

Cosmic strings

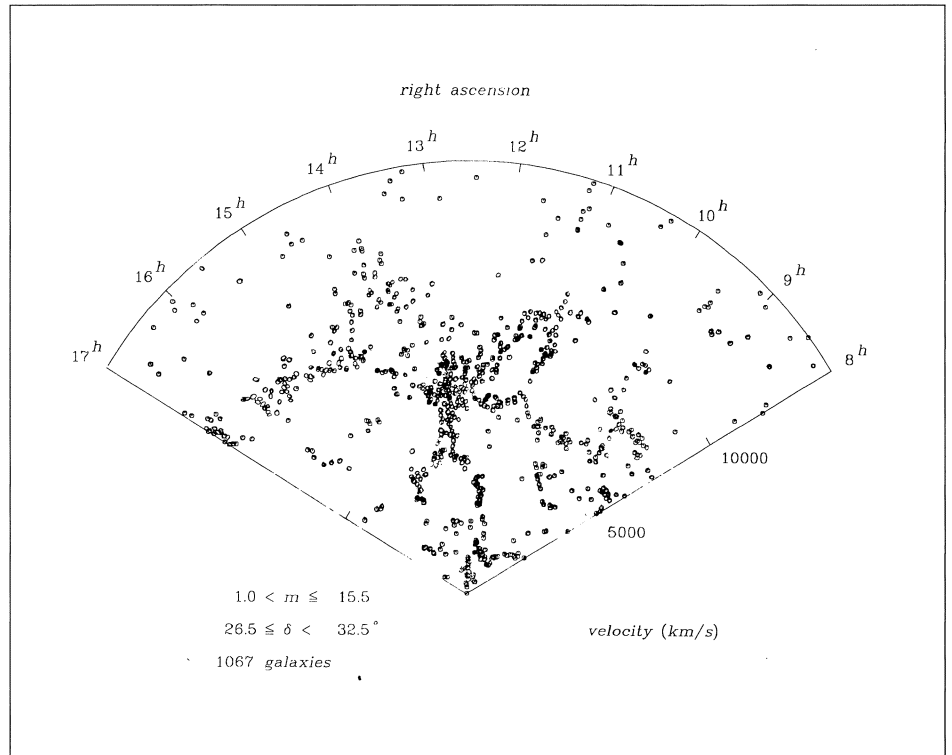
A particle physics solution to the large-scale structure of the Universe

The past decade has seen a developing interplay between elementary particle physics and cosmology. The former has had great success in demonstrating the unification of the weak and electromagnetic forces at energies just above 250 GeV (10^{16} degrees Kelvin). The 'Standard Model' of particle physics seems to describe accurately the interactions of quarks and leptons at and below these energies, as demonstrated daily in CERN's LEP electron-positron collider.

However the frontiers of particle physics also involve energies much greater than the energies available in terrestrial accelerators. Theories which attempt to unify the strong and electroweak forces (Grand Unified Theories – GUT) require energies of around 10^{15} GeV. For this reason many particle physicists have turned to the early Universe, where these sorts of energies were believed to exist just 10^{-35} seconds after the Big Bang. The Universe is a unique, exciting Laboratory for investigating physics at extremely high energies and very short distances.

In this article (first published in the Bulletin of the UK Science and Engineering Research Council) Ed Copeland of Sussex University looks at links between cosmology and elementary particle physics.

The large-scale structure of the Universe. Galaxies and clusters of galaxies appear to be located on the surface of huge 'bubbles' nested together. Inside the bubbles are enormous voids, up to 150 million light years across.



For cosmology, the standard hot Big Bang model seems to provide an accurate account of the history of the Universe from about 10^{-2} seconds after the bang when the temperature was 10 MeV until today, 10 to 20 billion years later, and a temperature of 2.7 K (10^{-10} MeV). Extending our knowledge of the Universe to earlier times and higher temperatures requires knowledge about the fundamental particles (quarks, leptons) and their interactions at very high energies – thus cosmology and elementary particle physics are linked together.

