ARE THERE ECHOES FROM THE PRE-BIG-BANG UNIVERSE? A SEARCH FOR LOW-VARIANCE CIRCLES IN THE COSMIC MICROWAVE BACKGROUND SKY

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ABSTRACT

In a recent analysis of Wilkinson Microwave Anisotropy Probe (WMAP) seven-year temperature maps, Gurzadyan and Penrose claim to find concentric circular patterns in the sky with anomalously low variances. These circles are presented as observational evidence for violent processes in a universe preceding our big bang as predicted by Penrose’s Conformal Cyclic Cosmology. We reassess the statistical significance of the detection of the claimed concentric low-variance circles by comparing the WMAP data with Monte Carlo simulations of the cosmic microwave background (CMB) sky plus realistic modeling of WMAP’s anisotropic noise. We find no anomaly in the variances compared with the ΛCDM cosmological model. The observed variances in the data are consistent with a Gaussian CMB sky as predicted by the inflationary cosmology model at better than 3σ.

Key words: cosmic background radiation – early universe – inflation – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

In a series of recent papers, Gurzadyan & Penrose (2010a, 2010b, 2011) reported a high significance detection of concentric circles in the cosmic microwave background (CMB) maps with anomalously low variances. They present the existence of these patterns as observational support for the Conformal Cyclic Cosmology (CCC) of Penrose. According to this model, concentric circles are generated by black hole encounters in an eon preceding our big bang. The existence of these circles, if true, poses a serious challenge to our understanding of the CMB as being a Gaussian random field within the framework of inflationary cosmology. It is also in contradiction with a large body of research on the search for non-Gaussianity and departures from statistical isotropy in the CMB data (see, e.g., Hajian & Souradeep 2006; Bennett et al. 2011, and references therein).

Gurzadyan & Penrose (2010a) used data from the Wilkinson Microwave Anisotropy Probe (WMAP) to look for concentric low-variance circles in the CMB sky. They examined 10,885 choices of center in the CMB sky after masking the galactic plane by excluding the |b| < 20° region from the maps. For each choice of center, they computed the variance of the temperature fluctuations in successively larger concentric rings of 0.5°, at increasing radii. They found three groups of rings of low variance at various radii and interpreted that as an observational evidence for the CCC model. The CCC model at its present stage lacks quantitative predictions of the actual observables needed for testing the model. It is natural to expect the qualitative prediction of the model outlined in Gurzadyan & Penrose (2010a) to be rings of large average temperatures (as it was in the early versions of the model). We looked for those signatures in the past and did not find a significant detection of such circles (unpublished work). In this paper, we only look for the low-variance circles of Gurzadyan & Penrose (2010a). We compare the variances of the claimed anomalous circles with the average variance of Monte Carlo simulations of the CMB sky to assess the statistical significance of the anomaly in the variances of those circles.

2. DATA

We use co-added inverse-noise weighted data from seven single year maps observed by WMAP at 94 GHz (W band) and 61 GHz (V band). The maps are foreground cleaned (using the foreground template model discussed in Hinshaw et al. 2007) and are at HEALPix1 resolution 9 (Nside = 512). The WMAP data are signal dominated on large scales, l < 548 ( Larson et al. 2011) and the detector noise dominates at smaller scales. The noise in WMAP data is a non-uniform (anisotropic) white noise that varies from pixel to pixel in the map. Pixel noise in each map is determined by Nobs with the expression

\[ \sigma = \sigma_0 / \sqrt{N_{\text{obs}}} \],

where \( \sigma_0 \) is the noise for each differencing assembly and can be found on the WMAP data products Web site on LAMBDA.\(^2\) Nobs is the number of observations at each map pixel which is directly proportional to the statistical weight, i.e., regions with larger number of observations have lower noise variances. Nobs is included in the maps available from the LAMBDA Web site. Scan strategy of the WMAP is such that it spends more time scanning the ecliptic poles and hence the Northern Ecliptic Pole and the Southern Ecliptic Pole are the two regions with smallest noise variances in WMAP data.

In all of our analysis, we use pixel masks to exclude foreground-contaminated regions of the sky from the analysis. We use temperature analysis KQ85 mask which masks 22% of the sky including the galactic plane and the bright point sources.

3. SIMULATIONS

In order to assess the statistical significance of the results, we use Monte Carlo simulations of the CMB sky. Simulated maps have two components:

\[ \Delta T(\hat{n}) = \Delta T_{\text{CMB}}(\hat{n}) \otimes B(\hat{n}) + N(\hat{n}), \]

where \( \Delta T_{\text{CMB}} \) is a realization of the Gaussian CMB field, \( N(\hat{n}) \) is the pixel noise, and \( \otimes B(\hat{n}) \) means convolved with the proper beam of the experiment.

We make 200 realizations of the CMB sky using the \texttt{synfast} routine of HEALPix\(^3\) with the underlying theory power spectrum computed with CAMB\(^4\) using the concordance model.

