Defect models of cosmic structure in light of the new CMB data

Andreas Albrecht
Department of Physics, University of California, Davis, CA 95616

Defect models of cosmic structure formation have faced a number of difficult challenges over recent years. Yet interestingly, new CMB data does not show strong evidence for secondary oscillations in the anisotropy power. Here I review the current standing of the cosmic defect models of structure formation in light of the current data.

1 Introduction

The idea that a network of defects seeded the formation of cosmic structure has received intensive study, and for a long period was viewed as the only viable competitor for the popular inflation-based models. This idea has intrinsic appeal due to its basis in spontaneous symmetry breaking (one of the central features of modern particle physics) and because the correct *amplitude* of the cosmic structure can be naturally produced. (The right amplitude requires a Grand Unification scale for spontaneous symmetry breaking, a very natural prospect in high energy physics.)

More recently the defect models have faced a number of serious challenges in the face of data that increasingly favor the inflation-based models. However, recent results from the Boomerang98[1] and MAXIMA[2] experiments do not show strong secondary peaks in the Cosmic Microwave Background (CMB) anisotropy power. The lack of these secondary oscillations has been established as a strong signature of cosmic defect models. It thus is natural to ask whether it is time to revisit the cosmic defect models. In this article I review the difficulties that face the defect models and discuss possible work-arounds. (The reader might also be interested in the recent reviews by Durrer[3] and Magueijo and Brandenberger[4] which provide a complementary discussion, and the excellent book by Vilenkin and Shellard[5] for background information.) I conclude that Boomerang98 and MAXIMA data actually add to the case *against* the defect models, and that radical variations from the standard picture (or even from the already radical attempts to save the defect models) would be required if a defect-based model were to eventually give the favored description of the formation of cosmic structure.

2 Past challenges

2.1 Overview

Cosmic defect models are notoriously difficult to calculate because, unlike inflation-based models, they in principle require one to track highly non-linear behavior from very early epochs (essentially from the Grand Unification epoch until today). However, early researchers in this area were encouraged by the pioneering work of Kibble[6] in which he argued that networks of cosmic defects might undergo a simple scaling behavior which would greatly simplify the required calculations.

The original numerical simulations focused on local cosmic strings[7,8]. The first local cosmic string simulations supported the idea of scaling, but then subsequent higher resolution simulations called the earlier results into question[9,10]. The new simulations always had very important dynamics occurring right at the scale of resolution, and these dynamics affected the behavior of the entire string network. This result violated the simple scaling picture, which held that one scale (proportional to the Hubble radius) dominated the defect dynamics at all times. While there seemed to be a physical basis for these multi-scale dynamics (namely the buildup of kinks on the string), the inability of the simulation results to decouple from processes at the limits of the numerical resolution cast doubt on the applicability of the numerical simulations to cosmology.

By contrast, “global” defects are the result of the breaking of global symmetries, and the defects are thus necessarily coupled to a massless particle (the Goldstone Boson). This coupling appears to damp out the small-scale dynamics sufficiently for global defects that their scaling behavior has been observed and has not been called into question.

Without scaling arguments it is truly impossible to achieve the dynamic range necessary for a calculation to confront the whole array of modern cosmological data. Thus, the global defects are at a significant practical advantage. However, arguments have also been made that the coupling of local strings to gravity, while weaker, ultimately has a similar effect to that of the Goldstone Boson, and creates a feedback mechanism that imposes scaling behavior after a sufficiently long period of time[11]. A new generation of local defect simulations have been constructed that (like the originals) exhibit scaling behavior[12]. This is not because they have incorporated gravitational back-reaction, but because they (again like the originals) have a sufficiently unprecise evolution of small scale features that the scaling behavior is recovered. The justification for this has been the idea that a full treatment including gravitational back-reaction would result in scaling behavior. A very interesting alternative approach used by Copeland *et al.*[13] has been to use extensions[11] to Kibble’s original phenomenological treatment[6]

The history of attempts to calculate cosmic structure formation from defect models is a long one. While the earliest work looks remarkably simplistic by current standards, important tools were developed that are still in use today. I start my discussion with the more modern work that came out in 1997, when a number of groups produced complementary results using somewhat different approaches.

