COSMOLOGICAL MAGNETIC FIELDS

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Abstract

We discuss the evolution of cosmological magnetic fields from the early universe to the present. We review different scenarios for magnetogenesis in the early universe and follow the subsequent evolution of these fields as the universe recombines. We then focus on the role primordial fields play after recombination in the seeding of stellar and galactic fields and the formation of structure. Cosmological magnetic fields in the intergalactic medium trace the turbulent history of the universe and may contain fossils of the early universe. We conclude by discussing observational probes of cosmological magnetic fields including the study of extragalactic cosmic rays.

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I. INTRODUCTION

Present cluster and galactic magnetic fields are observed to be in energy equipartition with the gas and the cosmic rays in these systems. Although the origin of these fields is still unclear, they are most likely the result of strong amplification of seed fields present in protogalactic clouds. These seed fields may be primordial in nature, being leftover from the early universe, or they may have been created when the first structures formed after recombination.

Determining if the origin of cluster and galactic fields are primordial or post-recombination is a difficult task, since the amplification by many orders of magnitude in these virialized systems overwhelms any signature of an early magnetic phase. In contrast, the presence of fields away from clusters and galaxies can more easily be related to the early history of cosmological magnetic fields. However, magnetic fields in extragalactic and extra-cluster regions are quite difficult to observe. At present, synchrotron maps and Faraday rotation measurements show some evidence for magnetic fields on inter-cluster scales, while Faraday rotation of high redshift objects give only upper limits to fields on cosmological scales [1].

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Improved direct observations of extragalactic fields, such as high resolution Faraday rotation maps, together with alternative methods that have been recently proposed, such as the study of extragalactic cosmic rays, may help determine the origin and evolution of cosmological magnetic fields. If large-scale fields are present throughout the universe today, their structure and spectrum should have clearer signatures of their origin.

Understanding the history of magnetic fields will help understand the dynamics of the early universe and the formation of the first stars and galaxies. In particular, magnetic fields may be as relevant to galaxies as they are to the Sun. In addition, large-scale magnetic fields also trace the hydrodynamic evolution of the universe, as magnetic fields are fossil records of shocks, outflows, and winds, as well as of early universe processes. In this respect, it is important to be able to differentiate between the present structure of extragalactic fields formed by primordial fields and those formed by pollution of galactic outflows.

In the following sections, we follow the history of magnetic fields from magnetogenesis in the early universe to the present and discuss possible ways of observing the unknown structure of cosmological magnetic fields. We start by reviewing early universe magnetogenesis. We then discuss the evolution and damping of magnetic fields up to recombination. Fields present at recombination can play a role on the formation of galaxies and stars by preserving fluctuations below the Silk mass and by generating density perturbations after recombination. Finally, magnetic fields on scales of clusters and larger play an important role on the origin and propagation of extremely-high–energy cosmic rays. As future experiments try to address the origin and nature of EHECRs, the structure of magnetic fields in the intergalactic medium around the Local Group will be simultaneously addressed.

II. MAGNETIC FIELDS IN THE EARLY UNIVERSE

Historically, the study of magnetic field generation in the early universe was motivated by the search for the origin of galactic large scale fields. For instance, typical spiral galaxies have large scale fields of about a few $\mu$G ($\equiv 10^{-6}$ G), coherent over the plane of their disks. (The Milky way has $B_{MW} \simeq 3\mu$G.) These galactic fields could have originated from a relatively large primordial seed field amplified by the collapse of the galaxy or by a much smaller seed field that is greatly amplified by a galactic dynamo. These two possibilities give very different estimates for the field needed to seed the galactic field. (In the absence of sources of currents, magnetohydrodynamic equations are linear in $B$, thus, seed fields are necessary for the growth of magnetic fields with time in a plasma.)

If the galactic dynamo is efficient at amplification, the seed field can be as low as $B_{seed} \simeq 10^{-23}$ G. This value is estimated assuming that the galactic dynamo amplified the field present at the newly formed galaxy by a factor of $\sim e^{30}$ corresponding to about 30 dynamical timescales or complete revolutions since the galaxy formed. After the dynamo amplification factor is taken into account, the present galactic field requires that the newborn galaxy had a field of $\sim 10^{-19}$ G. Finally, we can estimate the primordial field needed to explain present galactic fields by assuming that the newborn galaxy amplified a frozen-in cosmological field as the protogalactic primordial gas collapsed to present galactic densities. As the gas collapses, the magnetic field increases as $B \propto \rho^{2/3}$. This gives primordial fields of about $B_{seed} \simeq 10^{-23}$ G for a density increase of $10^6$ between the galactic density and the average density in
the universe. If a galactic dynamo is not efficient at amplification the primordial field requirements increase to $B_{\text{seed}} \approx 10^{-9} - 10^{-12}$ G.