1. http://healpix.jpl.nasa.gov

2. http://lambda.gsfc.nasa.gov/product/map/dr4/m_products.cfm

3. We use \texttt{healpy}, the Python version of HEALPix.

4. http://camb.info
a flat \( \Lambda \)CDM cosmology with \( \Omega_M = 0.274 \), \( \Omega_\Lambda = 0.726 \), \( H_0 = 70.5 \) km s\(^{-1}\) Mpc\(^{-1}\), and \( \sigma_8 = 0.81 \) (Hinshaw et al. 2009). The maps are then convolved with \( WMAP \) beams for \( W \) and \( V \) bands. Since the two frequency bands have different beam transfer functions, we make separate simulated maps for the two bands. Noise realizations are added to the beam convolved maps in the end. Noise maps are simulated using Equation (1) with \( \sigma_0 = 6.549 \) mK and \( \sigma_0 = 3.137 \) mK for the \( W \) and \( V \) bands, respectively. We test our simulations by comparing their average power spectra with the data power spectrum. Figure 1 shows a comparison between our simulations and the data. This is where this analysis differs from that of Gurzadyan and Penrose. Their first paper used a white-noise power spectrum in the simulations. Those simulations failed to account for correlations in the CMB sky. In real space a white-noise map looks like the map in panel (c) of Figure 1. Unlike the observed universe (Figure 1(b)), there is no correlation between adjacent regions in this map. The power spectrum of the simulations used by Gurzadyan and Penrose is similar to the dashed (green) line in panel (d) of Figure 1. A correct simulation of the CMB sky looks patchy because of the correlations in the map (Figure 1(a)) and has features (peaks and troughs) on its power spectrum (Figure 1(d)). In their most recent paper, Gurzadyan & Penrose (2011) revised their simulation method to account for the CMB fluctuations in their analysis. However, they reported inconsistency between their \( \Lambda \)CDM simulations and the \( WMAP \) data. The technical details presented in their paper are not enough to assess the performance of their new simulations. But the lack of large-scale fluctuations in their simulations, as they report, calls for a careful investigation of how those simulations are made.

4. STATISTIC

The statistic we use in this analysis is the variance of the temperature fluctuations along circles with a given radius, \( \theta \), in the sky:

\[
V_\hat{n}(\theta) = \frac{1}{S_\theta} \int_{S_\theta} (\Delta T(\hat{n}'))^2 \delta(\hat{n}' \cdot \hat{n} - \cos \theta) \, d\hat{n}',
\]

where \( S_\theta \) is the circumference of the circle and the integral is done along the circle with a given radius, \( \theta \), whose center is defined by a unit vector \( \hat{n} \) on the sphere. \( \mu_\hat{n} \) is the average temperature along the circle of radius \( \theta \) centered at \( \hat{n} \) in the sky. This expression can be generalized for circles of finite width. In practice, we use a discrete version of the above statistic by replacing the integral with a sum over pixels along each circle of finite width.

5. RESULTS

We apply the statistic defined in Equation (3) on \( WMAP \) data at \( V \) and \( W \) bands. We choose the three families of low-variance circles detected by Gurzadyan & Penrose (2010a). The centers of the three groups of rings are at \( \hat{n} = (37:00, 105:04), (-31:00, 252:00), \) and \( (80:25, 270:00) \). For each of these
Figure 2. Variances of the low-variance circles of Penrose & Gurzadyan compared with the average variances of the same circles in 200 Monte Carlo simulations of the CMB sky with the anisotropic noise of WMAP. Left/right panels show the results of W/V bands. The dashed blue line is the mean value of the simulations of a Gaussian CMB sky with WMAP noise. Dark and light blue bands represent 1σ and 3σ levels computed from the standard deviation of the simulations. Although we see the same patterns as reported by Gurzadyan & Penrose, none of the variances are anomalously low. These data do not support the existence of pre-big-bang circles in the CMB sky.

(A color version of this figure is available in the online journal.)

groups, we compute the variance of the temperature fluctuations of rings of 0.5 thickness as a function of the radius of the ring. Figure 2 shows the results. The left panels show the W band while the right panels show the results from the V band. The shapes of the ring variance curves are very similar to those of Gurzadyan & Penrose (2010a) and we see the same peaks and troughs at the same locations and radii as reported by the above authors. We confirm the existence of the low-variance circles of Gurzadyan & Penrose (2010a), but at a much lower significance. We compare the measured variances with the average of the variances done in the same way on 200 simulations of the Gaussian CMB sky with WMAP noise realizations. The dashed blue line shows the average variance from the simulations at the same radii. The dark blue band is the 1σ standard deviation from the mean of the simulations and the light blue band shows the 3σ region. As Figure 2 shows, there is no evidence of
anomalously low-variance circles in *WMAP* data and all low-variance circles of Gurzadyan and Penrose fall below $3\sigma$ deviation from the average of the simulated Gaussian random CMB sky. A quick estimate can give us a lower limit on the expected number of $3\sigma$ deviations in a map and can show how unlikely it is to get results like these in a random realization of the sky. There are 165,000 circle centers in the maps at 0\degree.5 smoothing and 32 rings of radius $<16\degree$. In a Gaussian random field, we expect 5% of these circles to fall beyond $2\sigma$ (that is, 8000 occurrences in one map) and about 0.3% (i.e., 500 circles) to be more than $3\sigma$ away from the mean. So, the low-variance circles are very well consistent with random deviations from the mean of the Gaussian random CMB realizations. One might find even more of such rings in a Gaussian random CMB map. As it is seen in Figure 2, most of the apparently low variances are close to $1\sigma$ deviation from the mean. The largest deviation happens at $\theta = 12\degree$ in the $W$ band. In order to investigate that data point further and to make sure the non-Gaussian distribution of uncertainties does not bias our conclusion, we plot the probability distribution function (pdf) of the simulated variances and compare it with the data in Figure 3. pdfs for all circles can be found at http://cita.utoronto.ca/~ahajian/pBB.html.

6. SUMMARY AND CONCLUSION

By comparing with Monte Carlo simulations of the CMB sky, we find that the low-variance circles of Gurzadyan & Penrose (2010a) are not anomalous. They can naturally occur in a Gaussian CMB sky consistent with the predictions of the inflationary cosmology. Our result is consistent with the results of Moss et al. (2011) and Wehus & Eriksen (2010) who performed independent analyses of the significance of these rings.

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