The experimental strategy of mating antigen-transgenic mice with antigen-receptor transgenic mice offers many advantages. Most importantly, it allows tolerance to be studied at the level of the whole animal, and yet provides a bridge between *in vivo* processes and the growing body of molecular and *in vitro* immunological data. Second, the induction of tolerance by a transgenic self antigen more accurately reproduces the physiological situation than does administration of exogenously synthesized antigens, particularly in view of the evidence that exogenous antigens may not be presented in association with class I major histocompatibility molecules[39,40]. Third, experimental manipulation of the structure of the transgenic self antigen, tissue site of synthesis, timing of expression, or concentration can be achieved either by altering the microinjected construct or simply by comparing mice with different integration sites[26,27]. Finally, the transgenic antigen receptor can be varied, for example by altering the fine specificity, isotype, or transmembrane domains encoded by the microinjected immunoglobulin genes.

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LETTERS TO NATURE

Self-excited cosmic string dynamos

David N. Spergel*, William H. Press† & Robert J. Scherrer†

* Institute for Advanced Study, Princeton, New Jersey 08540, USA
† Department of Physics and Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, Massachusetts 02138, USA

Cosmic strings, topological remnants of the earlier universe, arise in many grand unified theories. Witten[1] showed that under some conditions these strings can behave like superconductors: current is carried by massless charge carriers, which can be either fermions or bosons, that move at the speed of light along the string. These strings are superconductors in the sense that any induced constant current (d.c.) will persist. The persistence is guaranteed by topological index theorems[1], but no such theorem exists for alternating currents (a.c.), which can be damped by radiation or (as we report here) can even grow exponentially through dynamo self-interaction. This mechanism converts the mechanical energy of the string into electromagnetic fields.

When an oscillating cosmic string loop crosses a stationary magnetic field line, two sets of charge carriers are produced. One moves to the left and the other, carrying the opposite charge, moves to the right. When the string loop contracts and crosses the field line in the opposite direction, two sets of charge carriers are again produced, but the signs of the carriers are reversed. This oscillation produces an a.c. current, but no d.c. current. Because these charges move along the string loop with the same period as the oscillation of the loop itself, they will return to the same point when the string next crosses the field line. It has previously been shown[2,3] that there are growing a.c. modes in a cosmic string that is oscillating in an external inhomogeneous magnetic field. These modes grow only linearly in time, but their existence suggested the possibility of modes growing exponentially due to self-interaction[3].

