects of a cosmological constant (Λ) and acoustic oscillations generated by voids at early times. We find that models with relatively large voids on the last scattering surface predict too much CMB power in an Einstein–de Sitter background cosmology but could be consistent with the current CMB observations in a ΛCDM universe.

1 Introduction

Analyses of surveys such as the 2-degree Field Galaxy Redshift Survey and the Sloan Digital Sky Survey indicate large volumes of relatively empty space, or voids, in the distribution of galaxies\textsuperscript{12}. In the standard hierarchical model of structure formation, gravitational clustering is responsible for emptying these voids of mass and galaxies\textsuperscript{3}. However, standard cold dark matter (CDM) model simulations predict significant clumps of matter within voids that are capable of developing into observable bound objects and are not seen in the surveys\textsuperscript{5–7}. Peebles gives an in-depth discussion of the contradictions of this prediction with observation\textsuperscript{4}. He argues that the inability of the CDM models to produce the observed voids constitutes a true crisis for these
models. Additionally, deep field observations from the Cosmic Background Imager (CBI) show excess power on small angular scales, $\ell > 2000$, in the cosmic microwave background (CMB).

It may be possible to explain these 2 observations by postulating the presence of a void network originating from primordial bubbles of true vacuum that nucleated during inflation. In this scenario, the first bubbles to nucleate are stretched by the remaining inflation to cosmological scales. The largest voids may have had insufficient time to thermalise before decoupling and may persist to the present day. Such primordial voids are predicted to produce a measurable contribution to the CMB.

In this paper, we discuss the results of Griffiths et al. (2003) in which we develop a general method to approximate the void contribution to the CMB that allows the creation of maps and enables us to consider an arbitrary distribution of void sizes. We show that if the voids that we see in galaxy surveys today existed at the epoch of decoupling, they could contribute significant additional power to the CMB angular power spectrum between $2000 < \ell < 3000$. Further to this work, we describe how we improve our predictions. We include the effects of the cosmological constant as well as oscillations in the matter-radiation fluid that may be generated by primordial voids on scales up to the sound horizon. For full details of our improved methodology refer to our recently submitted manuscript on the subject.

2 First Approximation

2.1 Void parameters

We model the voids seen today as spherical underdensities of $\delta \rho / \rho = -1$. Each void is bounded by a thin wall containing the matter that is swept up during the void expansion. This forms a compensated void. This means that the overall cosmology is that of the background universe, since a compensated void does not distort space-time outside of itself. This is an extremely important property, as it allows us to place many voids into a universe without the worry that they might influence each other. As a first approximation we take the background universe to be an Einstein–de Sitter (EdS) cosmology. Conservation of momentum or energy can be used to show that compensated voids in an EdS background cosmology will increase in radius $r_v$ between the onset of the gravitational collapse of matter at equality and the present day such that

$$r_v(\eta) \propto \eta^\beta,$$

with $\beta \approx 0.39$ and where $\eta$ is conformal time.

Motivated by the extended inflationary scenario, we assume a power-law distribution of bubble sizes greater than a given radius $r$ of the form,

$$N_B(> r) \propto r^{-\alpha}.$$

Typically, extended inflation is implemented within the framework of a Jordan-Brans-Dicke theory. In this case, the exponent $\alpha$ is directly related to the gravitational coupling $\omega$ of the scalar field that drives inflation,

$$\alpha = 3 + \frac{4}{\omega + 1/2}.$$

Values of $\omega > 3500$ are required by solar system experiments. We take the limit of large $\omega$, leading to a spectrum of void sizes with $\alpha = 3$.

It has been shown that a distribution of void sizes that predicts the existence of arbitrarily large inflationary voids will cause significant effects on the CMB that contradict observations. We assume that the mechanism creating the voids imposes an upper cut-off on the size distribution. A possible mechanism for this cut-off could be that the tunneling probability of inflationary bubbles is modulated through the coupling to another field.
Figure 1: Top: The CMB anisotropies produced by the fiducial EdS void model (solid line) compared to the primary ΛCDM CMB anisotropies (dashed-triple-dotted). Also plotted are the sum of primary and void contributions (dotted) as well as the fluctuations induced purely by voids on the last scattering surface (dashed) and by those between last scattering and today (dashed-dotted). We show the “standard” cosmological concordance model: of course a combined analysis of primary and void-induced fluctuations would select a different cosmology for the primary contribution. Bottom: Example models depicting a range of void contributions to the CMB fluctuations. The models plotted are $\alpha = 3$, $r_{\text{max}} = 25 \, \text{Mpc}/h$ and $F_v = 0.4$ (solid line), $\alpha = 3$, $r_{\text{max}} = 40 \, \text{Mpc}/h$ and $F_v = 0.4$ (dotted), $\alpha = 3$, $r_{\text{max}} = 40 \, \text{Mpc}/h$ and $F_v = 0.2$ (dashed) and $\alpha = 6$, $r_{\text{max}} = 40 \, \text{Mpc}/h$ and $F_v = 0.4$ (dashed-dotted).

