Searching for concentric low variance circles in the cosmic microwave background

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Received August 24, 2015
Revised October 23, 2015
Accepted November 29, 2015
Published December 15, 2015

Abstract. In a recent paper, Gurzadyan & Penrose claim to have found directions in the sky around which there are multiple concentric sets of annuli with anomalously low variance in the cosmic microwave background (CMB). These features are presented as evidence for a particular theory of the pre-Big Bang Universe. We are able to reproduce the analysis these authors presented for data from the WMAP satellite and we confirm the existence of these apparently special directions in the newer Planck data. However, we also find that these features are present at the same level of abundance in simulated Gaussian CMB skies, i.e., they are entirely consistent with the predictions of the standard cosmological model.

Keywords: CMBR experiments, cosmology of theories beyond the SM

ArXiv ePrint: 1508.05158

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1 Introduction

The cosmic microwave background (CMB) can be used to constrain the physics of the Universe on the largest scales and at the earliest times. Many searches have been undertaken for anomalous signatures on the CMB sky (see ref. [1] and references therein); however, such searches are usually phenomenological in nature, because there are rarely definitive predictions from theoretical models. One exception to this is the assertion that in a particular cyclic cosmology picture proposed by Roger Penrose [2], one expects to see rings of low variance on the CMB sky [3]. Indeed Gurzadyan & Penrose claimed to have found such a signature in maps of the CMB made by the Wilkinson Microwave Anisotropy Probe (WMAP, [4]). However, this claim was quickly countered by three papers (Moss et al. [5], Wehus et al. [6], and Hajian [7]) pointing out that such low variance rings occur frequently in simulated CMB skies. As stressed by Moss et al. in particular, the fact that the CMB anisotropy power spectrum is known to have structure on the scale of the examined rings gives greater dispersion among their properties; this assures the existence of some low variance rings, even for a temperature field with entirely uncorrelated phases.

In a more recent paper (ref. [8], hereafter GP13) Gurzadyan & Penrose assert that the conformal cyclic cosmology model should give multiple concentric rings of low variance around points on the sky. In *WMAP* data, they claim to find an abundance of sets of three or more concentric rings, and use this to suggest that there may be evidence on the CMB sky for previous “aeons” in the history of the Universe, before the Big Bang. This is such an extraordinary claim that it certainly merits further investigation. As stressed by Penrose\(^1\) [9], the newer multiple-rings prediction was not explicitly checked in the previously published studies. We note that Wehus et al. [6], did look for several simple forms of concentric low variance circles in the CMB, however, they did not look for the specific prediction presented in GP13 (not to the fault of the authors of [6] since GP13 was released after their analysis).

In fact the test proposed in GP13 is specific enough that it is relatively straightforward to apply it to both real and (Gaussian random) simulated CMB skies, in order to determine whether our actual sky possesses an anomalously high abundance of concentric rings.

GP13 analysed maps from the *WMAP* 7-year data release. In particular they searched for directions around which there are annuli with low variance in the temperature field on the sky, finding instances of multiple concentric annuli with low variance. For each direction considered they calculated the standard deviation, \(\sigma\), for 28 annuli of width 0.5°, with radius in the range 2.5°–16°. An annulus around a given direction was considered to have low variance if its value of \(\sigma\) was at least 15 µK below the average among all annuli centred on

\(^1\)Talk available at: [http://physics.princeton.edu/cmb50/home.shtml](http://physics.princeton.edu/cmb50/home.shtml).
the same direction. As an additional criterion, if two or more exactly adjacent annuli for the same direction had low variance they were instead treated as a single, wider, low variance annulus. Amongst all directions, those having three or more low variance annuli surrounding them were considered to be special directions. A simple $20^\circ$ cut about the Galactic plane ($|b| < 20^\circ$) was made and no directions were selected within this region, nor were any pixels within the masked region considered for the purpose of calculating the annuli variances. Following this approach, the abundance of these low variance directions was stated to be more than a statistical feature of the CMB sky, but rather claimed as cosmological in nature and possible evidence for pre-Big Bang phenomena. In addition, the substantial decrease in the number of low variance annuli at large radius was asserted to be a further signature of previous aeons.

In this paper we have tried to reproduce the analysis of GP13, also applying it to improved data available from the Planck satellite, as well as to simulations. In doing so we attempted to assess whether the abundance of sets of concentric rings is unexpectedly high. In a later section we examine different approaches to determining the threshold for selecting an annulus as having low variance, and in doing so we address the issue of how the abundance is expected to depend on the radius of the annulus.

