Cosmic Strings in the age of Boomerang

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We show how two simple modifications to the standard cosmic string scenario for structure formation compare to the recently released Boomerang data set. Namely we consider pure string closed models and mixed models where both inflation and strings are responsible for the perturbations. In the closed models we find that pure string models would require a universe with roughly $\Omega_M = 0.8$, $\Omega_\Lambda = 1.6$ to agree with the peak position revealed by the data and in agreement with the SNIa data. In the hybrid scenario with local strings we find that we require even more tilt and baryon content ($n_s \sim 0.8$, $\Omega_b = 0.08$, $H_0 = 70$) to match the data than with pure inflation models. The case with global strings fares better with a standard period of $\Lambda$CDM inflation and $a \sim 30\%$ contribution from strings being in good agreement with the data.

The recently published Boomerang data [1] has mapped the peak in the CMB power spectrum to new accuracies. The peak position and shape heavily support the idea that the perturbations at angular scales around $\ell \sim 200$ are dominated by acoustic fluctuations of the photon-baryon fluid at last scattering. In fact the observation of a peak in such agreement to that predicted for the tight coupling adiabatic scenario will probably come to be recognized as one of the major achievements of modern theoretical and observational cosmology.

In an inflationary context, the models most favoured by the Boomerang data, for a flat universe, seem to be $\Lambda$CDM models with a high baryon content or considerable spectral tilt $n_s$ in the primordial power spectrum [2]. The best fit models strongly depend on the priors imposed from other cosmological observations such as measurements of $h$ and nucleosynthesis limits on $\Omega_b h^2$. Imposing strong constraints on these parameters seems to indicate slightly closed models with $\Omega_\Lambda \sim 0.7$, $\Omega_b \sim 0.05$, $\Omega_C \sim 0.3$ $H_0 \sim 70$ and $n_s \sim 0.85$. The indication that the spectral index might not be very close to unity may rule out some of the simplest and most appealing models of inflation.

The presence of such a well defined peak at $\ell \sim 200$ heavily disfavours the standard topological defect scenarios (see e.g. [3,4]) which have been the the classic rivals to inflation theories in the structure formation debate over the past decade. Passive models of structure formation such as those where the perturbations are set up by inflation produce acoustic peaks in the CMB power spectrum because the equations of motion are homogeneous and the perturbations linear so that the coherence of the initial perturbations is preserved. In active defect theories such as cosmic strings the coherence is lost because the perturbations are being sourced continuously by the non-linearly evolving stress-energy of the string network. The acoustic peaks are therefore not usually present in defect theories unless some extreme coherence conditions are imposed on the defect evolution [5].

Theories for global defects [6] predict a wide peak for the CMB power spectrum due to the relatively large contribution to the total $C_\ell$s from the vector and tensor modes which tends to smear out the rise in the spectrum relative to the Sachs-Wolfe plateau. On the other hand theories for local cosmic strings seem to predict a more pronounced peak due to the relative suppression of the tensor and vector modes but its position is consistently shifted to higher scales with $\ell_{\text{peak}} \sim 450 - 600$ [6] in obvious disagreement with the Boomerang data.

In Fig 1 we show various spectra from defect theories plotted with the COBE and Boomerang data sets. The ‘local numerical’ curve indicates a typical spectrum for local cosmic strings obtained via numerical simulations of Nambu-Goto strings [7]. The spectrum is obtained by sourcing the perturbations with a complete set of scaling correlation functions for the components of the network’s stress-energy tensor. The scaling correlators are measured directly from simulations. The ‘global strings’ and ‘global texture’ curves show examples of a spectrum obtained using global defect simulations [8]. The ‘semi-analytic’ curve shows a comparable spectrum from [9] where a semi-analytic model is employed to produce histories for the sourcing terms. A standard CDM inflationary spectrum is included for comparison.

One of the most interesting aspects of the data that has already generated much interest [10] is the low power at scales $\ell > 350$ and the absence of a pronounced secondary peak. As pointed out in the initial reactions to the data, this might indicate a tilted spectrum or a higher than expected baryon content. It has also been suggested [11] that topological defects might be involved in explaining this apparent discrepancy from the standard $\Lambda$CDM scenario by delaying the onset of recombination.

The aim of this letter is to carry out an initial survey of possible non-standard cosmic string scenarios and establish whether they are still viable or indeed whether they might help to explain this effect.

