CMB anisotropy
from
Cosmic Defects

Levon Pogosian
Case Western Reserve University

with Tanmay Vachaspati
Why study topological defects?

- They are inevitable
- Alternative to inflation
- They are interesting

Observational constraints

- Ruling out is just as important
- Calculating is hard! Passive vs. active
- Simple models are ruled out
- What is next?
\[ \ell (\ell + 1) C_\ell / (2\pi) \]

\[ \text{[\text{mK}^2]} \]

**MAXIMA-1** ○

**Boomerang-98** ×

**DMR** ♦

Combined MAXIMA-1+B98+DMR ●

- Best fit
- Best fit $\Omega_{\text{tot}}=1$

| multipole $\ell$ | $\Omega_{\text{total}} = 1$, $\Omega_\Lambda = 0.7$, $\Omega_b h^2 = 0.03$, $\Omega_c h^2 = 0.12$
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{\text{total}} = 1.2$, $\Omega_\Lambda = 0$, $\Omega_b h^2 = 0.03$, $\Omega_c h^2 = 0.17$</td>
</tr>
<tr>
<td>$h = 0.71 \pm 0.08$, $\Omega_b (\text{BBN}) h^2 = 0.019 \pm 0.002$</td>
</tr>
</tbody>
</table>
. Peak at $l = 200$

. 2$^{nd}$ peak low

. Need high $R_b$

. 3$^{rd}$ peak ?
are simply chosen to be \( v(\tau) \) and \( \xi(\tau) \), but for technical reasons we now pick a fixed value of \( v \) rather than choosing it from a random distribution, which has been shown to make very little difference to the resulting power spectrum. The number density of strings is taken to be \( \langle \xi(\tau) \rangle^{-3} \), that is, there is one string per correlation length cubed.

Figs. 3 and 4 show the matter power spectra and CMB anisotropies for the same values of \( \Omega_{\Lambda} \) as Fig. 1, with \( \xi \), \( v \) and number density of strings given by this model. Coupled with the effects of the background, the deviations from scaling improve \( b_{100} \) significantly for \( \Omega_{\Lambda} \neq 0 \), with the best fit for \( \Omega_{\Lambda} = 0.7 \) (and hence, for a similar value of \( \Omega_m \) as favoured in refs. [8,9]), although the inclusion of the time dependence on \( \xi \) has slightly affected the shape of the power spectrum. We estimate that a bias of \( b_{100} = 2.6 \) would give a good fit to the observations on large scales at the expense of an overproduction of power on smaller scales. A robust feature of the CMB spectra appears to be a peak at around \( l = 400 \) to 600, whose height is increased as \( \Omega_{\Lambda} \) increases. Finally, we should note that the value of string density per unit length \( \mu \) required to normalize to COBE is around \( 1 \times 10^{-6} \), almost independent of \( \Omega_{\Lambda} \), if we assume that the effective mass per unit length is \( \mu \approx 1.7\mu \). This is well below the upper bound imposed by the absence of timing residuals in measurements of milli-second pulsars [15].

We have shown, therefore, that the inclusion of a cosmological constant can improve the amount of matter power of larger scales, and that an interesting byproduct of this is a peak in the CMB angular power spectrum. We now illustrate that once the lack of large scale power has been remedied, it is relatively simple improve the fit to the observations on smaller scales. Ignoring for the moment the constraints on \( \Omega_b h^2 \) from Big Bang Nucleosynthesis (BBN), Fig. 5 contains three curves created using the velocity dependent one-scale model and \( \Omega_{\Lambda} = 0.7 \) with (1) \( \Omega_b = 0.05 \) and \( h = 0.7 \), (2) \( \Omega_b = 0.15 \) and \( h = 0.7 \). (3) \( \Omega_b = 0.125 \) and \( h = 0.5 \). Model (1) has the distinction that it fits the amplitude of the small scale matter data \( (b_8 \sim 1.0) \) though the shape is clearly not right, with a bias of 2.4 on 100h\(^{-1}\)Mpc scales. Models (2) and (3) rectify the small scale slope of the spectrum by increasing the baryon fraction, which damps out small scale power. A similar effect could be obtained by the introduction of hot dark matter.

As a final point we return to the approach adopted in refs. [3,4] of finding the transition which fits the data best, since the exact nature of the deviation from scaling at the onset of cosmological constant domination has not yet been simulated. We implement a transition using the model described in ref. [4] by varying \( \mu \) with \( \tau_7 = 10000 \), \( L_T = 0.1 \) and \( \chi = 4 \), such that the time and length of the transition closely mirror those obtained in the one-scale velocity model and the amplitude chosen to give the best fit to the data. The results are shown in Fig. 5 first without bias and, to emphasize the goodness of the fit to the shape of the matter data, with a scale invariant bias of \( b = 2.0 \). This model has been shown by Gawiser and Silk [16] to give a good fit to the entire dataset, including CMB and matter power spectra, peculiar velocities and cluster abundances.

Our results demonstrate that some of the problems of standard defect scenarios in underproducing power in the large scale matter distribution can be remedied by the introduction of a cosmological constant. Within this scenario, there are two distinct effects, a change in the
Predictions of current cosmic string models

1. There no secondary peaks
2. The main peak is too broad
3. The main peak is in the wrong place
4. Matter P(k) needs large bias

Is there hope?
What determines the peaks?