2 Finding low variance rings

We first tried to reproduce the result presented in GP13, using the same method and the same WMAP data set. The WMAP W-band data are used, smoothed with a 20 arcminute full-width at half-maximum (FWHM) Gaussian beam. For the set of directions considered we used the centres of $N_{\text{side}} = 32$ pixels (12,288 directions) in the HEALPix [10] pixelization scheme, skipping those that were within $20^\circ$ of the Galactic plane. The annuli are bound by $R$ and $R + \Delta R$, with $\Delta R = 0.5^\circ$ and $R$ in the range $2.5^\circ$–$16^\circ$ (this range and annulus width were chosen to match GP13). Figure 1 (left) shows the distribution over the sky of low variance annuli for directions with three or more such annuli. We found 228 low variance directions (defined as a direction with three or more annuli with $\sigma$ being $15 \mu K$ or more below the average for that direction), distributed in a manner that closely matches the distribution seen in figure 3b of GP13. We note that the visually striking asymmetry in the distribution of low variance circles in the WMAP data is not present to the same degree in the Planck Commander data. Despite the appearance of more rings in one hemisphere than the other, we find that about 25% of simulations produce a distribution of low variance directions with a higher dipole asymmetry than seen in the data. We conclude that the asymmetry is not statistically significant. The difference between the WMAP and Commander data is most likely due to the inhomogeneous noise that is non-negligible at these scales.

Next we investigated the same statistic in the newer data from the Planck satellite [11], specifically using the Commander component-separated map [12]. The results of this paper are not sensitive to the choice of component-separation algorithm. The Commander data set was selected, since it is the preferred map for large and intermediate angular scales [12], which are the most relevant in this analysis. Note that although Planck is more sensitive and has higher resolution, at the angular scales relevant for this study, the Planck and WMAP data were expected to be very similar. To speed up the computations this data set was downgraded to $N_{\text{side}} = 512$ and smoothed with a 20 arcminute FWHM Gaussian beam and the same analysis as performed on the WMAP data set was repeated. We applied the same

\footnote{Obtained from the LAMBDA site: \url{http://lambda.gsfc.nasa.gov/}.}
Figure 1. (left) All-sky map showing the distribution of low variance directions (i.e., directions with three or more low variance annuli around them, using the same criteria described in GP13) in the WMAP W-band data set, smoothed with a 20 arcminute FWHM Gaussian. There are 228 directions satisfying the search criteria. (right) The equivalent map using the Commander data set smoothed with a 20 arcminute FWHM Gaussian. There are 166 directions satisfying the search criteria. Note that the differences between the data sets are due to the non-negligible, inhomogeneous, noise present in the WMAP data.

Figure 1 (right) shows the distribution over the sky of low variance annuli for directions with three or more such annuli. We found 166 low variance directions (defined as a direction with three or more annuli with $\sigma$ being $15\mu K$ or more below the average for that direction), distributed in a manner that closely matches the distribution seen in the WMAP data (figure 1, left). Figure 2 shows a histogram of the number of directions with three or more concentric low variance rings found in simulations. It is clear that we see just as many directions in simulations as in the real sky; in other words the presence of these concentric low variance annuli is not significant when compared to simulations.

3 Defining low variance

We next turned our attention to the particular definition of a “low variance annulus” used by GP13, namely a single average variance value per direction in order to define a threshold. The average radial profile of the annular standard deviation of simulations (created as mentioned before) and Planck data are shown in figure 3. The variance increases as the annular radius increases, as described in Moss et al. [5], this being the result of the scale-dependence of CMB anisotropies. This fact makes a simple single value average a poor choice when defining a threshold for low variance. An additional complication is that the variance of an annulus changes depending on what fraction of the annulus is masked. This is because the masking yields a horizontal cut to the annulus, excluding some fraction of the circle and thus effectively cutting out some large-scale modes that contribute to the variance. Figure 3 shows the average radial profile for unmasked annuli and partially masked annuli. It is clear that a simple single-value average will not capture the tendency for masked rings to have a lower variance.

To address this we used simulations to devise an adaptive threshold based on the direction and annular radius considered. For 1000 simulations, masked in the same manner as
Figure 2. Number of low variance directions (i.e., directions with three or more low variance annuli around them) in the Planck data (blue vertical line) compared to 1000 simulations (histogram). The threshold used here for a low variance annulus about a given direction is that the standard deviation should be at least $15\mu K$ below the average value across all annuli for that direction (as defined in GP13). The data do not prefer high numbers of low variance directions.

In the data (a $\pm 20^\circ$ Galactic cut) the variance was calculated for each annulus bounded by $R$ and $R + \Delta R$, with $\Delta R = 0.5^\circ$ and $R$ in the range $2.5^\circ - 16^\circ$, around 12,288 directions defined by the centres of $N_{\text{side}} = 32$ pixels, ignoring points within the masked region. By averaging across all simulations we obtained an estimate of the expected variance for every annulus around every direction considered. Since the simulations were masked in the same way as the data, these estimates provided a variance value to compare to for any given direction and annular radius encountered in the analysis, which accounts for the masking due to the Galactic cut.

We then repeated the search for low variance annuli, using the criterion that the standard deviation should be at least $15\mu K$ below this comparison value for each direction. We stuck to the same choice of threshold, simply because it was used in GP13; we make no claims to the optimality of this selection.