As well as avoiding the well known problems associated with arbitrarily large voids existing at the epoch of decoupling, this assumption allows us to match the observed upper limit on void sizes from the galaxy redshift surveys. We choose the average value that is found, $r_{\text{max}} = 25 \, \text{Mpc}/h$. The minimal present void size is also chosen to agree with redshift surveys, $r_{\text{min}} = 10 \, \text{Mpc}/h$.

We normalise the distribution by requiring that the total number of voids satisfies the observed fraction of the universe filled with voids today, $F_v$. Redshift surveys indicate that approximately 40% of the fractional volume of the universe is in the form of voids of underdensity $\delta \rho/\rho < -0.9$, ie. $F_v \approx 0.4$. The positions of the voids are then assigned randomly, making sure that they do not overlap. In order to speed up this process, we consider only a $10^\circ$ cone. This limits our analysis to $\ell > 100$, which is satisfactory for our purpose since the main contribution from voids is on much smaller scales.

2.2 Stepping through the void network

Refer to Griffiths et al. (2003) for a more detailed description of our methodology. We ray trace photon paths from us to the last scattering surface (LSS) for the $10^\circ$ cone in steps of 1’. Each void in the present day distribution that is intersected by the photon path is evolved back in time according to equation 11 to determine whether the photon encounters the void.

If a photon intersects a void between us and the LSS, we compute the Rees–Sciama (RS) effect due to the deviation in the redshift of the photon as it passes through the expanding void and the lensing effect due to the deviation in its path. If a photon intersects a void on the LSS, we calculate the Sachs–Wolfe (SW) effect due to the photon originating from within the underdensity. We take into account the finite thickness of the LSS, which suppresses the SW effect for small voids, by averaging the contribution from a number of photons originating from a LSS of mean redshift 1100 and standard deviation in redshift 80. We also calculate the partial RS effect that arises due to the expansion of the void on the LSS as the photon leaves it.

Once the photon has reached the last scattering surface, we know the variation of its temperature as well as its position on the LSS and can create a temperature map. We then use a flat sky approximation to obtain the $C_\ell$ spectrum of the anisotropies (see Fig. 1).
point out that primordial void parameters are still poorly constrained by both observation and theory. The bottom panel of Fig. 1 shows a few further example models.

For a power-law size distribution (as motivated by the inflationary scenario), large voids become rarer as $\alpha$ is increased. Therefore, since void analyses of redshift surveys only sample a fraction of the volume of the universe, there may exist voids of larger $r_{\text{max}}$ than currently observed. Models with high $r_{\text{max}}$ voids in an EdS background cosmology tend to predict too much power on scales $\ell \approx 1000$. However, if we take inflationary models with $\alpha > 6$ then the peak moves to larger $\ell$ and the total power drops. The filling fraction mainly adjusts the overall power.

3 Improved Prediction

3.1 Void Evolution in a $\Lambda$CDM background cosmology

The addition of a cosmological constant ($\Lambda$) to the cosmology is expected to slow down the conformal evolution of the voids at late times. We test this hypothesis by simulating the comoving evolution of a single void of radius 25 Mpc$/h$ starting at $z = 1000$ in a $(100$ Mpc$/h)^3$ box containing $64^3$ particles. We find that the void size evolution in a $\Lambda$CDM background deviates from that of the EdS scaling solution at late times as expected. However, the final radius is underestimated by less than 2%. The EdS void scaling relationship given by equation (1) with $\beta = 0.39$ is therefore a good approximation for a void in a $\Lambda$CDM background.

Since a $\Lambda$CDM universe evolves for substantially longer, we would expect the voids that we see today to appear smaller on the last scattering surface for this cosmology than in our first approximation EdS background. We would therefore predict that voids in a $\Lambda$CDM universe will have a more suppressed effect on the CMB than we have first approximated. This can be modelled by taking the horizon size of our cone of voids to be that of a $\Lambda$CDM cosmology. Fig. 2 compares the predicted power from a uniform distribution of equally sized voids in EdS and $\Lambda$CDM background cosmologies. The overall contribution to the CMB from the voids is suppressed as expected and the peak is moved to smaller angular scales since the voids now appear smaller on the last scattering surface.

3.2 Modelling acoustic oscillations

So far we have studied voids which do not interact with their surroundings. Specifically, they do not perturb the matter-radiation fluid themselves. While this is a reasonable approximation...
Figure 3: A “zoom” onto the sound horizon showing the behaviour of the perturbations in real space at last scattering (LS) from a single void. The void, which has a radius of 40 Mpc today, has a size of 9 Mpc at LS. The black solid curve is the input perturbation $\Phi_S(x, \eta_{LS})/2$, while the red dotted curve is the total metric perturbation $\Phi/2$. The blue small dashed curve shows $-2\Psi = 2\Phi$. The cyan large dashed curve is the temperature perturbation from the photons, $D_g/4$. The baryon velocity is shown as the magenta dot-dashed curve. The green small dashed-large dashed curve is $D_g/4 - 2\Phi$, which is very similar to $\Phi_S/2$.

for the RS effect after recombination, it has been pointed out\textsuperscript{23} that this is not true before last scattering. A void could therefore set up oscillations in the matter-radiation fluid on scales up to the sound horizon which might be clearly visible in the power spectrum.