The hot Big Bang model accounts for the expansion of the Universe today, the 2.7K cosmic microwave background radiation, and through primordial nucleosynthesis, the abundances of the light elements helium, deuterium, and lithium. The microwave background is a fossil record of the Universe from the time when matter and

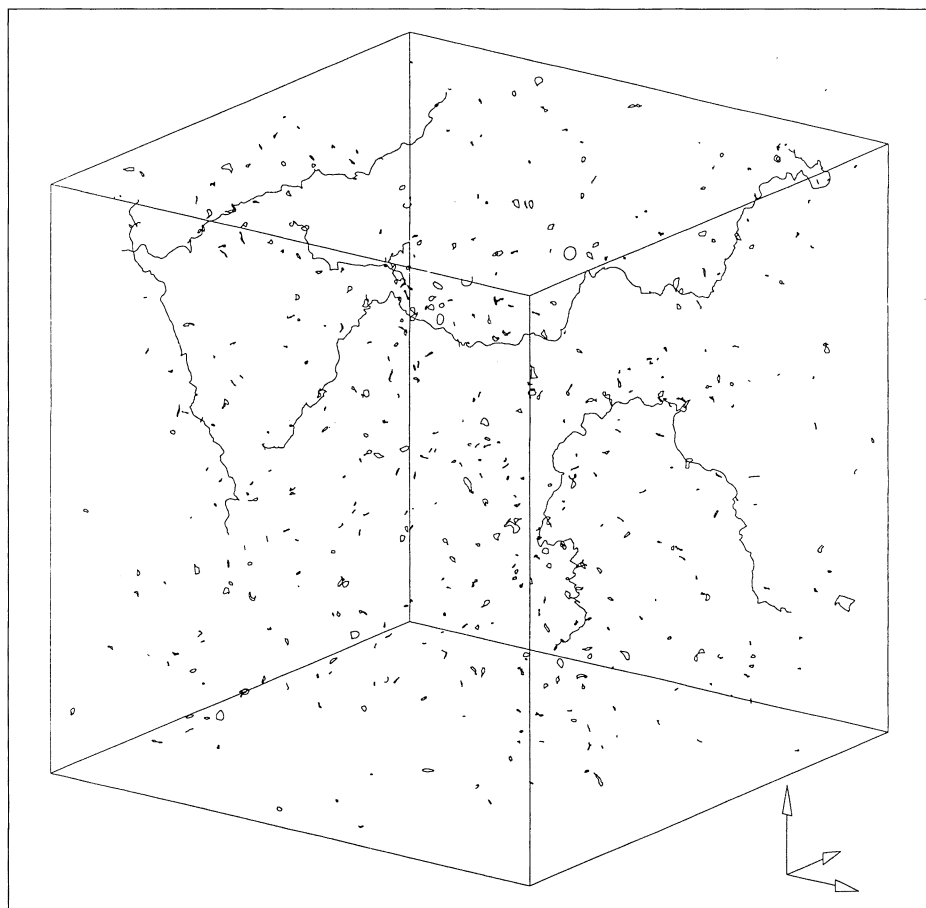
radiation decoupled (100,000 years after the bang). Its incredible isotropy (we observe the same temperature in all directions to better than one part in 10,000) and pure blackbody spectrum in all wavelengths are consistent with the standard cosmological picture. Our Universe is very smooth, homogeneous and isotropic on the scales of our observable horizon.

Therein lies the problem. Each evening, weather permitting, we can look at the night sky and see no evidence for isotropy and uniformity. Rather we see lots of structure. If the Universe started off as smooth as is indicated from the microwave background, what were the seeds that led to all this structure?

Actually the Universe is full of interesting structure on scales much larger than we can see with the naked eye. Recently astronomers have been devoting a great deal of

time and effort to mapping the large-scale structure, and their initial results are fascinating. They indicate that galaxies and clusters of galaxies appear to be located on the apparent surface of huge bubbles nested together. Inside the bubbles are enormous voids, up to 150 million light years across, empty of all but a few galaxies. Galaxies form at the intersections of these bubbles, along filaments 200-300 million light years in length. On these scales the Universe is anything but smooth. Many cosmologists believe that there has not been enough time for gravity alone to push galaxies into these special positions. The bubbly structures are an imprint of processes that occurred at the earliest moments of creation, some 10^{-35} seconds after the Big Bang. It is in this era that the candidate seeds for the observed structure could be born; cosmic strings provide one such candidate.

The unification of the forces of nature is mediated through phase transitions, during which a particular symmetry, which previously unified the forces at a high temperature, is broken as the temperature falls below a critical value, leaving behind distinct separate forces. Experimentally this is seen in the weak and electromagnetic forces, around 250 GeV. Above this energy they are described together as one electroweak force, whereas at home (well below this energy) we do not associate turning on an electric light bulb (electromagnetic effect) with the radioactive decay of an atomic nucleus (weak force). The same principle applies at the GUT scale, 10^{15} GeV. Above this energy, the strong and electroweak forces are described as one. Cooling below the energy, a phase transition occurs as the symmetry



Evolution of a cosmic string system. Note the large number of small loops and the few infinite strings stretching right across the box. The event horizon is about 3.5 times the side of the box. (Picture Shellard, Cambridge; and Allen, Wisconsin).

unifying the forces is broken, and we are left with two distinct forces.

