Cosmic Strings: Lovely Objects!

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Abstract

Cosmis strings are the most promising among the cosmological defects. They also constitute earliest possible observable strings, therefore prove vital for string theorists. Here I review different kinds of cosmological defects, then focus on the cosmic strings. I give a short theoretical derivation first and then discuss experimental efforts to detect them.

1 Introduction

Topological defects are stable configurations of matter formed at phase transitions in the very early universe. There are a number of possible types of defects, such as domain walls, cosmic strings, monopoles, textures and other 'hybrid' creatures. The type of defect formed is determined by the symmetry properties of the matter and the nature of the phase transition.[1] The critical temperature T_c is determined by the symmetry-breaking scale η.

Domain walls are two-dimensional objects that form when a discrete symmetry is broken at a phase transition. A network of domain walls effectively partitions the universe into various "cells". Domain walls have some rather peculiar properties. For example, the gravitational field of a domain wall is repulsive rather than attractive.

A cosmic string is a hypothetical 1-dimensional topological defect in the fabric of spacetime. Cosmic strings are hypothesized to form when different regions of spacetime undergo phase changes, resulting in domain boundaries between the two regions when they meet. This is somewhat analogous to the boundaries that form between crystal grains in solidifying liquids, or the cracks that form when water freezes into ice. In the case of our universe, such phase changes may have occurred in the early days as the universe formed. The tension or energy per unit length μ of these strings is proportional to $\eta^{1/2}$.

Monopoles are zero-dimensional (point-like) objects which form when a spherical symmetry is broken. Monopoles are predicted to be supermassive and carry magnetic charge. The existence of monopoles is an inevitable prediction of grand unified theories (GUTs); this is one of the puzzles of the standard cosmology. However, monopoles could be eliminated by introducing an inflationary period. This is only one of the advantages of the inflation hypothesis.

Textures form when larger, more complicated symmetry groups are completely broken. Textures are delocalized topological defects which are unstable to collapse.

Most of these defects except cosmic strings, if exist, will cause drastic deviations from astronomical observations. This provides a good ground for arguing on their existence in reality.

The idea of cosmic strings was given first by Vilenkin[11]. Cosmic strings became very popular during eighties and nineties, since they could offer an altenative to the inflation theory. They were aimed to explain the primordial density perturbations which resulted in the early growth of the galaxies and clusters. However, data from COBE, WMAP, and BOOMERanG excluded cosmic strings as the main source for such perturbations. However, they could still count partially for primordial density fluctuations.

In the early 2000s, theorists of string theory revived interest in cosmic strings. It was pointed out by Joseph Polchinski that the expanding Universe could have stretched a "fundamental" string (the sort which superstring theory considers) until it was of intergalactic size. Such a stretched string would exhibit many of the properties of the old "cosmic" string variety, making the older calculations useful again. Furthermore, modern superstring theories offer other objects which could feasibly resemble cosmic strings, such as highly elongated one-dimensional D-branes (known as "D-strings"). As theorist Tom Kibble[6] remarks, "string theory cosmologists have discovered cosmic strings lurking everywhere in the undergrowth". Older proposals for detecting cosmic strings could now be used to investigate superstring theory.

String theorists are in deep demand of cosmic string, not only because if observed, provides the first experimental evidence for their theory, but also because any symmetry breaking chain–which results in G_{321} Group of the standard model starting from M-theory–demands a GUT intermediate stage which in turn by itself definitely predicts the formation of cosmic strings at the end of the inflation era.

2 Geometry of Cosmic Strings

The energy-momentum tensor of a cosmic string could be written in the following way[4]:

$$T^{\mu}_{\nu} = \rho(r) diag[1, 0, 0, -1], \tag{1}$$

where $\rho(r) = \rho_0$ for $r < R$ and zero otherwise. We assume that the string is lying along the third axis. R shows how thick the string is. Moreover, $\mu = \pi R^2$ is the energy per unit length of the string. Note that the effective gravitational mass of the string vanishes, i.e. $\rho + 3p = \rho - \rho = 0$.[12]