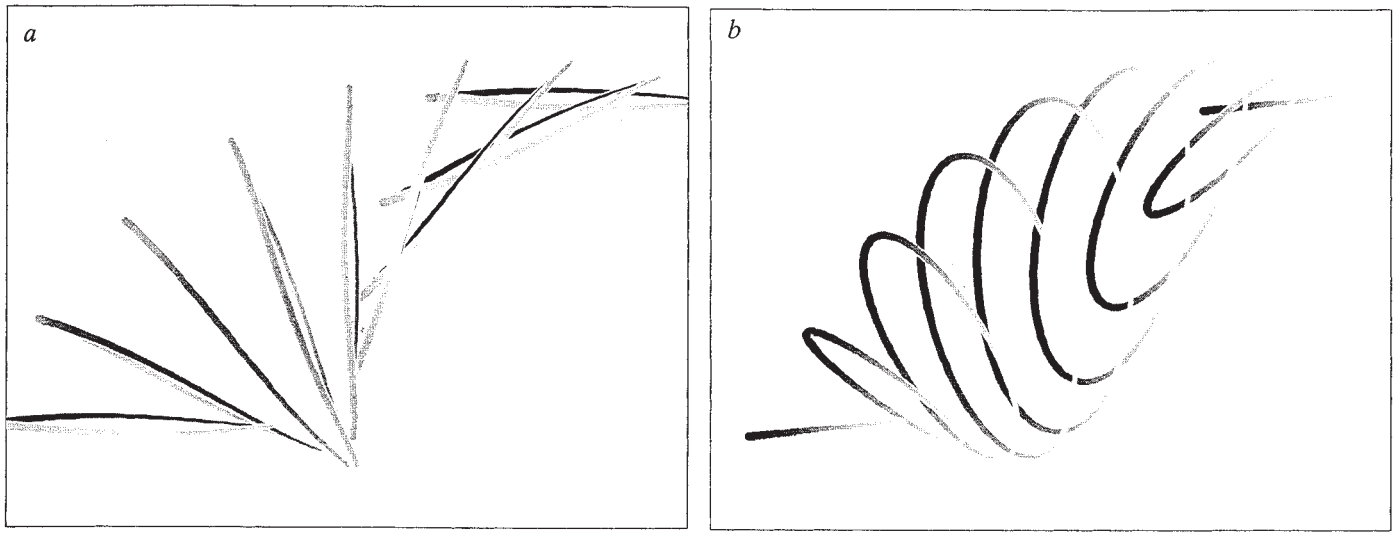

Fig. 1 The mechanical evolution of a string trajectory that (*a*) admits growing modes and (*b*) does not. Each loop in the picture represents the string at a different phase in its oscillation. The darker, thicker lines indicate depth in dimension perpendicular to the page.

We have investigated the behaviour of self-interacting test currents on isolated, oscillating loops of string[4]. 'Test' means that the current is small enough not to act back on the string's mechanical motion. We determine the electromagnetic fields produced by charges moving along the string and calculate the currents produced on the string by these fields. We have explored the behaviour of currents in the family of string oscillation modes described by Chen *et al.*[5-7] and in the $m=1$, $n=2$ trajectories described by Burden[8]. These trajectories are solutions to the wave equation. We find that on the highly symmetric Burden strings, all a.c. modes are damped, but in the less symmetric trajectories of Chen *et al.*[7] a large fraction of the solutions contain at least one growing a.c. mode. This directly demonstrates the existence of superconducting cosmic string dynamos. (Details of the calculation will be given elsewhere[4]).

The rotating loop-like string trajectory shown in Fig. 1*a* admits growing modes; the one illustrated in Fig. 1*b* does not. In the loop of Fig. 1*a* the charge carriers rearrange themselves so that there is always a net leftward current at one tip and a net rightward current at the other. There is always a net positive charge on the near side of the string and a net negative charge on the far side.

If a weak current is generated on a superconducting string with a growing a.c. mode, it will grow exponentially: the current generates a field that acts back on the string and produces additional current. The characteristic growth time for these modes is $1/\alpha$ (~ 137) times the string oscillation period, much shorter than the timescale for the dynamic evolution of strings. Any external seed field could produce this initial current. The current will grow either until it becomes large enough to affect the dynamics of string motion or until it is suppressed by other effects, such as collisions between charge carriers along the string, vacuum polarization effects or interaction with the surrounding plasma.

While bosonic strings can carry a substantial current without ill effect, some fermionic strings may have their superconductivity suppressed. In certain theories in which strings have fermionic charge carriers, the a.c. current may be dissipated through weak resistive effects[9]. Another potential obstacle to field generation arises if the fermionic charge carriers have finite mass along the string[10].

When the current exceeds an electric charge per electron Compton wavelength, it can dissipate its energy through pair creation. The alternating current will generate in places an *E*-like field strong enough to polarize the vacuum and create electron–positron pairs, which will dissipate some of the energy in the electromagnetic field.

In the early universe, the string is not oscillating in a vacuum, but in a dense plasma, an excellent conductor which is opaque to low-frequency electromagnetic radiation. The interaction of this plasma with the string will affect the growth of the magnetic field.

While both plasma effects and vacuum breakdown may fight the growth of currents along the string, our calculations of strings *in vacuo* show that there is no symmetry or conservation law that forbids the exponentially increasing conversion of a string's mechanical energy into electromagnetic modes. In complex systems, if equilibration of energy between modes is not forbidden, it will often occur. The existence of a mechanism for transfering the kinetic energy of the string into electromagnetic energy suggests that seed currents can grow, even in complicated situations. These current-carrying strings can have profound effects on their surrounding environment: the formation of large scale structure[11], the powering of quasars[12], the emission of gamma-ray bursts[13], the creation of ultra-high-energy cosmic rays[14], and the radiation of synchotron emission[15].

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