Viewpoint

The Seeds of a Magnetic Universe

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Published July 29, 2013

A mechanism for generating primordial magnetic fields, called the Biermann battery, could have occurred in a much younger Universe than previously thought.

Subject Areas: **Cosmology, Plasma Physics**

A Viewpoint on:
Generation of Primordial Magnetic Fields on Linear Overdensity Scales
Smadar Naoz and Ramesh Narayan
Phys. Rev. Lett. ***111****, 2013* – Published July 29, 2013

The Universe is magnetized. This is true on "small" length scales, such as in planets and stars, and over much larger scales, such as across the tenuous gas in galaxies and galaxy clusters and, possibly, the even more rarefied intergalactic medium. Physicists are fairly certain that these magnetic fields weren't created in the big bang (the reason has to do with the symmetry of Maxwell's equations). Rather, for the most part, they assume that small "seed fields," which formed some time after the big bang, were amplified into what we observe today. But how these seed fields materialized remains one of the great, unsolved problems in cosmology.

In *Physical Review Letters*[1], Smadar Naoz and Ramesh Narayan at the Harvard-Smithsonian Center for Astrophysics, Massachusetts, propose a possible solution. They have revisited a model for the generation of small magnetic fields in a plasma, called the Biermann battery, and shown that this process could have generated seed fields in the Universe much earlier than was previously thought possible. Although the fields they calculate are weak, the fact that they could have existed early in the age of the Universe means there was more time for other processes to amplify them into the fields we observe today.

Theories of the origin of cosmological fields, or, magnetogenesis, are either top down or bottom up. Top down theories invoke a process that operates everywhere, producing a pervasive field. In bottom up theories, magnetogenesis occurs in small objects, and the magnetic fields are then dispersed to large scales. Both types of theory require two stages. The first is to create a seed field. In the second phase, the existing field grows by a process called a dynamo, in which the kinetic energy in the flowing magnetic plasma is converted, by induction, into magnetic energy. (The 22-year solar magnetic activity cycle is a famous example of an astrophysical dynamo.) Although it's still unclear exactly how plasma flows amplify magnetic fields, large-scale shear and small-scale turbulence are both thought to play a role [2].

One challenge in explaining magnetogenesis is figuring out how to make seed fields large enough that a dynamo can amplify them to what is observed. In an attempt to do so, Naoz and Narayan have invoked one of the best-understood candidates: the Biermann battery process. Before describing what they do that is new, it helps to explain how the battery process generates a seed field. Imagine a plasma of protons and electrons that is hotter on the right than the left and denser on the top than the bottom (Fig. 1). Because electrons have so little inertia, they will drift down the temperature and density gradients faster than the positively charged protons, generating a net electric field. (More precisely, the electrons drift down a gradient in the electron pressure, which is the product of the electron temperature and density.) When the temperature and density gradients aren't parallel, the integral of the electric field over a closed loop in the plasma is nonzero. In other words, the gradients produce an electromotive force. And by Faraday's law, this electromotive force generates a magnetic flux.

Biermann's battery can explain both a top down and bottom up scenario for magnetogenesis. The process will generate fields fastest in small systems where the temperature and density change rapidly in space, as in the accretion disks of matter that swirl around a dense object. But it can also generate fields on cosmological scales (that is, scales greater than the largest gravitationally bound bodies). Physicists have used the process to explain magnetic fields generated in cosmological shock fronts [3] and in cosmological ionization fronts [4]. In both cases, however, the calculated magnetic fields were very weak, of order 10^{-19}—10^{-21} gauss. These levels are far below observed intracluster and interstellar fields, which typically fall in the tenths to tens of microgauss range. Clearly, a dynamo is needed to amplify such weak seed fields into

