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## COSMOLOGY: Magnetic Mysteries

 Axel Brandenburg <sup>\*</sup>

At present—some 14 billion years after the Big Bang—magnetic fields of appreciable strength are found in virtually all galaxies and also in galaxy clusters. Although weak compared with the fields at Earth's or the Sun's surface, these fields are enormous considering the scales involved and may influence the formation of stars and galaxies, the dynamics of galaxy clusters, and energy transport within galaxy clusters. Even 1 to 2 billion years after the Big Bang, such fields must already have existed at about the same strength as today ( [1](#) ). How did these fields arise? And did primordial magnetic fields exist in the early universe? Answers to these questions remain speculative, but upcoming space missions promise exciting insights.

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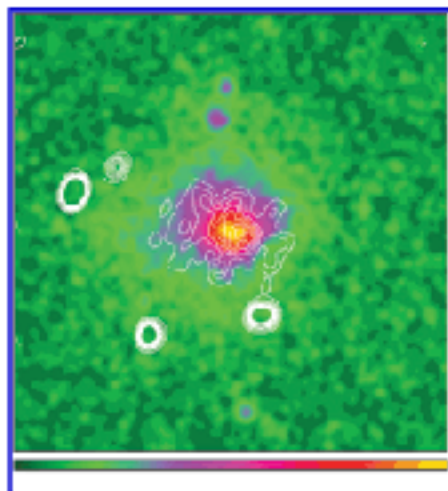
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**Strong emission.** Radio synchrotron emission contours are superimposed on a color-coded x-ray image of the galaxy cluster Abell 2163. The strongest radio emission comes from the center. Cluster diameter, ~2 megaparsecs.

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Galactic magnetic fields are usually inferred through the presence of polarized (synchrotron) emission at radio and shorter (down to submillimeter) wavelengths. Most galaxies show synchrotron emission, but not all galaxy clusters. However, this may be a result of a lack of relativistically fast electrons, which emit such radiation under the influence of a magnetic field, rather than a lack of the field itself. Abell 2163 is an example of a cluster with very strong radio emission (see the first figure).

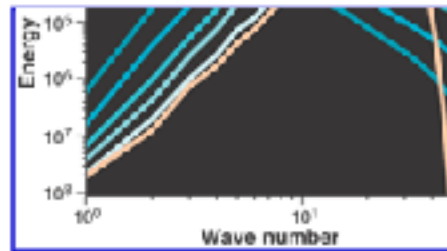
According to one leading theory, magnetic fields in galaxies and galaxy clusters may have arisen through battery mechanisms in ionization fronts just after the first stars formed ([2](#), [3](#)). Differential forces acting on opposite charges generated a relative drift between them. The resulting field was amplified exponentially through gas motions ([4](#)). Such "dynamo" processes are certainly possible in principle but cannot easily explain why in some galaxy clusters, the fields are very coherent over several galactic radii ([5](#)). According to another theory, the ejecta of starburst galaxies may have magnetized galaxy clusters ([6](#)). In both cases, the field strength may have been boosted by mergers and collisions among clusters, but simulations indicate that the scale of the fields would remain small ([7](#)).

In contrast, if a magnetic field on the scale of several galactic radii already existed at the time of galaxy formation, this would provide an important clue to the origin of fields on large scales. New missions may soon enable detection of very early magnetic fields through measuring the temperature and polarization anisotropies of the cosmic microwave background (CMB) ([8](#)). The PLANCK space telescope, to be launched in 2007, is expected to detect fields as weak as  $10^{-9}$  gauss ([9](#)). Later missions are likely to detect even weaker fields. In the meantime, theorists are making ever more detailed predictions of the temperature and polarization signatures of a primordial magnetic field.

Particle physicists have come up with rather speculative processes, which may have generated huge magnetic fields during or just after inflation (the period of very rapid expansion before the universe was  $10^{-30}$  s old) ([9](#)). These fields would have been diluted during the subsequent "normal" cosmological expansion, probably to something close to the detection limit of PLANCK. Initially, it was not clear how they could have any bearing on the question of large-scale magnetic fields. A field generated at such an early time would not exceed the scale of the horizon, which was just  $\sim 3$  cm at  $10^{-10}$  s. Such a field would now be at a scale of the solar system,  $\sim 10$  orders of magnitude smaller than the scale of galaxies.

An unusual feature of turbulence physics may provide the answer. A random magnetic field can display an "inverse cascade" ([4](#)). This means that structures do not just split up into ever smaller scales, as in ordinary turbulence. Rather, the opposite happens. This is because in highly conducting fluids, in addition to total energy, another quantity is conserved: magnetic helicity, which measures the twist and mutual linkage of magnetic flux structures. Think of the field as being made up of helically polarized waves. There is a limit to how much magnetic helicity can be packed into a wave of given wavelength. If two helical waves interact, it is very hard to dispose of the helicity at small scales without violating magnetic helicity and total energy conservation. It is much easier to accommodate the magnetic helicity in a wave of larger wavelength.





**Growth of magnetic structures.** In this simulation, the spectral energy propagates to successively smaller wave numbers, that is, successively larger scales, as a result of inverse cascade turbulence. Red line, initial time; blue lines, later times (increasing from right to left).

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A dramatic example of such behavior is seen in a numerical simulation (see the second figure) ( [10](#) ). An initially random and helical magnetic field was left to decay through viscous and Joule dissipation. The dissipation happens mostly at small scales. At all other scales, magnetic energy gets pumped into progressively larger scales. These results suggest that we may well expect primordial fields at the scales of galaxies if the field has helicity ( [11](#) ). It remains uncertain whether the net magnetic helicity required to drive the inverse cascade comes mostly from the original field ( [12](#) ) or whether small helicity perturbations can grow to substantial levels.

The increase of the length scale of the primordial magnetic field will not be of much interest if its magnitude was small. Upcoming space missions will soon provide hard facts. If the field was weak, then the fields we observe today must have been generated later. On the other hand, if a strong field (expanded to a present-day value of  $10^{-9}$  gauss) was present, then its detailed structure could be determined and interpreted, with important consequences for the theory of galaxy formation.

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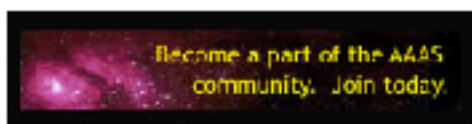
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