At present, a successful galactic dynamo model remains elusive. Dynamo models work well for the Earth where fluctuations about the large scale field are small compared to the average field. This hierarchy of scales does not hold in stars and galaxies, making the dynamo problem more challenging. A compass would not be very useful on stars or galaxies since the fluctuation fields are of the same order of or stronger than the large scale coherent field. Here we follow the two extremes of primordial seeding, with and without dynamo amplification.

The challenge for early universe magnetogenesis depends on the magnitude of the needed seed fields. A useful way of comparing the magnitude of fields at different times is to write the magnetic energy density, $\rho_B \equiv B^2 / 8\pi$, in units of the radiation background energy density, $\rho_\gamma \equiv \pi^2 g_* T^4 / 30$ where $g_*$ is the number of degrees of freedom and $T$ is the temperature of the cosmic background radiation (CBR). The present CBR temperature implies $\rho_\gamma \approx (4\mu G)^2 / 8\pi$. Both energy densities redshift the same way with the expansion of the universe and can be compared as comoving quantities ($B \propto a^{-2}$ and $\rho_B \propto a^{-4}$, where $a(t)$ is the cosmic scale factor). In these units the field strength required to seed galactic fields with an efficient galactic dynamo translates into $\rho_B \approx 10^{-34} \rho_\gamma$, while the primordial seed without dynamo amplification requires $\rho_B \approx 10^{-14} \rho_\gamma$.

Once a primordial field is generated, it redshifts with the expansion of the universe and damps due to viscous processes. The most significant damping occurs at decoupling due to photon viscosity (see §2.3). Magnetic diffusion is usually insignificant due to the high conductivity of the plasma. The residual ionization of the universe today is sufficient to guarantee that field diffusing is insignificant on scales above $\sim$ A.U. Here we discuss fields on scales larger than a parsec, with emphasis on galaxy scales which correspond to comoving scales of about 1 Mpc.

A. Primordial Magnetogenesis

A number of authors have proposed scenarios for generating seed fields in the early universe [4]–[13]. These models make use of the few out-of-equilibrium epochs of the pre-recombination era. Phase-transitions are usually necessary, with models ranging from inflation (when the universe had temperatures, $T \gtrsim 10^{16}$ GeV) to the QCD transition ($T \sim 100$ MeV).

Standard inflationary models give rise to insignificantly small vector perturbations in contrast to the observable scalar and tensor perturbations. The simplest inflationary models give $\rho_B \sim 10^{-104} \rho_\gamma$ which is too small to act as a seed field. Reasonable seed fields can be generated if one breaks electromagnetic gauge invariance, or changes the gravitational couplings. String cosmology may also give rise to primordial fields but the magnitude of the effect is still under debate.

Although somewhat contrived, inflation based models for seed field generation have the advantage that large scale fields can be easily generated due to the exponential expansion during vacuum domination. On the other hand, observations of the cosmic background radiation (CBR) seem to strongly constrain these models, leaving little room for their viability.
Several scenarios have been proposed below the GUT scale such as during the Electroweak and the QCD transitions [11–13]. These are usually based on out-of-equilibrium processes during first or second order phase-transitions where shocks, interfaces, and turbulent motions may generate significant fields through battery and amplification mechanisms.

Models based on phase-transitions other than inflation are limited by causality and result in less power on large scales. In order to compare different models, we use the definitions in [14] where the Fourier transform, $\tilde{B}(k)$, of the magnetic field at a point in space, $B(x)$, can be described by a scalar power spectrum $\tilde{B}^2(k)$ when $B(x)$ is assumed to be a random, homogeneous, and isotropic field. The total magnetic energy density is then given by:

$$\rho_B \equiv \frac{1}{2} \int \tilde{B}^2(k) d^3k.$$ 

The spectrum generated by different models can then be described by power laws on length scales above the horizon, $H^{-1}_{\text{pl}}$, (or wavenumbers below $2\pi H_{\text{pl}}$) of the particular phase transition. During radiation domination, the horizon for any given phase-transition is much smaller than the typical intergalaxy separation, ($H^{-1}_{\text{pl}} \ll \text{Mpc}$), thus a power law behavior is a good description of the spectrum on the scales of interest. (The last transition of interest is the QCD transition when the universe had a horizon that corresponds to a comoving scale of $H^{-1}_{\text{QCD}} \simeq 1$ pc today. Earlier transitions have much smaller horizon scales.) Thus, we can write $\tilde{B}^2(k) = Ak^n$, where the constant $A$ is related to the total magnetic field energy density, $\rho_B$, the spectral index, $n$, and the cutoff scale of the spectrum, $k_{\text{max}}$, as $A \simeq (n + 3)8\pi\rho_B/k_{\text{max}}^{n+3}$.

Causality limits the spectrum of fields generated at transitions during radiation dominated epochs to have spectral index $n \geq 0$, while inflationary models can, in principle, generate fields with negative spectral indices, i.e., more power is present on large scales.

Independent of the specific mechanism for magnetic field generation, we can estimate the ability of phase transitions to seed galactic fields, given the limit on the total energy available for magnetic fields, the power index limit due to causality, and the maximum cutoff scale given by the horizon. The maximum energy density in magnetic fields that any scenario can generate is $\rho_B = \rho_\gamma$. This is an overestimate since hydrodynamical processes usually lead to magnetic energies in equipartition with plasma motions and $\rho_B \simeq \rho_{\text{plasma}}v^2 \lesssim 0.1 \rho_\gamma$ for most phase transitions. The cutoff together with the maximum energy limit the amplitude of the spectrum for a given spectral index. For the electroweak transition the cutoff is $k_{\text{EW}} \simeq 2\pi H_{\text{EW}} \simeq 2\pi/10\text{AU}$ while for the QCD transition the cutoff is $k_{\text{QCD}} \simeq 2\pi H_{\text{QCD}} \simeq 2\pi/\text{pc}$.

The best case scenario for large scales fields generated in phase transitions is the white noise spectrum with $n = 0$ [3]. In this case, we can estimate the maximum strength of the magnetic field on Mpc scales by choosing a window function that extracts the contribution of the field spectrum on these scales. Following [14], for $n = 0$ the average field on a scale $l$ is:

$$\bar{B}(l) \leq \frac{\pi^{3/4}}{6} \left(\frac{\rho_B}{l k_{\text{max}}^3}\right)^{1/4}$$

This model-independent estimate gives upper limits for fields generated in the electroweak transition of $\bar{B}_{\text{EW}}(\text{Mpc}) \lesssim 10^{-22}$ G and for the QCD transition $\bar{B}_{\text{QCD}}(\text{Mpc}) \lesssim 10^{-16}$ G. Therefore, neither transition can seed the galactic field without dynamo amplification since the generated fields are much smaller than the needed $B_{\text{seed}} \sim 10^{-9} - 10^{-12}$ G.
B. Evolution up to Recombination

After primordial fields are generated, they redshift with the expansion of the universe, being frozen into the plasma for most of the early universe’s history. Although magnetic diffusion is insignificant, during certain epochs in the early universe, magnetic field energy is converted into heat through the damping of magneto-hydrodynamic (MHD) modes. This damping is caused by dissipation in the fluid due to the finite mean free path of photons and neutrinos. The result of these fluid viscosities is the efficient damping of MHD modes similar to the Silk damping of adiabatic density perturbations.

The evolution of MHD modes, such as fast and slow magnetosonic, and Alfvén waves, in the presence of viscous and heat conducting processes can be studied in both the radiation diffusion and the free-streaming regimes of the early universe. Fluid viscosities damp cosmic magnetic fields from prior to the epoch of neutrino decoupling up to recombination. Similar to the case of sound waves propagating in a demagnetized plasma, fast magnetosonic waves are damped by radiation diffusion on all scales smaller than the radiation diffusion length. The characteristic damping scales are the horizon scale at neutrino decoupling ($M_\nu \approx 10^{-4} M_\odot$ in baryons) and the Silk mass at recombination ($M_\gamma \approx 10^{13} M_\odot$ in baryons). In contrast, the oscillations of slow magnetosonic and Alfvén waves get overdamped in the radiation diffusion regime, resulting in frozen-in magnetic field perturbations. Further damping of these perturbations is possible only if before recombination the wave enters a regime in which radiation free-streams on the scale of the perturbation. The maximum damping scale of slow magnetosonic and Alfvén modes is always smaller than or equal to the damping scale of fast magnetosonic waves, and depends on the magnetic field strength and its direction relative to the wave vector.