DOI: 10.1103/Physics.6.85
URL: http://link.aps.org/doi/10.1103/Physics.6.85

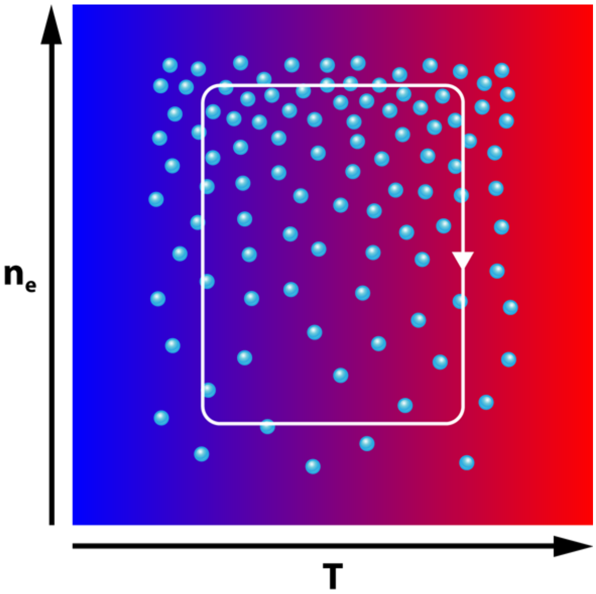

FIG. 1: A cartoon of how the Biermann battery process generates a magnetic field. The product of electron temperature and density in a plasma of electrons (white spheres) and protons (not shown) is a quantity called the electron pressure. (In the figure, the pressure is highest at the upper right corner and lowest at the lower left corner.) Electrons flow down this pressure gradient faster than the heavier protons, generating an electromotive force (emf) over a closed contour (white line.) By Faraday's law, this emf generates a magnetic flux through the surface bounded by the contour. (In this figure, the emf generates a magnetic field out of the page.) (APS/Alan Stonebraker)

what is observed. But it is also possible that the calculations were underestimating the seed fields. The calculations were based on numerical simulations, which may have been too coarsely grained (in space) to resolve the smaller structures that produce larger fields.

Naoz and Narayan add a new ingredient to the picture. They explore magnetogenesis by the Biermann battery further back in time than was done in previous calculations [3, 4]—still long enough after the big bang that electrons had combined with protons and neutrons to form atoms, but in a Universe sufficiently young that fluctuations in the cosmological density and temperature were still small. When these fluctuations are small, it is possible to write down their effect on magnetic field growth in closed form. It is also possible to compute the power spectrum of magnetic fluctuations down to much smaller length scales than in Refs. [3] or [4], without any limits imposed by numerical resolution.

At the time they stop their calculations, the authors find the spatial scale of the strongest fields extends from kiloparsecs to tens of kiloparsecs (about the size of a large galaxy). However, because they start with density and temperature fluctuations that have small amplitudes, the resulting fields are very weak—10^{-24}—10^{-25} gauss. It may seem that nothing has been gained over the numerical calculations. But what Naoz and Narayan have shown is that a model linear in the density and temperature fluctuations can generate seed fields. This theoretical step is important because it pushes magnetogenesis to an earlier epoch, allowing more time for the fields to be amplified and to feed back on their environments.

It is interesting to ask: At what point does magnetic field amplification by the Biermann battery give way to amplification by a dynamo? This crossover turns out to occur roughly when the ratio of the thermal ion Larmor radius to the typical pressure gradient length scale is less than the Mach number of the flow. Naoz and Narayan stop their calculations at a time when the proton Larmor radius is still larger than the extent of the fields. Thus it is likely that the era of battery amplification continued well past the time Naoz and Narayan terminated their calculations [1].

The Biermann battery is not the only possible source of seed magnetic fields. Plasma instabilities, which produce magnetic fields on kinetic scales—as opposed to the macroscopic scales characteristic of the battery—have also been proposed [5, 6]. This mechanism could operate at later times than the battery considered by Naoz and Narayan. On the other hand, a variety of other processes, based on nonstandard physics, could have operated at much earlier times [7].

Are there observations that could tell us which theories are on the right track? Until recently, magnetic fields had only been detected in galaxies and galaxy clusters, and the upper limits on a pervasive intergalactic field were rather high. But a recent study estimates that intergalactic fields must be at least 10^{-18} gauss in order to explain their effect on charged particles pairs created by extragalactic gamma rays [8]. The number of sight lines sampled by such observations is still relatively low, but the method may be the best possibility of probing the very weakest cosmological fields.

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