УДК 531.49

TOPOLOGICAL DEFECTS IN COSMOLOGY

Petrash A.N.
Sebastopol National University of Nuclear Energy and Industry
99033 Sevastopol, Kurchatov St.
E-mail: alexei.petrash@gmail.com
Roshchupkin S.N.
Vernadsky National University,
95007 Simferopol, Vernadsky St., 4
E-mail: rsn@crimea.edu

Останнім часом питання космічних топологічних дефектів привернуло увагу астрофізичного суспільства науковців. мі надаємо вступ до цієї дисципліни та деякі характеристики, які підлягають спостереженню.
Ключові слова: топографічні дефекти, космічні послідовності, спонтанне руйнування, темна енергія, гравітаційне випромінювання

В последнее время потенциальная роль космических топологических дефектов подняла интерес в астрофизическом обществе на много лет. Мы даем вступление в предмет космических топологических дефектов и некоторые из них возможные, поддающиеся наблюдению, характеристики.
Ключевые слова: топологические дефекты, космические последовательности, спонтанное разрушение, темная энергия, гравитационное излучение

Introduction. Current theories of particle physics likewise predict that a variety of topological defects would almost certainly have formed during the early evolution of the Universe [1]. Just as water turns to ice when the temperature drops, so the interactions between elementary particles run through distinct phases as the typical energy of those particles falls with the exposition of the Universe. When condition favor the appearance of a new phase, it generally crops up in many places at the same time, and when separate regions of the new phase run into each other topological defects are the result. The detection of such structures in the modern Universe would provide precious information on events in the earliest instants after the Big Bang. Their absence, on the other hand, would force a major revision of current physical theories.

A central concept of particle physics theories attempting to unify all the fundamental interactions is the concept of symmetry breaking. As the Universe expanded and closed, first the gravitational interaction, and subsequently all other known forces would have begun adopting their own identities. In the context of the standard hot Big Bang theory the spontaneous breaking of fundamental symmetries is realized as a phase transition in the early Universe. Such phase transitions have several exciting cosmological consequences and thus provide an important link between particle physics and cosmology.

There are several symmetries which are expected to break down in the course of time. In each of these transitions the space-time gets “oriented” by the presence of a hypothetical force field called the “Higgs field” [2]. This field orientation signals the transition from a state of higher symmetry to a final state where the system under consideration abbeys a smaller group of symmetry rules. As an everyday analogy we may consider the transition from liquid water to ice; the formation of the crystal structure ice, breaks the symmetry possessed when the system was in the higher temperature liquid phase, when every direction in the system was equivalent. In the same way, it is precisely the orientation in the Higgs field breaks the highly symmetric state between particles and forces.

In the context of the standard Big Bang theory, cosmological phase transitions are produced by the spontaneous breaking of a fundamental symmetry, such as the electroweak force, as the Universe cools. For example, the electroweak interaction broke into the separate weak and electromagnetic forces when observable Universe was 10^{-12} seconds old, had a temperature of 10^{15} degrees Kelvin, and was only one part in 10^{15} of its present size. There are also other phase transitions besides those associated with the emergence of the distinct forces. The quark-hadrons confinement transition, for example, took place when the Universe was about a microsecond old .

Different models for the Higgs field lead to the formation of a whole variety of topological defects, with very different characteristics and dimensions. Some of the proposed theories have symmetry breaking patterns leading to the formation of “domain walls”: incredibly thin planar surfaces trapping enormous concentrations of mass-energy which separate domains of conflicting field orientations, similar to two dimensional sheet-like structures found in ferromagnets. Within other theories, cosmological fields get distributed in such way that the old (symmetric) phase gets confined into a finite regions of space surrounded completely by the new (non-symmetric) phase. This situation leads to the generation of defects with linear geometry called “cosmic string”. Theoretical reasons suggest these strings (vortex lines) do not have any loose ends in order that the two phases not get mixed up. This leaves infinite strings and closed loops as the only possible alternatives for these defects to manifest themselves in the early Universe [1].

Defects in the Universe. Geometrically topological defects will be produced if the conditions for their existence are met. Then for example if the unbroken group *H* contains a disconnected part, like an explicit *U(1)* factor, monopoles will be left as relics of the transition. This is due to the fundamental theorem on the second homotopy group of coset spaces [3], which states that for a simply-connected covering group *G* we have

$$p_2(G/H) \cong p_1(H_0), \qquad (1)$$

with H_0 being the component of the unbroken group connected to the identity. Then we see that since monopoles are associated with unshrinkable surfaces in G/H, the previous equation implies their existence if *H* is multiply connected.

