# UNIFIED GAUGE THEORIES AND GALAXY FORMATION

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Abstract. Grand Unified strings may provide us with the primordial density fluctuations needed for galaxy formation. The properties and the cosmological evolution of such strings are discussed. A Grand Unified Theory with strings is constructed.

Grand Unified Theories (GUTs) of strong weak and electromagnetic interactions (Georgi and Glashow 1974) predict that the universe, as it cools down after the big bang, undergoes a series of phase transformations during which the original unifying gauge symmetry is reduced in stages down to the zero temperature symmetry $SU(3)_c \times U(1)_{em}$. During some of these transitions topological objects may be produced (Kibble 1980). These objects may be points, lines or surfaces where the higher temperature phase is preserved by a topological conservation law. They are called magnetic monopoles, strings or domain walls respectively.

We will concentrate on the strings because, as suggested by Zel'dovich (1980), they may be of great cosmological importance. They have the right properties needed to produce the primordial density fluctuations that lead to galaxy formation. Consider a gauge group G which breaks down to H by the vacuum expectation value (VEV) of a scalar field $\phi$ (for GUTs, $M \sim 10^{15}$GeV, and g is the gauge coupling),

$$G \xrightarrow{\langle\phi\rangle \sim (M/g)} H ,$$

To decide whether this breaking leads to string production, we must look at the topology of the vacuum manifold V=G/H. Strings are produced iff the fundamental group $\pi_1(G/H)$ is non-trivial, i.e., iff there exist loops in G/H that cannot be continuously deformed down to a point. Such loops are called homotopically non-trivial. A string is a tube of thickness $d \sim M^{-1} \sim 10^{-29}$cm. Outside this tube $\langle\phi\rangle \in G/H$. As one describes a loop around the string, $\langle\phi\rangle$ describes a non-trivial loop in G/H. This guarantees the topological stability of the string. On the string axis, $\langle\phi\rangle=0$ and the symmetry G is unbroken. The string carries an energy per unit length $\sigma \sim M^2/\alpha \sim 10^{20}$gm/cm$(\alpha=g^2/4\pi)$.



*G. O. Abell and G. Chincarini (eds.), Early Evolution of the Universe and Its Present Structure, 469–471.*


https://doi.org/10.1017/S0074180900039541 Published online by Cambridge University Press

At a cosmic time $t \sim 10^{-35}$ sec or at a critical temperature $T_c \sim M/g \sim 10^{15}$GeV, G breaks down to H and a network of superheavy strings is produced. Initially, the scale of this network(i.e., the mean distance between two neighbouring strings) is $\sim M^{-1}$. It, then, grows very rapidly and soon becomes of the order of the particle horizon t and remains so thereafter (Kibble 1980). We, thus, essentially have one string piece per horizon volume $\sim t^3$. This produces a density fluctuation $\delta\rho/\rho \sim \rho_s/\rho_r$, where $\rho_r$ is the radiation energy density and $\rho_s$ the energy density due to strings. This fluctuation has the right magnitude $\sim 10^{-3}$ for galaxy formation. $\delta\rho/\rho$ remains constant until decoupling at $t_d \sim 10^{12}$ sec; only the scale of the fluctuation grows as t. After matter domination and decoupling $\delta\rho/\rho$ grows as $t^{2/3}$, becomes $\sim 1$ at $t \sim 10^{16}$ sec, and galaxies are formed.

A very simple and elegant example (Kibble, Lazarides and Shafi 1982) of a string producing theory is based on the gauge group Spin(10). The symmetry breaking goes as follows:

$$\text{Spin}(10) \xrightarrow[\underline{126}]{M_s} SU(5) \times Z_2 \xrightarrow[\underline{45}]{M_x} [SU(3)_c \times SU(2)] \otimes U(1)$$

$$\times Z_2 \xrightarrow[\underline{10}]{M_w} SU(3)_c \otimes U(1)_{em} \times Z_2 .$$

At the first stage of symmetry breaking the unbroken group contains a <u>discrete</u> factor $Z_2 = (1,-1)$contained in the centre of Spin(10) which is a $Z_4$ subgroup generated by $i\Gamma^0$. Here $\Gamma^0 = i^5 \Gamma^1\Gamma^2 \ldots \Gamma^{10}$ is the "chirality operator" and $\Gamma^i$'s are the generalized Dirac Matrices in 10 dimensions. One can show that $\pi_1$ (Spin(10)/SU(5) x $Z_2$) = $Z_2$. Thus a superheavy string network is produced during this phase transition. The strings remain unaffected down to T=0 since the $Z_2$ never breaks.

This work is partially supported by the Department of Energy, Grant No. DE AC02-82ER 40033.B000.

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## Discussion

*Contopoulos:* 1) What is the relation between your strings and the superclusters we discussed here? 2) Can the monopoles you are considering be of galactic size?

*Lazarides:* 1) Since the strings act as seeds for galaxy formation, there may be a relation between these gauge theory strings and the linear structures in the universe. This deserves further investigation. 2) No, the monopoles are actually of microscopic size. Their core has a radius of order $10^{-29}$ cm.

*Segal:* Why is $i\gamma_5$ representative of an element of Spin (10)?

*Lazarides:* The center of Spin (10) is a four-element group generated by $h = \exp(i\ \pi/2\ \sigma_{12}) \cdots \exp(i\pi/2\ \sigma_{9,10}) \in$ Spin (10), where $\delta_{ij} = 1/2i[\Gamma^i, \Gamma^j]$. It is trivial to show that h is equal to $i\Gamma^0$, where $\Gamma^0 = i^5\Gamma^1 \cdots \Gamma^{10}$ in the "chirality" operator in ten dimensions. It is also easy to see that $[h, \sigma_{ij}] = 0$.

*Bond:* Are the strings absolutely stable, and if so, how would they interact with matter?

*Lazarides:* Strings are absolutely stable against any local disturbance. This is seen by the topological argument in my talk.

Strings have a negative tension whose magnitude is equal to the string mass per unit length. Because of this, their gravitational field has the following "peculiar" properties: It does not affect slowly moving nonrelativistic particles, but it does cause deviation of light rays.

*Hogan:* What are the most realistic observational tests of this picture?

*Lazarides:* Strings produce deviation of light rays. Tests based on this are the most realistic.

https://doi.org/10.1017/S0074180900039541 Published online by Cambridge University Press