Allen *et al.*[12] performed calculations based entirely on numerical simulations. Their strength was that the fewest additional assumptions needed to be made, but their weakest point was that with limited dynamic range, many important questions could not be addressed. My collaboration[14] was at the other extreme. Over the years my concern had been growing that there were so many uncertainties surrounding numerical simulations that it was important to take a more flexible approach, where the impact of the uncertainties could be fed through to the final result. The possible uncertainties ranged from numerical uncertainties in the simulations

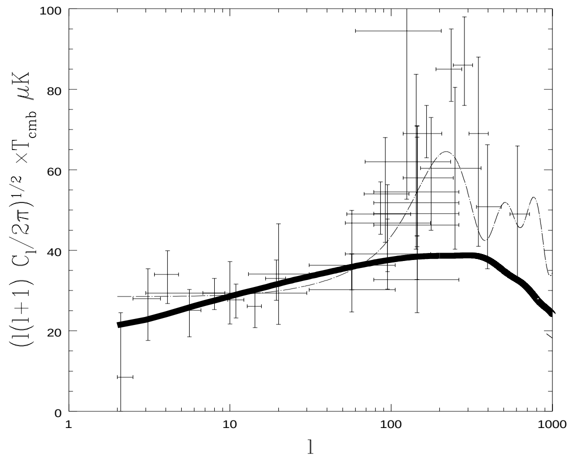

Figure 1: The heavy curve shows a typical defect prediction for the CMB anisotropy power in an EDS model with perfect scaling. This figure is from Albrecht *et al.*[14] and also shows data of that time and the standard Cold Dark Matter model

to the fact that a great variety of defect models were possible. There was a growing tendency (among non-experts) to assume that a single defect simulation could be representative of the whole range of possible defect models. Our collaboration used parameterized forms for the defect two-point functions and imposed scaling "by hand" (a method originated by Albrecht and Stebbins[15]) to achieve dynamic range. Our strength was that at last some of the defect uncertainties could be explored in a systematic way, but our weakness was that it was not clear that any given choice of our parameters would reproduce a given defect model exactly. In fact, we relied considerably on results from Allen *et al.*[12] to set crucial parameters in our models. A similar approach was taken by Durrer and Kunz[16] who focused on modeling global defects. Turok's collaboration lay in between these two extremes[17]. All the defect two-point functions were calculated from simulations, and then scaling arguments were used to produce dynamic range. Because they studied *global* defects, the scaling assumption was well justified. All the groups found their results showed serious problems when confronted with the data. These problems are the subject of the next subsection:

2.2 EDS Universe with "perfect" scaling

The major publications of 1997 all considered defects in an Einstein De Sitter (EDS) universe and "perfect" scaling. The most obvious problem that was observed by all the groups was the serious lack of power at moderate scales in the CMB anisotropies, when normalized to COBE. Figure 1 illustrates the problem. Even with the relatively poor data of that time the defect models appeared to be in trouble. At this stage, many people outside the field came away with the impression that defect models were in trouble because of the low CMB power.

However, Albrecht *et al.*[14] and Durrer *et al.*[18] examined the effect of the various uncertainties on this conclusion. Our results showed that very modest deviations from perfect scaling would result in significant power in the CMB at the relevant scales. We emphasized the point that many defect networks are known to experience a transient deviation from scaling during the radiation-matter transition (a point that has been known for a long time[6]). We found that modest uncertainties about this transient were enough to prevent the CMB power from being a problem for defect models at that time. (I note here that such transients are much less likely to occur in global defect models, because again the back-reaction from Goldstone Bosons drives the network more firmly toward the scaling solution.) Durrer *et al.*[18] explored other uncertain-