1. The geometry ($S_{total}$)
2. Causality
3. Coherence
The geometry

Parameters from sources other than CMB

\[ \Omega_m = 0.35 \pm 0.1 \]

\[ \Omega_\Lambda \approx \frac{4}{3} \left( \Omega_m + \frac{1}{4} \pm \frac{1}{8} \right) \]

\[ \Omega_\Lambda \approx 0.8 \pm 0.16 \]

\[ \Omega_{\text{total}} \approx 1.15 \pm 0.25 \]

\( \Omega = 1 \) is just as likely as \( \Omega = 1.3 \).
$\Omega_m = 0.4$

$\Omega_{\Lambda} = 0.9$

$\Omega_{total} = 1.3$
Height of the main peak

- Add wiggles (small-scale structure)
- Add radiation & loops

Work in progress,
high resolution numerical simulations
FIG. 10. The total angular power spectrum for wiggly (solid line) and smooth (dashed line) strings when $\Omega_{\text{baryon}} = .05$, $\Omega_{\text{CDM}} = 0.25$ and $\Omega_{\Lambda} = 0.7$ and using small values for the string velocities: $v = 0.12$ in the radiation era and 0.1 in the matter era.

FIG. 1. The CMB power spectra predicted by cosmic strings decaying into loop and radiation fluids with $w^X = 1/3, 0.1, 0.01, 0.0$. We have plotted $((\ell + 1)C_\ell/2\pi)^{1/2}$ in $\mu K$, and superposed several experimental points. The higher curve corresponding to $w^X = 1/3$ shows what happens if 5% of the energy goes into the radiation fluid.
The width of the main peak and the secondary peaks

- Coherence ← inflation
- Incoherence ← defects (usually)

Albrecht, astro-ph/9612015

All passive perturbations are coherent.

- see next page
Different patches on the sky = different members of ensemble.
with $\delta x_c = \delta x_c - \theta_c / \sqrt{2}$. We see that finite coherence time tends to increase the oscillations strength above their totally incoherent value, but not by much if $\theta_c \ll \sqrt{2} \delta x_c$.

5.5 Translation into $C_l$'s

![Image of Figure 6: $l(l+1)C_l$ spectra for a grid of models with various values of $x_c$ (related to the defect coherence length) and $\theta_c \approx 2.35 \tau_c$ (the defect coherence time). We have included the monopole term (dash) and dipole term (point-dash), Silk damping, and free-streaming. The monopole term is always dominant.](image)

With topological defects, as with inflation, the monopole power spectrum is the dominant term in the Doppler peak region. We illustrate this statement in Fig. 6 using a grid of incoherent models as in Fig. 5, with variable values for $x_c$, and scaling coherence time $\theta_c \approx 2.35 \tau_c$. We have included the monopole and dipole terms, but dropped the ISW term. We also included Silk damping and assumed that $\Omega_b = 0.05$, $h = 0.5$, and $T_0 = 2.725 K$ (where $T_0$ is the CMB average temperature). We see that the dipole (Doppler) term is always subdominant, and that the monopole free-streaming further softens the spectrum’s oscillations present in $P_l(\theta_0 + \Psi)$.

Figure 6 confirms in terms of $C_l$'s what we have inferred from the monopole power spectrum regarding
Can defects be more coherent?

Possible ways out:

1. Guest conductor (see graph) (that's parameter fixing as of today)

2. Speculations
   - Textures
   - Extra dimensions
   - ?

3. Strings + inflation (see graph)
In the above equation, the $C_\ell$ are to be compared with the observed data and the coefficient $\alpha$ is a free parameter giving the relative amplitude for the two contributions. In this preliminary work, we do not vary $C_\ell$ characteristics and simply use the model of Ref. [12] to make our point.

The figure shows the two uncorrelated spectra as a function of $\ell$, both normalized on the COBE data, together with the weighted sum. The best least-square fit, having $\alpha \sim 0.62$ yields a contribution in strings which is far from negligible, although the inflation produced perturbations still represent the dominant part for this spectrum. We note here that for other sets of cosmological parameters, the best fit, actually rather worse in all cases, can lead to a bigger contribution from cosmic strings than from inflation. It is also intriguing to notice at this point that although the fraction of string contribution is very much model dependent, the best fit always yields essentially the same angular spectrum, with $\chi^2$ of order unity.

We would like to briefly comment upon the “biasing problem” in structure formation. Topological defect models have been sometimes claimed to be ruled out, since they would not lead to large enough matter density perturbations, once normalized to the COBE data on very large scales. This normalization fixes the only free parameter of a given defect model, namely the symmetry breaking scale. More precisely, on scales of $100 h^{-1} \text{Mpc}$, which are most probably unaffected by non-linear gravitational evolution, standard topological defect models, once normalized to COBE, require a bias factor of $b_{100} \approx 5$, whereas $b_{100}$ is most probably close to unity. In cosmic string models, the biasing problem is definitely not that severe, since it is model dependent. More precisely, the matter power spectrum is very sensitive to the assumptions made about string decay [13,2].

We are aware that the analysis presented in this paper is very coarse. For instance, the actual shape of the cosmic string spectrum which we used is yet very uncertain and a more detailed study is required. In particular, it could
Conclusions

1. Current models are far from fitting the data

2. One real problem: incoherence
   (can be solved by 1 new parameter)

3. Let's wait...
   • 3rd peak?
   • New physics