Cosmic strings are without any doubt the topological defect most thoroughly studied, both in cosmology and solid-state physics (vortices). The canonical example, also describing flux tubes in superconductors, is given by the lagrangian

$$L = -\frac{1}{4}F_{mn}F^{mn} + \frac{1}{2}\left|D_m j\right| - \frac{l}{4!}\left(|j|^2 - h^2\right)^2 \qquad (2)$$

with $F_{mn} = \partial_{[m}A_{n]}$, where A_n is the gauge field and the covariant derivative is $D_m = \partial_m + ieA_m$, with e the gauge coupling constant. This lagrangian is invariant under the action of the abelian group $G = U(1)$, and the spontaneous breakdown of the symmetry leads to a vacuum manifold M that is a circle, S^1, i.e., the potential is minimized for $j = h\ \exp(iq)$, with arbitrary $0 \le q \le 2p$. Each possible value of q corresponds to a particular “direction” in the field space.

Now due to the overall cooling down of the Universe, there will be regions where the scalar field rolls down to different vacuum states. The choice of the vacuum is totally independent for regions separated apart by one correlation length or more, thus leading to the formation of domains of size $x \sim h^{-1}$. When these domains coalesce they give rise to edges in the interface. If we now draw a imaginary circle around one of these edges and the angle q varies by $2p$ then by contracting this loop we reach a point where we cannot go any further without leaving the manifold M. This is a small region where the variable q is not defined and, by continuity, the field should be $j = 0$. In order to minimize the spatial gradient energy these small regions line up and form a line-like defect called cosmic string.

Many of the proposed observational test for the existence of cosmic string are based on their gravitational interactions. In fact, the gravitational field around a straight string is very unusual. As is well known, the Newtonian limit of Einstein field equations with source term given by

$$T_n^m = \mathrm{diag}(r, -p_1, -p_2, -p_3) \qquad (3)$$

is terms of the Newtonian potential Φ is given by

$$\Delta\Phi = 4pG(r + p_1 + p_2 + p_3) \qquad (4)$$

just a statement of the well known fact that pressure terms also contribute to the “gravitational mass”. For an infinite string in the z-direction one has $p_3 = -r$, i.e., strings possess a large relativistic tension (negative pressure). Moreover, averaging on the string core results is vanishing pressures for the x and y directions. This indicates that space is flat outside of an infinite straight cosmic string and therefore test particles in its vicinity should not feel any gravitational attraction. In fact, a full general relativistic analysis confirms this and test particles in the space around the string feel no Newtonian attraction; however there exists something unusual, a sort of wedge missing from the space surrounding the string and called “deficit angle”, usually noted d, that makes the topology of space around the string that of a cone.

We saw above that test particles at rest in the spacetime of the straight string experience no gravitational force, but if the string moves the situation radically changes. Two particles initially at rest while the string is far away, will suddenly begin moving towards each other after the string has passed between them. Their headon velocities will be proportional to d. Hence, the moving string will be built up a wake of particles behind it that may eventually form the “seed” for accreting more matter into sheet-like structure [3]. Also, the peculiar topology around the string makes it act as a cylindrical gravitational lens that may produce double images of distant light sources, e.g., quasars. The angle between the two images produced by a typical GUT string would be $\sim G_m$ and of order of a few arcseconds, independent of the impact parameter and with no relative magnification between images.

There is recent mounting evidence that our current Universe is been dominated by unexpectedly large amount of dark energy. Recent observations with type Ia supernovae, together with other astrophysical tests, suggest that more than 65 percent of the critical energy density is made up by some yet unknown energy component. Cosmic defects can also be seen as a novel form of dark energy.

Cosmic defects in perspective. Cosmic defects have proved very interesting and fruitful in high-energy physics and astrophysics. Their generic production in GUT has made defects an active field of research for over two decades. Primordial gravitational waves, extremely high-energy phenomena associated to cosmic rays, electroweak baryogenesis and, finally, the active condensed matter cosmology interface, dubbed cosmos in the lab, equally and unjustly received no attention. With regards to the most transparent test of current cosmology, namely the CMB and matter power spectra, recent investigations have pointed out severe problems in virtually all models where cosmic defects are the main source of the seeds of structure in the Universe.

REFERENCES

1. Pebbles P.S.E. Principles of physical cosmology. – Princeton, 1994. – 623 p.

2. Cneng T.-P, Li L.-F. Gauge theory of elementary particle physics. – Oxford, 1984. – 583 p.

Стаття надійшла 30.09.2008 р.

Рекомендовано до друку д.ф.-м.н., проф.

Єлізаровим О.І.