Before showing the results for this “adaptive threshold” we will discuss another choice, which is based on the spread of the variance for each direction and annular radius. Smaller annuli are composed of a smaller number of pixels than larger annuli and thus will have a larger spread in variance. In the same manner that we used simulations to create a comparison variance value for each direction and annular radius, we can also calculate a variance of this annular variance, hereafter $\sigma_v$. Thus, rather than using $15\mu K$ as the low variance...
Figure 3. Standard deviation of annuli bounded by $R$ and $R + \Delta R$, with $\Delta R = 0.5^\circ$, averaged across 12,288 directions for Planck data (solid blue), ignoring points within a $\pm 20^\circ$ Galactic latitude cut. We also plot the average of simulations without masking (dot-dashed red) and for simulations with each ring half-masked by a horizontal cut (dashed green). This shows that the expected variance depends both on the amount of masking and on the radius of the annulus. Hence it is important to track these effects in the variance estimation.

criterion, we can use a cut of $2\sigma_v$ below the comparison variance for each direction and annular variance. The choice of $2\sigma_v$ was made since it effectively lies close to $15\,\mu$K, therefore keeping quantitatively in line with the threshold used by GP13. Again, we do not claim that this is the best choice, but it certainly accounts for the nature of the annuli better than a flat $15\,\mu$K cut. The specific choice of this threshold will alter the number of low variance directions found in the data; however, since the same analysis is performed on the simulations the assessment of significance is not sensitive to this choice.

The effect of picking different ways to calculate the threshold can be seen in figure 4. GP13 claim that the lack of low variance annuli at large radii is of crucial importance for their particular model. However, this appears simply to be due to their particular definition of the threshold - because the annular variance increases monotonically with radius it becomes less likely that a large radius annulus will be classified as having low variance by their selection procedure (see the red curve in figure 4). The other two choices of threshold shown in the figure do not show this large drop in the number of low variance annuli at large radius, since they compensate for the fact that the annular variance increases with radius. In particular, the combination of the adaptive comparison and the $2\sigma_v$ threshold shows no preference for any particular radius (see the green curve in figure 4). The equivalent curves in figure 4 for simulations show the same behaviour.
Figure 4. Frequency with which annuli bounded by $R$ and $R + \Delta R$, with $\Delta R = 0.5^\circ$, are classified as “low variance” within the Planck data for the three threshold choices defined previously: a single average value for each direction, as used by GP13 (dot-dashed red); the adaptive comparison curve defined using simulations, with a $15\mu K$ threshold (solid blue), and with a $2\sigma$ threshold (dashed green). Comparing the dot-dashed red curve to the others shows that the lack of low variance rings found at large radii is a consequence of the choice in threshold.

We would suggest that these other choices of threshold are better suited to defining low variance rings. But regardless of the threshold used, the remainder of the analysis remains the same as previously described. Figure 5 shows the number of directions with three or more concentric low variance rings found in data and simulations using the adaptive threshold with a $15\mu K$ cut for a low variance annulus. Once again, the number of low variance directions seen in simulations matches that seen in the real sky. In addition to the $2\sigma$ threshold, we also looked across a range of possible $\sigma$ levels; the results remain the same for all values considered, i.e., the data do not prefer high numbers of low variance directions compared to simulations.

GP13 further claim that there is a crucial dependence on circularity, seen in a lack of low variance ellipses compared to low variance circles. They carry out this analysis using a procedure that rotates the sky to produce approximate ellipses from circles. However, this will entirely change the temperature correlations on the sky, i.e., the expected variance properties, and in particular the variance profile as a function of radius (see figure 3). We explicitly tested this and found that the variance profile does indeed depend on the amount of “twist” applied in the procedure. Thus, this is not a fair comparison, particularly when using the threshold defined by GP13. To properly study ellipses on the sky would require...
calculating the expected variance as a function of the full parameter space of ellipse properties and then searching over those properties in the data. Such a task would be much more computationally intensive than the analysis that we have carried out here.

4 Conclusions

In summary we have confirmed that there are many sets of concentric low-variance rings in the CMB sky; however, the number of such directions (regardless of search criteria used) containing such rings are consistent with what one would expect from Gaussian random skies containing the usual CMB anisotropy power spectrum. As shown in figure 5, in a perfectly standard $\Lambda$CDM universe, about half of the observers in separate Hubble patches will see a greater abundance of concentric low-variance rings in their CMB sky than we see in ours. Furthermore, we have shown that the apparent drop in low variance rings at large annular radius is merely a result of the particular search criterion used and has no statistical significance.

Therefore we conclude that based on searching for concentric low-variance rings in our CMB sky we have found no evidence for previous cycles in the history of our Universe prior to the Big Bang, as might be predicted by the conformal cyclic cosmology model.
The analysis presented here adds another test to an ever growing list that the standard ΛCDM model passes with ease. We stress that when performing such tests care must be taken to assess the significance of the results using simulations, since we must always ask how likely it is that a random realization of a ΛCDM sky will exhibit a signature with similar characteristics to the one we see in the real sky. Despite the null result reported here, it is nevertheless important to continue to carry out further searches for anomalies in the large-scale pattern of CMB anisotropies, since it is still a promising avenue for exploring physics beyond the standard cosmology.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council of Canada. We thank Jim Zibin for his assistance and for many helpful discussions.

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