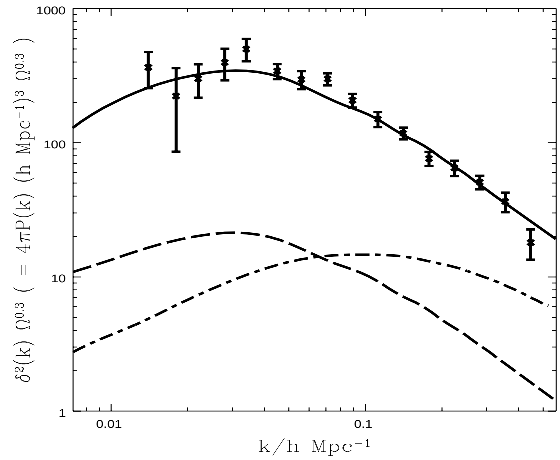

Figure 2: Matter power from the Λ defect model (solid curve) using a realistic radiation-matter transient, and assuming a bias factor of 2. The dot-dashed curves show the matter power for a perfectly scaling EDS string model. The dashed curve is for the Λ universe with perfect scaling. (These last two have the bias set to unity.) The curves are from Battye *et al.*[20] and are all COBE normalized.

ties and also concluded that the CMB power could be increased. As an explicit illustration of the potential effect of of numerical uncertainties, contrast the results of Contaldi *et al.*[19] with those of Allen *et al.*[12]

The real problem for the EDS models was the matter power spectrum. When the perturbations were COBE normalized, the matter power was completely wrong. This result was so dramatic that there had been hints of this problem in earlier work, but the 1997 calculations were the first to have sufficient dynamic range to confront this problem head-on. The problem became known as the "b100 problem" because it was on scales of 100 Mpc where the matter power spectrum performed particularly badly (the predicted power was many times lower than the observations, as illustrated in Fig. 2). Earlier work might have revealed this problem more clearly if it had not focused on the matter power on 8 Mpc (a traditional point of comparison) which was not nearly as problematic as the power on 100 Mpc. The problem was so extreme, that few expected possible non-Gaussian effects could provide a resolution.

2.3 Λ models with Radiation-Matter transients

The uncertainties in the defect models that we explored were unable to significantly reduce the b100 problem[14]. However, we soon realized that things were quite different for models with a cosmological constant[20]. For these models the scales affected by the defects during the radiation-matter transition affected different scales today, and it turned out for $\Omega_\Lambda = 0.7$ the transition was perfectly placed for transients to resolve the b100 problem, as illustrated in Fig. 2. In fact, we used a fit to the transients actually observed in one of the simulations[21] to produce a model that looked very realistic. The building evidence that there is a cosmological constant (or something similar) added support for this model, and for a while cosmic defects were again in the running as a realistic picture of cosmic structure formation.

3 The current picture

Figure 3 shows a compilation of the current data[22] along with two (dashed) curves from defect-based models, and one (solid) curve from a "best fit" inflation-based model[22]. The upper defect curve is from the "successful" model discussed in Section 2.3. Clearly in the face of new CMB

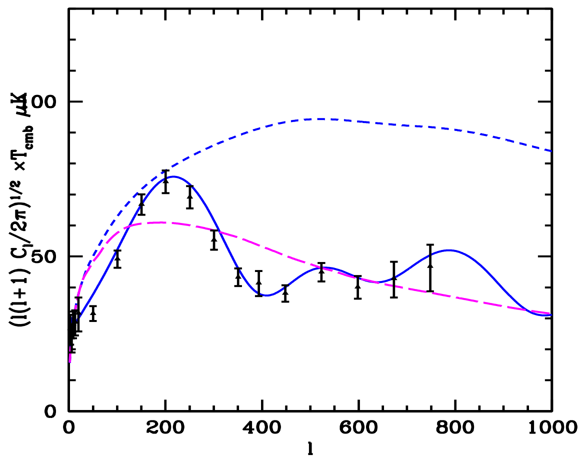

Figure 3: Current data (as complied by Knox[22]) with two defect models (dashed) and an inflation-based model (solid). The upper defect model has a standard ionization history and the lower model has an ionization history specifically designed to produce a sharper, shifted peak.

data this model is in trouble. While the upper defect curve assumed the standard ionization history, the lower curves use a non-standard ionization history specifically designed to shift the peak in the curve[23].

Considering that the lower defect curve was calculated well before the new data came in, it is striking how it appears to give a best "smooth fit" to the data. However, there is no question that the inflation-based curve gives a much better fit to the same data. Using RADPACK[22] and using the COBE, Boomerang98 and MAXIMA data, (46 data points) we get $\chi^2 = 132.5$ for the best defect model, and $\chi^2 = 47.9$ for the inflation-based model. The new data has re-focused the problem back onto the CMB, were defect models have great difficulties reproducing the observed spectrum.