Let us take the following ansatz for the metric

$$ds^2 = dt^2 - dr^2 - f^2(r)d\theta^2 - dz^2. \tag{2}$$

The nontrivial components of the Einstein tensor become

$$G^0_0 = G^3_3 = -\frac{f''}{f} = 8\pi\rho(r) \tag{3}$$

The solution is then

$$f(r) = \begin{cases} k^{-1}\sin kr & \text{for } r < R \\ A + Br & \text{for } r > R \end{cases}, \tag{4}$$

where $k = \sqrt{8\pi\rho_0}$. You can see that this solution assures that everything remains regular near $r = 0$. Furthermore, $f(r)$ and its first derivative must remain continuous at $r = R$, thereby we get the full solution outside the string

$$f(r) = (r - R)\cos(kR) + \frac{\sin kR}{k}. \quad (5)$$

Now it's time to expand this for $r \gg R$ and $kR < 1$

$$f(r) = (1 - 4\pi\rho_0 R^2)r = (1 - 4\pi\mu)r. \quad (6)$$

Therefore we finally obtain the line element for the spacetime around a cosmic string:

$$ds^2 = dt^2 - dr^2 - (1 - 8\pi\mu)r^2 d\theta^2 - dz^2. \quad (7)$$

Of course, we may transform this metric *locally* into the Minkowskian metric with $\phi = (1 - 4\mu)\theta$:

$$ds^2 = dt^2 - dr^2 - r^2 d\phi^2 - dz^2. \quad (8)$$

However, it does not represent a Euclidean space, since ϕ only changes from 0 to $(1-4\mu)2\pi$. For example, circumference of a circle of radius $r = a$ in a t=const., z=const. plane would be

$$C = (2\pi - 8\pi\mu)a, \quad (9)$$

which shows that we are in a conical space with a "deficit angle" given by

$$\Delta\theta = 8\pi\mu = 5.2'' \left(\frac{\mu}{10^{-6}}\right). \quad (10)$$

Indeed, as a light ray gets from very far away close to the string and then again to very far away, ϕ changes by π and hence θ changes by $\pi(1+4\mu)$. Therefore, light deflection is $\delta\theta = 4\pi\mu$, independent of the impact parameter. Thus cosmic objects behind the string within $\delta\theta$ from the string will have two distinct images of the same size. For a GUT-string, $\delta\theta \sim 10^{-5}$, which is indeed well withing the current limits of observational resolution. For standard strings, $\delta\theta \sim 10^{-31}$ which is certainly negligible.

We basically assumed that the strings are not kinky but straight. Nevertheless, we neglected motion of the string itself. They can generally move with quite high velocities. Inclusion of these two effects [3][5] would give more accurate formulae, though the basic phenomenon remains intact.

3 Observation of cosmic strings and loops

Cosmic strings were once thought to be an explanation of the large scale structure of the universe, but all that is known today through galaxy surveys and precision measurements of the cosmic microwave background fits an evolution out of random, gaussian fluctuations. These precise observations therefore tend to rule out a significant role for cosmic strings.[2]

A recent discovery of a "double galaxy" Capodimonte-Sternberg lens candidate 1 (CSL-1) has some interesting implications for cosmic string theory. In 2003 a group led by Mikhail Sazhin reported the accidental discovery of two seemingly identical galaxies very close together in the sky.[8]

The cosmic string producing this double image could have been detectable in precision measurements of the cosmic microwave background but at the spatial resolution of WMAP, the result was inconclusive. Re-examination with the PLANCK detector could decide the issue. However, observations by the Hubble Space Telescope in January 2005 have shown that CSL-1 is a pair of distinct galaxies rather than a pair of images of the same galaxy.[9]

A second piece of evidence supporting cosmic string theory is a phenomenon observed in observations of the "double quasar" called $Q0957+561A, B$. Originally discovered by Dennis Walsh, Bob Carswell, and Ray Weymann in 1979, the double image of this quasar is caused by a galaxy positioned between it and the Earth. The gravitational lens effect of this intermediate galaxy bends the quasar's light so that it follows two paths of different lengths to Earth. The result is that we see two images of the same quasar, one arriving a short time after the other (about 417.1 days later).

However, a team of astronomers at the Harvard-Smithsonian Center for Astrophysics led by Rudolph Schild studied the quasar and found that during the period between September 1994 and July 1995 the two images appeared to have no time delay; changes in the brightness of the two images occurred simultaneously on four separate occasions. Schild and his team believe that the only explanation for this observation is that a cosmic string passed between the Earth and the quasar during that time period traveling at very high speed and oscillating with a period of about 100 days.[10]

The Laser Interferometer Gravitational-Wave Observatory (LIGO) and upcoming gravitational wave observatories will search for cosmic strings as well as other phenomenon with the byproduct of gravitational waves.

4 Conclusion

String theory and M-theory demand cosmic strings to play a role, although small, in the early stages of our universe.

Although CSL-1 initially seemed to provide a strong proof for the existence of the cosmic strings, the only good evidence as of today is the synchronous oscillations in the lensed quasar pair which could be explained in terms of a very close oscillating loop.

If it turns out that μ is significantly less than 10^{-7}, then we should almost forget about observing them through lensing. We may instead try to observe them through their emisson of gravitational waves.[7]

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