An initial, admittedly, crude attempt to bring the local cosmic string spectra back into line with the data is to assume a closed universe. In analogy with the peak position in inflation models a closed geometry would shift scales to lower $\ell$s. The angular size of the peaks in both inflation and defect theories are relatively insensitive to the cosmological parameters [12,13] except for the total...
energy density $\Omega$. In inflation $\ell_{\text{peak}}$ depends on both the size of the sound horizon at decoupling $d_s(z_*)$ which limits the largest wavelength which has had time to start oscillating and the angular diameter distance to the last scattering surface $d_A(z_*)$ which tells us how the angular size of an object is affected by the geometry of the space on the line of sight. For $\Omega$ close to unity and high redshifts these are insensitive to the individual energy density components and the peak position scales simply as

$$
\ell_{\text{peak}} \sim \frac{d_s(z_*)}{d_A(z_*)} \approx \frac{200}{\Omega^{1/2}}.
$$

In the case of cosmic strings the peak position in an $\Omega = 1$ universe depends on the detailed structure of the network stress-energy forcing the perturbations [3,12–14] and is in general at smaller angular scales than the scale of the sound horizon. As a first approximation to a spectrum for a closed universe we can therefore shift angular scales according to $d_A(z_*)$. Since we expect large ($\sim 1$) deviations from unity for $\Omega$, $d_A(z_*)$ will now depend explicitly on the different matter components and their relative contributions and requires numerical integration.

In Fig. 2 we show how the projection would shift the peak to the appropriate scales. The spectrum being used is that obtained for the evolution of a cosmic string network in a flat $\Lambda$CDM universe using a modified Einstein-Boltzmann code [12] with $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ and $H_0 = 70$. The shift shown in Fig. 2 is obtained by increasing the $\Lambda$ contribution to $\Omega_\Lambda = 1.6$ and the total matter contribution to $\Omega_M = 0.8$. The shift is degenerate with respect to $\Omega_\Lambda$ and $\Omega_M$. The values shown is the most ‘conservative’ model which is within the 68% contour of the SNIa [16] $\Omega_\Lambda$, $\Omega_M$ confidence plot and gives an accelerating expansion at the present epoch.

As usual when dealing with a closed universe one has to be careful about the age of the universe which is too small for large $\Omega_M$ values but including a relatively large contribution from the cosmological constant gets around the problem with the above closed model giving a total age $T_0 \sim 15$ Gyrs and $\Lambda$ domination occuring at redshifts $z \sim 0.4$. Other traditional constraints against closed models such as peculiar velocities or gravitational lensing limits (see e.g. [17]) are usually derived in an adiabatic CDM context and hence do not relate straightforwardly to a closed defect model and require a more detailed treatment.

This simple example highlights the fact that there is an unexplored region in the $(\Omega_\Lambda, \Omega_M)$ parameter space given by $\Omega_\Lambda > 1$, $\Omega_M > 1$ and $\Omega_M < 1$ which is very relevant for topological defects given the Boomerang results and which should be investigated further. Naturally Fig. 2 serves only as an illustration of the effect as the details of the spectrum can only be obtained by a numerical treatment of actively sourced perturbations in closed universes which is currently unavailable. In particular the ISW scales would not be affected to such a large degree greatly improving the tilt at COBE scales. Also the high $\ell$ tail of the spectrum will change considerably as damping effects are not expected to scale back so simply, intuitively we’d expect to see a slightly broader peak. Even so it is hard to see how the spectrum might
reproduce the structure already observed in the data at \( \ell > 350 \).

Another approach which has generated interest recently is to have a model where both inflation and defects are responsible for seeding and sourcing cosmological perturbations. This can occur in hybrid inflation models (see e.g. [18,19]) where one field is responsible for the potential energy dominated era and the other provides a non-zero VEV, after a suitable symmetry breaking phase, for the production of topological defects. These models were initially seen to suffer from an increased fine tuning problem due to the requirement that the defects were formed at a sufficiently late stage or at the end of inflation. Their extensions to supersymmetric models of inflation and in particular to supergravity theories however do not suffer as badly from this problem as the parameters in the theory seem to have more natural justifications in superstring theory [20].

An example of such a model is D-term inflation [21,22] where a symmetry breaking phase occurs after inflation in one of the flat directions in the potential. In particular, supergravity theories tend to favour D-term inflation where local cosmic strings are produced when an extra gauged U(1) symmetry is broken. The energy per-unit length \( \mu \) of the strings produced in D-term inflation is related to the Fayet-Iliopoulos term \( \xi \) as \( \mu = 2\pi \xi \). This parameter is essentially added in by hand in anomaly free models in order to obtain symmetry breaking but it may be related to the gauge coupling \( g_{\text{str}} \) of weakly coupled string theory when an anomalous \( U(1) \) symmetry is present. The strings are expected to contribute significantly to the CMB spectrum [21].