4 How much trouble are defects models in?

4.1 Coherence

Probably the most fundamental distinguishing difference between inflation-based models and defect models of cosmic structure is connected with "coherence". Passive models of structure formation have a primordial spectrum of perturbations imposed at some very early time, which then experiences an extended period of *linear* evolution. Inflation-based models of structure formation are examples of passive models[24,25,26]. Active models, such as the defect models, have non-linear processes figuring significantly in structure formation throughout time. The oscillating behavior ("Sakharov", or "acoustic" oscillations) exhibited by the curve from the inflationary model in Fig. 3 is a characteristic of passive models, and no realistic active model has exhibited any oscillatory structure in the CMB anisotropy power[a].

Considerable attention has been given to the suggestion in the new data that the 2nd acoustic peak is absent, or suppressed, compared with inflation models that are favored for other reasons[28]. It is natural to ask whether this is an indication that defect models should be coming back into favor. Unfortunately for the defect models, the coherence issues are already showing

[a] There is one active model, the "mimic model"[27] which achieves a peak structure just like that of a passive model (although the signal is *not* identical in the CMB polarization power). However, the mimic model requires the non-linear matter to exhibit extraordinary coherence itself, and to press hard against the limits set by causality. No one has offered a clear picture of how the mimic model could be realized.

up strongly in the first peak, which clearly *does* exist in the data. In particular, no realistic defect model has been able generate a first peak with anywhere near the sharpness exhibited in the data[b].

The fundamental problem is that realistic defect models do not affect the cosmic structure on one scale with a single easily isolated defect motion. If this were possible, perhaps the defect physics could be specially designed to created peaks and dips in the CMB anisotropy power (it was necessary to assume this could be done to construct the "mimic model" referred to in footnote *a*) . The known defect models make contributions to a given scale of cosmic structure from many different defect motions occurring at many different times. Furthermore, the non-linearity of the defects gives the defect motion an effectively "random" component. This tends to wash out any attempts one might make to create a sharp peak. Also the work of Weller *et al.*[23] attempted to doctor the ionization history (quite artificially) to produce a sharp first peak, but the degree of sharpness exhibited by real acoustic oscillations could not be duplicated. The result of our best efforts can been seen in Fig. 3.

So within the familiar scope of defect behavior, the shape of the observed CMB anisotropy power appears to be impossible to achieve. The contrast with the success of the passive (coherent) models in generating the first peak is certainly striking, and thus we are already seeing a serious failure of the defect models due to their decoherent behavior. Any concerns that might exist within the inflationary paradigm regarding the apparently low 2nd peak at this stage appear much more minor.

4.2 Scaling

Recall that in most calculations the scaling property (or modest deviations from it) was put in by hand. In some cases there was only indirect evidence that scaling was a realistic assumption. Could certain cosmic defect models save themselves by dramatically violating the scaling assumption? The problem here is that overall a scaling spectrum of perturbations is just what is needed to account for the observed cosmic structure over many scales. It appears that any violation of scaling would have to be localized specifically to generate a peak in the CMB anisotropy power, rather than be a general property of the defect evolution. Then we are back facing the problem mentioned in Section 4.1, that the impact of the defects is not highly time-localized, so it is unlikely that a sharp peak could be produced by any "glitch" in the defect network.

4.3 Numerical Uncertainties

There are many places where numerical uncertainties significantly detract from our understanding of cosmic defects, especially in the case of local defects where the numerical work has hardly converged. However, much has been done to model the possible numerical uncertainties, and the problems defect models have in fitting the apparent first acoustic peak do not seem to be resolved by assuming any particular type of numerical error.

4.4 Filling out the picture

The reader may have noticed that the above discussion uses words like "appears" and "seems" extensively. Exactly why am I not taking a more concrete stand? The fact is that despite the progress and simplification that has been made over the last several years, working out the predictions from defect models remains a pretty complicated business. Instead of saying "it is

[b]Contaldi[29] has speculated that defects could produce a sharp peak in a universe with supercritical density. However, this approach fails by producing large deficiencies in anisotropy power for $l > 350$.