These GUT transitions could have important cosmological consequences. One comes from the fact that the transition would probably be 'flawed', as noted by a number of authors, including T. Kibble, A. Vilenkin and Y. Zeldovich. As the Universe expands and cools, the phase transition could leave regions of space trapped in the 'old' high energy phase (where the forces are still unified), surrounded by the 'new' low energy or broken phase. Such 'defects' are regularly seen at much lower energies in condensed matter physics.

They can take many forms; for example they could be pointlike

(monopoles), sheetlike (domain walls) or one-dimensional stringlike objects, hence cosmic strings. Monopoles and domain walls are potential problems for cosmology, but cosmic strings appear to be ideal candidates to act as structure forming seeds. They are extremely thin, about 10^{-29} cm (the radius of an atomic nucleus is around 10^{-13} cm) but possess an immense tension (the 'old' phase of high energy still exists there) of 10^{36} Newtons.

Numerical and analytical calculations indicate that at birth the strings emerge as a tangled mesh; around 80 % of the network is in long 'infinite' strings winding their way across the visible Universe and the rest is in closed loops (for topological reasons they must be

either infinite or closed).

As the Universe expands, the string network begins to evolve. The long strings moving at close to the speed of light intersect each other as they stretch out, chopping off loops as they do so. Some of the loops chop themselves up further, others reconnect on to the long strings, but a picture emerges where the initial high density of infinite string diminishes as more and more loops are formed. Eventually a 'scaling solution' is reached where the density of long strings is a constant fraction (around 10^{-5}) of the total energy density of the Universe.

The evolution equations are non-linear and difficult to solve analytically, so most of the work is numerical with different groups independently running codes. The simulations differ on the exact evolution of the loops of string. One group reaches a scaling solution as with the long strings, but others appear not to reach this point. Because of the large amount of small-scale structure on the long strings, created each time they intercommute, they tend to find that most of their loops are close to the smallest possible allowed size. Although this difference needs to be accounted for, most of the string 'action' for galaxies comes from the long strings, an area where there is general agreement.

The strings lose energy primarily through gravitational radiation. As they oscillate rapidly, close to the speed of light, the loops radiate, shrink and eventually disappear. The detection (or lack of detection) of such radiation could well confirm or rule out the whole scenario.

The extreme tension of the long strings distorts the spacetime in which they live, causing a flat spacetime to become conical, the

string passing through the vertex of the cone. This distortion causes particles moving by the string to be drawn in, effectively attracted behind it into wakes. All the long strings passing through a sea of particles will then leave wakes in their trail.

In these regions, where there is now an excess of matter, conditions are established for the formation of large-scale structure, as the massive particles become gravitationally bound to one another. As matter, both luminous and dark, is attracted into these regions, they leave behind empty spaces. The important question is whether this scenario can produce enough density perturbations to account for the observed distribution of galaxies, clusters and voids, as well as the bubbly nature of the distribution. This is a complicated issue, and groups are currently running large many-body codes to investigate these questions. It appears that the answer could depend critically on the scaling density of long strings. If it is too high then the strings are close together and the voids produced are not large enough.

Models which rely on physics from 10^{-35} seconds after the Big Bang are of little use if they do not leave some observationally verifiable signature. Fortunately cosmic strings leave some unique calling cards. A string situated between Earth and a faraway galaxy would bend the flow of light passing either side of it from the galaxy, due to the conical nature of the spacetime around the string. The result is that we would see two images of the galaxy instead of just one, an effect known as gravitational lensing.

There are a number of potential lensed quasars, but also many can-

didate lensing objects, not just strings. However a chain of galaxy pairs across the sky would be a strong signature of a string, indicating the lens was long and thin, not pointlike.

Perhaps the most convincing evidence for their existence would be from the unique signature they would leave in the Universe's microwave background. This background, the residual glow of the Big Bang itself, is extremely uniform, but a string moving rapidly through it would heat up the microwave slightly in the wake of the string, and cool it in front of the string. The microwave background would appear roughly 10^{-4} of a degree hotter on one side of the string than on the other. Maps of the microwave background would show this temperature jump as a line tracing the position and shape of the otherwise invisible string: a truly unique signature. It says a great deal for the expertise in this area of detection that such a small jump may soon be detectable, so cosmic strings should soon be confirmed or ruled out.

Particle physics is having a dramatic and exciting effect on cosmology. Many astronomers are trying to get valued telescope time to search for the exotic cosmic strings. There are other topologically-inspired candidates that have not been mentioned here, but are causing great interest as possible seeds for large-scale structure. They include superconducting cosmic strings and global textures. If discovered in astronomical observations, cosmic strings will provide substantial evidence for Grand Unified Theories.

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Brookhaven National Laboratory

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