

# Cosmic Defects

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## 1 Defect zoo

Many interesting developments in cosmology over the last 20 years have come from the realization, due to Kirzhnits [1], that (almost) each spontaneous symmetry breaking in particle physics corresponds to a phase transition in the early universe. For a typical grand-unified theory, the early moments after the big bang are characterized by the full grand unified symmetry. The exact number of phase transitions that break this symmetry down to  $SU(3) \times U(1)_{em}$  is model-dependent, but one can expect at least two. One at the energy scale of about  $10^{16}$  GeV where the strong interaction became distinct from the electroweak interaction, and another at 100 GeV where the electroweak symmetry was broken. Of course, there could be additional phase transitions at intermediate scales.

Just like phase transitions in more familiar solids and liquids, cosmological phase transitions can give rise to defects of various kinds. The defects are formed, roughly speaking, because the directions of symmetry breaking are different in different regions of space. When these regions try to match at the boundaries, they sometimes run into topological problems, and as a result we get defects which trap the high-energy symmetric vacuum in their cores. The spatial variation in the directions of symmetry breaking is inevitable due to causality. At cosmic time  $t$ , correlations cannot extend beyond the horizon distance,  $d_H \sim ct$ , since that would require superluminal signal propagation. The characteristic correlation length,  $\xi_c \leq ct$ , which depends on the dynamics of the phase transition, determines the typical distance between defects. This mechanism of defect formation was first discussed by Kibble [2].

Depending on the topology of the symmetry groups involved, the defects can be in the form of surfaces, lines, or points. They are called domain walls, strings, and monopoles, respectively. All three types of defects are stable, in the sense that domain walls cannot develop holes, strings cannot break, and monopoles cannot decay into other particles. This is guaranteed by topology and is independent of the details of the models.

In addition to these elementary defects, the cosmic zoo includes hybrid animals: monopoles connected by strings, and domain walls bounded by strings. These can be formed in a sequence of phase transitions, e.g., the first transition produces monopoles, which get connected by strings at the second phase transition. In some models each monopole gets attached to  $N$  strings. For  $N \geq 3$  this results in the formation of a monopole-string network.

The defect zoo also includes textures, which do not have localized cores and create a small region of high-energy vacuum only for a brief instance of time, in the process of the unwinding of a topologically non-trivial field configuration.

The physical properties of defects can be very different depending on whether they are formed as a result of gauge or global symmetry breaking. Global defects have long-range Goldstone fields; the energy density of these fields decreases rather slowly with the distance, so that much of the defect energy is distributed outside the core. For gauge defects, the energy is very well localized, and such defects can be well approximated as points, lines, or surfaces of vanishing thickness.

A tremendous amount of research has been done on the formation, evolution, and cosmological consequences of various defects. One finds that domain walls and monopoles are disastrous for cosmological models and should be avoided [3]. The simplest hybrid defects, monopoles connected by strings and domain walls bounded by strings, are not dangerous, but they decay soon after they are formed. The remaining defects may exist in the present universe and can produce potentially detectable observational effects. All types of defects, including the ‘dangerous’ and transient ones, have been proposed for one cosmological role or another.

For a review of topological defects and their cosmological implications, the reader is referred to [4]. The literature on this subject is rapidly expanding, and below I give only scattered references to some work that appeared after the publication of Ref. [4].

## 2 Cosmic roles for defects

Much of the research on topological defects was motivated by defect models of structure formation. Gauge strings and global strings, monopoles and textures have all been suggested as possible seeds of galaxies and large-scale structure. Only superheavy defects, with a grand-unification scale of symmetry breaking, are suitable for this role. An attractive feature of this class of structure formation scenarios is that they are directly verifiable: peculiar gravitational interactions of defects should allow one to detect their presence in the universe today. The most promising observational probe appears to be the pattern of temperature distribution of the microwave background on small angular scales. All defects introduce non-Gaussian features in this pattern, distinguishing them from one another and from the competing models based on inflationary scenarios

[5].

Superheavy cosmic strings can also produce multiple images of distant galaxies and clusters and can generate an observable gravitational-wave background ranging over many decades in frequency. Hybrid defects, which will have decayed long before the present time, may still leave a characteristic signature in this background [6]. Global defects create a background of massless Goldstone bosons. In axion models, where strings are produced due to an approximate global symmetry breaking, the resulting pseudo-Goldstone bosons (axions) have a small mass and are prime candidates for cold dark matter.

If the constituent fields of the defects have baryon-number-violating interactions, their decay could result in the generation of the observed baryon asymmetry of the universe. ‘Regular’ cosmic strings, monopoles connected by strings, and monopole-string networks have been suggested for this role.

Topological defects can produce high-energy particles by a variety of mechanisms and can contribute to the observed spectrum of cosmic rays. A particularly intriguing possibility is that ultra-high energy cosmic rays with  $E \geq 10^{11}$  GeV, which are hard to explain by the standard Fermi acceleration mechanism, may be due to vacuum defects [7]. The prime suspects here are superconducting cosmic strings and monopole-string networks. I should also mention the idea that cosmic rays are produced as a result of monopole-antimonopole annihilation [8] and the astonishing proposal that the ultrahigh-energy particles *are* magnetic monopoles [9].

In this list of the proposed roles for the defects, I made no attempt at completeness. Different roles require different types of defects with different energy scales and couplings to ordinary matter. Which, if any, of these proposals are true depends on the particle physics at very high energies (of which we know very little). Even if defects played no prominent cosmological roles, the search for their observational signatures is still very much worth pursuing. Needless to say, if topological defects are discovered, we are likely to learn a great deal both about particle physics and early universe cosmology.

### 3 Defects and inflation

Inflationary cosmological models explain the homogeneity, isotropy and flatness of the universe. Since no competing theories that can explain these facts have surfaced in the 15 years since inflation was first proposed, we seem to have little choice but to assume that the early universe did go through a period of inflation. Quantum fluctuations during this period *could* create cosmologically significant density fluctuations. But it is quite possible that they did not, in which case the observed structures could be seeded by topological defects.

Topological defects which formed before inflation would have been drastically diluted by the expansion and never seen again. On the other hand, the thermalization temperature of the universe after inflation is unlikely to exceed

$10^{16}$  GeV, and it is often said that superheavy defects needed for structure formation are incompatible with inflation. This, however, is far from being true: in a wide class of particle physics models, defects and inflation can peacefully coexist with one another.

Here are some of the possibilities. (i) The symmetry-breaking phase transition could occur during inflation, but sufficiently close to its end, so that the defects are not completely inflated away. Such phase transitions are driven not by the temperature, but by the curvature or by the evolving inflaton field. If defects are formed within 30 e-foldings of the end of inflation, they can generate density fluctuations on galactic and larger scales. (ii) In models of ‘extended’ inflation, superheavy defects can be produced in bubble collisions at the end of inflation. (iii) Defects can be produced in a ‘pre-heating’ transition after inflation. The amplitude of scalar-field fluctuations at pre-heating can reach Planckian values, and superheavy defects can be formed even if the eventual thermalization temperature is very low [10]. (iv) In some supersymmetric models, certain couplings can be naturally small, and superheavy strings can be formed as late as the electroweak phase transition. None of these options requires any drastic fine-tuning of the parameters, and some of them require none.

## 4 Concluding remarks

In conclusion, I would like to emphasize that formation of topological defects at a phase transition is a very generic phenomenon. Since the early universe probably went through several phase transitions, it is rather unlikely that no defects at all were formed. A discovery of topological defects would open a direct window into the physics of very high energies. And I think there is a reasonable chance that this will actually happen in not so distant future.

## References

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