The dissipation of magnetic energy into heat during neutrino decoupling weakens big bang nucleosynthesis constraints on the strength of magnetic fields present during nucleosynthesis. The observed element abundances require that $\rho_b < \rho_\gamma / 3$ during nucleosynthesis. Even if processes prior to neutrino decoupling generate magnetic fields with $\rho_b \approx \rho_\gamma$ initially, neutrino damping causes the magnetic energy to decrease substantially relative to that of radiation by the time of nucleosynthesis. This ensures that most magnetic field configurations generated prior to neutrino decoupling satisfy big bang nucleosynthesis constraints.

Dissipation during recombination weakens the ability of primordial magnetic fields to generate galactic magnetic fields or density perturbations. Since a sizable fraction of the energy in magnetic field fluctuations is erased up to the Silk scale, it becomes even more difficult to produce the observed galactic fields without dynamo amplification. Models which generate primordial fields in sub-horizon scales during phase transitions are particularly constrained since these models have more power on small scales where damping is most efficient.

Although Alfvén and slow magnetosonic modes also undergo significant damping, these modes survive on scales smaller than the damping scale for fast magnetosonic modes and magnetic energy can be stored on scales well below the Silk mass. The survival of these modes help the seeding of galactic fields by preserving magnetic energy on scales of interest to galaxy formation, and may also be of significance to the formation of structure on relatively small scales. In particular, these modes may be responsible for fragmentation of early structures.
and the seeding of early star or galaxy formation.

C. Early Dynamos

The nature of hydrodynamic flows as the universe recombines is an important factor in the evolution of cosmological magnetic fields. If there are velocity flows present as the universe evolves, these flows may have enough helicity to set up early dynamos. Magnetic energy can be regained at the expense of the kinetic energy of the flow and primordial fields may be amplified to the necessary level to seed galactic fields [12,13]. Some simulations of pre-recombination MHD systems show dynamo behavior [15,19]. However, viscous damping due to photon and neutrino decoupling damp velocity flows as well as MHD modes through recombination. If velocity fields exist at recombination, the most likely scale for driving the flow will be close to the Silk mass. Since the couplings in this problem are non-linear, it is possible that the driving at large scales cascades down to small scales and back to large scales, amplifying fields during and after recombination. Constrains on such pre-recombination flows should be studied in the light of recent CBR observations.

Alternatively, the collapse of density perturbations generated by inflation and imprinted in a non-baryonic cold dark matter component may generate the necessary seed field and amplification. Numerical simulations of the growth of density perturbations after recombination show the formation of shocks that can generate seed fields, which can then be amplified by large scale dynamos [20].

III. MAGNETIC FIELDS IN THE LATE UNIVERSE

A. Galaxy Formation

While magnetic fields are recognized as central agents in regulating the dynamics of star formation and the general interstellar medium in galaxies, it is generally assumed that they do not play a significant role during the epoch of galaxy formation. However, if fields of the order of $10^{-9} \text{G}$ to $10^{-12} \text{G}$ are present in protogalactic clouds, this view should be questioned. Depending on the spectrum of such cosmological fields, structure formation can be initiated by magnetic fields [14,23].

Magnetic fields may act as seeds for density perturbations. The evolution of density perturbations and peculiar velocities seeded by primordial magnetic fields give rise to a steep spectrum of density perturbations [14], namely $P(k) \sim k^4$. This spectrum is too steep to account for the observed large-scale structure of the universe, thus, magnetic fields alone cannot reproduce the observed clustering on large scales. On the other hand, magnetic fields do generate small-scale structure shortly after recombination, even if the rms magnetic field on intergalactic scales is as small as $10^{-12}$ Gauss today. Thus, magnetic fields may provide a natural source of (scale-dependent) bias of the luminous baryonic matter with respect to the dark matter in the universe.

Another consequence of primordial magnetic fields is to add power on small scales to the primordial density perturbation spectrum, a welcome ingredient for models of structure...
formation which lack small-scale power, such as tilted cold dark matter, mixed dark matter, and hot dark matter.