The standard way to include the full behaviour of matter and radiation perturbations is to solve the Boltzmann equation numerically. But it is not possible to model a void self-consistently inside the Boltzmann solver. A similar problem was encountered a few years ago while investigating topological defects\textsuperscript{24}. As opposed to defects, which are entirely external sources, the voids represent a perturbation of the dark matter itself. We have chosen to model this by making the approximation that the dark matter is completely decoupled from the rest of the universe. Therefore, the cold dark matter acts only as an external seed where the perturbations are concerned (of course it is taken into account for the background quantities). We insert our source into a modified version of CMBEasy\textsuperscript{25} and then write out a snapshot of the fluids at the time of last scattering and Fourier transform them back.

Fig. 3 shows a close up of the perturbations for our model of void formation around the sound horizon. We see that the amplitude of the sound waves is only about 1% of the amplitude of the temperature perturbations inside the void. For smaller voids, the relative amplitude will be even less. This seems quite unimportant, however, the void itself covers a surface of only about $9^2\pi (\text{Mpc}/h)^2$ on the LSS, the sound horizon in our flat matter dominated universe of the example case is at 111 Mpc/$h$ and the sound waves extend out to about 100 Mpc/$h$, ten times further than the size of the void. Therefore, the total power in the fluctuations is approximately 100 times larger than expected from their amplitude and is comparable to the the power from the void predicted by our ray tracing method. Indeed, we see oscillations appear on large angular scales in the angular power spectrum (see Fig. 4). For further details of our method, please refer to Ord \textit{et al.} (2005)\textsuperscript{12}.

4 Summary

Fig. 4 compares the void $C_\ell$ from ray tracing and the Boltzmann approach for a uniform distribution of 40 Mpc/$h$ sized voids. The overall effect from the first approximation ray tracing method appears to be suppressed using the improved Boltzmann solution. Evidence of acoustic oscillations generated in the photon-baryon fluid can also be seen on large angular scales. The RS effect due to $\Phi_v$ alone, using the same approximations in both calculations, is in agreement for both methods as expected.
Figure 4: We compare the $C_\ell$ from ray tracing and the Boltzmann approach. The dotted curve shows the total $\delta T$ for a $\Lambda$CDM model with voids of a size of 40 Mpc/$h$ and a filling fraction of 40%, computed by ray tracing a void network. The solid curve shows the same but computed with a Boltzmann code. The small and large dashed lines show the RS effect due to $\Phi_v$ alone for both methods and with the same approximations, these two curves should coincide.

Figure 5: Top: The CMB anisotropies produced by a $\Lambda$CDM void model (solid line: $\alpha = 3$, $r_{\text{max}} = 55$ Mpc/$h$ and $F_v = 0.4$) compared to the primary $\Lambda$CDM anisotropies (dotted). Also plotted are the sum of primary and void contributions (dashed). We show the “standard” cosmological concordance model. Again a combined analysis of primary and void–induced fluctuations would select a different cosmology for the primary contribution. Bottom: The large dashed curve shows the fiducial EdS model of Fig. 1 ($\alpha = 3$, $r_{\text{max}} = 25$ Mpc/$h$ and $F_v = 0.4$) using our ray tracing method. The same model is shown for our Boltzmann solution with EdS (small dashed) and $\Lambda$CDM (dotted) background universes. The solid bold line is the same $\Lambda$CDM void model for $r_{\text{max}} = 55$ Mpc/$h$ maximally sized voids as in the panel above.

The suppression that is evident using the Boltzmann solution over the ray tracing approach is due to a number of factors. In the ray tracing method we assume that the density contrast $\delta = -1$ and we take $(a'/a)^2$ to be $4/\eta^2$. Close to radiation domination (ie. at early times, just after last scattering, when we get the biggest effect) both these approximations act to increase the ray tracing result with respect to the more accurate Boltzmann prediction, together by more than a factor of 2. The ray tracing method also neglects the Doppler contribution from the baryon velocity, which suppresses the result further. Finally, the finite thickness of the LSS and Silk damping were not fully taken into account in our first approximation ray tracing method.

As discussed in subsection 2.2, there may exist voids of larger $r_{\text{max}}$ than currently observed. Models with $\alpha = 3$ and high $r_{\text{max}}$ voids in an EdS background cosmology tend to predict too much power on scales $\ell \approx 1000$. Our results show that this is less of a problem for a $\Lambda$CDM universe. Furthermore, since the Boltzmann solution predicts the CMB power from voids to be lower than implied by the ray tracing estimation, relatively large voids on the last scattering surface may be consistent with the current CMB data, even for void distributions with low
values of $\alpha$ (see Fig. 5).

Experiments such as CBI are able to directly probe small angular scales and constrain void parameters. We will present a Markov Chain Monte Carlo constraints analysis of a wide range of void models in a future paper. We will further constrain models that are compatible with CMB observations using cluster evolution,[26] and also investigate the non-Gaussian signal of void models that are compatible with the observations.

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