As pointed out in [22,19,23], if we assume that the two perturbations are uncorrelated and that the strings are formed sufficiently late during inflation so as not to be diluted significantly, obtaining the total CMB power spectra is trivial with,

\[
C_\ell^{\text{tot}} = \alpha C_\ell^{\text{inf}} + (1 - \alpha) C_\ell^{\text{str}} \tag{2}
\]

where \( \alpha \) is the parameter giving the relative contribution from inflation versus strings and the two spectra are normalized to COBE. The parameter \( \alpha \) can vary between 0 and 1 and is related to the number of e-foldings and slow roll parameters \( \epsilon \) and \( \eta \) [21]. It may therefore help to constrain the form of the potential. In [21] it was shown how a particular implementation of D-term inflation gives \( \alpha \sim 0.25 \) for \( N = 60 \) e-foldings. The assumption that the two effects are indeed uncorrelated in this simple scenario is well motivated since cosmic string networks have very short coherence times and lose memory of their initial conditions very quickly.

An interesting development is in the case of local strings, the new Boomerang data restricts the possible mixing scenarios quite strongly. Fig. 3 shows a very good fit to the data for a mixed model but this is quite deceptive as it requires a heavily tilted inflation spectrum \( (n_s = 0.8) \) and a high baryon content \( (\Omega_b = 0.08) \) to suppress the power even further below the Boomerang data at high \( \ell \). The reason for this is simple, the local string spectrum peaks at scales \( \ell > 350 \) so that even modest amounts of string contributions \( (\alpha \sim 0.8) \) will only make things worse for the low power problem that the data is apparently implying. In effect one has to tweak the inflation spectrum even further than in a pure inflation scenario to make the mixed scenario work.

The scenario fares better if global defects are produced towards the end of the inflationary. Although it is often stated in the phenomenological literature that SUSY inflation results inevitably in local strings this is not necessarily so [20]. Different types and even mixtures of defects can be produced in such models with the stability and type of the defects depending on the exact symmetry breaking. In Fig. 4 we use an example of a global string spectrum from [6] (we do not have any ΛCDM spectra in the global case but as with the local string case a non-zero cosmological constant is not expected to alter the shape of the spectrum drastically). As shown, a considerable contribution from the strings to a standard ΛCDM inflation picture agrees very well with the data. We plot the mixed spectrum obtained for two ΛCDM inflation models with \( \Omega_{\Lambda} = 0.7, \Omega_b = 0.05, \Omega_C = 0.25 \) but with different spectral indeces \( (n_s = 1.0 \text{ and } n_s = 0.95) \). In both cases the drop-off in the global string spectrum suppresses the power of the secondary peaks with respect to the first peak which helps reconcile the standard ΛCDM model without having to increase the baryon density. This may prove to be useful if future high \( \ell \) data does indeed confirm a conflict between infla-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{The hybrid scenario with local cosmic strings. Both the string and inflation spectra are those of an \( H_0 = 70, \Omega_{\Lambda} = 0.7, \Omega_b = 0.8 \) model with a primordial power spectrum tilt of \( n_s = 0.8 \) for inflation. The extreme values are required to bring the power at \( \ell > 350 \) down to acceptable levels when mixing contributions from both spectra.}
\end{figure}
FIG. 4. A hybrid scenario with global strings. The two inflation spectra are for standard ΛCDM models ($Ω_Λ = 0.7$, $Ω_b = 0.8$, $Ω_C = 0.25$ and $H_0 = 70$) with $n_s = 1.0$ and $n_s = 0.95$. The string spectrum is an example of a SCDM global model.

Invention scenarios and nucleosynthesis constraints on $Ω_b$ or smoothed out (decohered) peaks.

In summary we have shown how two simple modifications to the standard cosmic string scenario compare to the new CMB data. In the first case we have seen that closed models may help to bring the position of the peak in line with the data although we can only speculate how the string model could reproduce the structure seen in the boomerang data. Hybrid inflation models, where both inflation and strings are responsible for the perturbations, only help in the case with global defects. Adding even small amounts of local strings only makes matters worse as the inflation spectrum has to be ‘tweaked’ to unattractive levels.

It should be stressed that the hybrid models considered here are extremely simplistic and the weighted sum mixing should only be regarded as a useful tool to question the viability of the simplest models. In fact the evolution of defects produced in supersymmetric theories may differ quite significantly to the standard models and the defect scenario might be much more exotic. A likelihood analysis for these mixed models would be quite premature at this time as we do not have the necessary tools yet to build a grid of models in the case of global defects.

During the preparation of this work a separate group has submitted similar work on the archive [24] dealing with hybrid inflation models involving global strings. The spectrum reported in [24] is essentially that of Fig. 4.

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