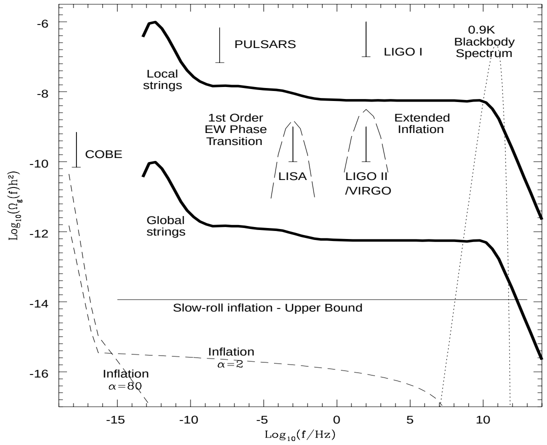

Figure 4: This summary figure from a review by Battye and Shellard[30] shows the possible gravity wave signals from two different cosmic defect models. The failure of defect models of structure formation puts a small downward pressure on the defect curves, but still allows interesting possibilities for a concrete detection.

unlikely that that a sharp peak could be produced by any 'glitch' in the defect network" it would be nice to be able to say that all possible glitches have been checked and it is 100% certain that none could produce a sharp peak. Similar comments apply to other discussions throughout this section.

The fact is that given the effort involved, and the declining fortunes of the defect models in the face of new data, there is less and less interest in undertaking the effort to check out all possibilities. Of course that situation could change if the passive models run into serious problems.

It should also be clear from this paper that my years of experience have built up certain prejudices about how defects behave. Perhaps someone free of these prejudices will discover some new defect behavior out there in the vast non-linear world of the different types of defects. This remains to be seen.

One last comment on this topic: When modeling different possible defect behaviors, one of the great problems is coming up with models of the defect stress-energy that are consistent with known constraints (especially those imposed by causality). If someone were starting from scratch to explore the possibilities, my advice would be to use the excellent techniques developed by Pen *et al.*[17]. Pen *et al.* applied their techniques to calculate the implications of particular numerical simulations, but the same techniques could also be combined with the parameterized approach similar to those of Albrecht *et al.*[14]. I suspect this would be the most effective way of moving forward.

4.5 Other roles for defects

The entire discussion thus far has been about models where the universe started in a completely homogeneous state and defects were solely responsible for the formation of cosmic structure. I have concluded that all known models of this type have failed to reproduce the observed cosmic structure. However, reducing the mass scale of the defects slightly would make them completely irrelevant for cosmic structure, but they could still have many interesting observable effects as sources of cosmic rays, gravitational waves[30] (see Fig. 4), or as players in the out of equilibrium processes that produce baryon asymmetry[31,4]. The only things that have been ruled out are the defect models of cosmic structure formation.

There also has been much discussion recently of the "middle ground", where the defects have a partial role in cosmic structure[32]. While my gut reaction is quite negative to this idea, the reason for this reaction is purely due to the prejudice that nature should do things in a simpler way. If nature goes through all the trouble to produce passive perturbations, why bother adding defects to the mix? I suppose this argument can be countered by the fact that if defects are formed by symmetry breaking at the grand unification scale (a likely enough prospect), they will naturally have masses *around* values that will contribute noticeably to structure formation without requiring that they account for everything. Fortunately, on this point we should eventually be in a position where experiment, rather than prejudice, determines the outcome.

5 Conclusions

In this brief review a have addressed three different aspects of the defect models of cosmic structure. First of all, I have shown how the defect models, as they have long been understood to behave, are clearly ruled out by the modern CMB data. Then I discussed whether some gap in our understanding could mean that the defect models are not really in as much trouble as they appear to be. I have argued that it is hard to see how any of the uncertainties in defect scenarios could come around to save defect-based structure formation. I have also tried to be frank about the limitations inherent to this type of argument. Finally, I have emphasized that there are a host of other potentially interesting cosmological effects from defects. The failure of defect models of structure formation only serves to place a modest constraint on the overall amplitude of these other effects.

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