B. Pollution of the IGM

When trying to measure the magnitude of cosmological magnetic fields today, the most significant observations are those of magnetic fields on the largest scales and away from virialized systems such as galaxies and clusters of galaxies. Thus, observations of magnetic fields in the intergalactic medium are the most helpful in understanding the origin of cosmological magnetic fields.

Intergalactic and intercluster magnetic fields of significant magnitudes have been observed, but their interpretation is not unique. One of the questions is the ability of galaxies to pollute the intergalactic medium and if “pollution” fields can be differentiated from primordial fields. Galactic outflows may pollute a significant fraction of the IGM depending on models of galaxy outflows, galaxy formation, and cosmological evolution.

With the discovery of the highest energy cosmic rays and the possibility of studying the sources of these events in the future, the question of whether an extragalactic magnetic field exists outside of clusters has gained a new observational tool.

IV. OBSERVING COSMOLOGICAL MAGNETIC FIELDS

A. Direct Observations

Of great relevance to understanding the history of cosmological magnetic fields are observations of intergalactic magnetic fields and magnetic fields at high redshifts. Reports of Faraday rotation associated with high-redshift Lyman-α absorption systems (see, e.g., [1]) suggest that dynamically significant magnetic fields (of order μG) may be present in condensations at high redshift. Together with observations of strong magnetic fields in clusters, these observations support the idea that magnetic fields play a dynamical role in the evolution of structure and maybe present throughout the universe.

Present Faraday rotation measurements of intergalactic fields using the emission from high-redshift quasars place limits of $\lesssim 10^{-9}$ G for fields with Mpc reversal scales, and $\lesssim 10^{-11}$ G for fields coherent on the present horizon scale. Future measurements may help determine the strength of galactic magnetic fields at high redshifts as well as the presence of significant fields in the IGM today.

B. CBR Signatures of B

Future observations of CBR anisotropies by MAP and PLANCK will be able to detect the acoustic Doppler peaks from sound waves at recombination and polarization. If magnetic fields of significant magnitude are present at recombination, they polarize the CBR photons and generate signatures of the different MHD modes. The precise signatures are likely to depend on the nature of the mode, since each MHD mode evolves differently through recombination.
C. Extragalactic Cosmic Rays

The detection of extremely high-energy cosmic rays (EHECRs) has triggered considerable interest in the origin and nature of these particles. To date, more than 60 cosmic ray events with energies above $\sim 5 \times 10^{19}$ eV have been observed by experiments such as Haverah Park, Fly’s Eye, and AGASA. The Fly’s Eye experiment has recorded a $3 \times 10^{20}$ eV event, the highest energy event so far. These EHECRs most likely originate from extragalactic sources and their spectrum and spatial as well as temporal distributions are affected by the presence of extragalactic magnetic fields.

The study of EHECRs is closely related to the study of cosmological magnetic fields [26]. Charged particles of energies $\sim 10^{20}$ eV can be deflected significantly in cosmic magnetic fields. Thus, detailed information on the structure of extragalactic magnetic fields may be contained in the time, energy, and arrival direction distributions of charged extremely-high energy particles emitted from powerful discrete sources. In this context, the clustering among EHECRs suggested by recent AGASA data is very encouraging and its confirmation would have important consequences for understanding the nature and origin of cosmological magnetic fields as well as for EHECRs [27].

Another signature of cosmological magnetic fields is in the shape of the spectrum of $\gamma$-rays secondaries to EHECRs. The $\gamma$-ray spectrum depends on synchrotron losses versus inverse-Compton regeneration of the electromagnetic cascade. This signature is most sensitive to extragalactic magnetic fields around the Faraday rotation limit of $\sim 10^{-9}$ G [28]. Weaker fields may be detected TeV electromagnetic cascades [29,30].

V. CONCLUSION

We followed some of the history of cosmological magnetic fields. At each step of this history, new questions arise. Magnetogenesis in phase transitions alone cannot generate galactic fields, but is there a pre-recombination dynamo or does the amplification occur as galaxies form? Decoupling damps fast magnetosonic waves, but do Alfvén and slow magnetosonic modes play a role on scales below the Silk mass? Protogalactic shocks may generate small seed fields, but do these get amplified on large scales?

These are some of the questions that future observations of large scale magnetic fields will address. In addition to traditional direct observations, the study of extremely high-energy cosmic rays will play an important role in probing cosmological fields in a 50 Mpc volume around us.

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