Can Electric Charges and Currents Survive in an Inhomogeneous Universe?

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Although observations point to the neutrality and lack of currents on large scales in the universe, many mechanisms are known that can generate charges or currents during the early universe. We examine the question of survivability of relic charges and currents in a realistic model of the universe. We show that the dynamics of cosmological perturbations drive the universe to become electrically neutral and current-free to a high degree of accuracy on all scales, regardless of initial conditions. We find that charges are efficiently driven away in a time small compared to the Hubble time for temperatures 100 GeV $\gtrsim T \gtrsim 1 \,\text{eV}$, while the same is true for currents at all temperatures $T \gtrsim 1 \,\text{eV}$. The forced neutrality relaxes constraints on the generation of an electric charge in the early universe, while the forced erasure of currents disfavors many mechanisms for the early origins of large-scale magnetic fields.

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The universe, on its largest scales, appears to be electrically neutral and current-free. Many scenarios exist, however, which can lead to the production of either a net electric charge or an electric current in the early universe. The presence of either charges or currents at early times has been discussed in the past as possible candidates for generating seed magnetic fields in the early universe, as well as causing other consequences for cosmology. In this *letter*, we expand upon our previous work [1], and demonstrate that although relic electric charges and currents may reasonably exist at early times, they are driven away in a realistic, inhomogeneous universe.

Many symmetries which appear to be good symmetries today may not have been so in the past. Such symmetries are often related to conserved quantities, such as global symmetries (conserving baryon and lepton numbers), or gauge symmetries (conserving color and electric charges). Although no direct experimental evidence exists for the violation of these conservation laws [2], the matter-antimatter asymmetry is a compelling indicator that perhaps baryon number conservation was violated at some point in the past [3]. Indeed, so long as the Sakharov conditions [4] are met, barvon number violation appears to be quite likely. Many mechanisms exist that could explain the generation of a baryon asymmetry (baryogenesis), including the decay of GUT-scale particles [5], sphaleron processes [6] at the electroweak scale [7], sphaleron processing of a lepton asymmetry [8], or through a coherent scalar field [9].

In a similar fashion to the global symmetry preserving baryon number, it may be possible to break the gauge symmetry preserving electric charge conservation. These scenarios can result in a process we refer to as *electrogenesis*, since they admit the production of a net electric charge in the universe. Perhaps the simplest pathway for electrogenesis is a theory where the electromagnetic gauge symmetry $U(1)_{em}$ was temporarily broken in the past, only to be restored later at lower temperatures. Langacker and Pi [10] demonstrated this possibility in the context of grand unification, while Orito and Yoshimura [11] and Nambu [12] showed that electrogenesis is possible in higher dimensional theories such as Kaluza-Klein. Another possibility that could lead to electrogenesis is that the U(1)_{em} symmetry is not exact. This arises in variable speed-of-light cosmologies [13], varying- α theories [14], extensions of the standard model with massive photons [15], brane-world models [16], and models admitting electron-positron oscillations [17].

Additionally, electric currents can be generated at very early times by many means, such as during inflation [18]. during the QCD phase transition [19, 20], the electroweak phase transition [20, 21], or by relativistic decays [22]. The earliest stages of structure formation also generate small electric currents [1], but these are too small to be of any significance until much lower temperatures $(T \ll 1 \,\mathrm{MeV})$. Prior treatments of a universe with some sort of electromagnetic asymmetry have assumed that charges and/or currents within a comoving volume remain constant [11, 22, 23, 24]. However, charge conservation still allows the local charge to change, provided there is a flow of current, and therefore there can be local changes in the charge-per-baryon (Δ) at different epochs. Observational constraints on Δ at different epochs are as follows: the anisotropies of cosmic rays place a constraint that at present, $|\Delta| < 10^{-29} e$ [11]; the isotropy of the microwave background constrains $|\Delta| < 10^{-29} e$ at $z\simeq 1089$ [25]; and big bang nucleosynthesis requires that $|\Delta| \lesssim 10^{-32} e$ at $z \simeq 4 \times 10^8$ [26].

In order for a local cosmological charge or current to have any major significance, they must be correlated with the density inhomogeneities which will grow into the collapsed structure observed today. It is expected that charge over- and under-densities should possess the same types of inhomogeneities as baryons [22], and their evolution should therefore be calculable in the same fashion. We have recently shown that gravitational forces, in combination with Coulomb forces and Thomson scattering, all impact the evolution of a charge asymmetry [1]. The remainder of this *letter* examines the evolution of a relic electric charge or current, and studies the associated cosmological ramifications.

A realistic cosmological model of the universe will necessarily include inhomogeneities on both subhorizon and superhorizon scales, as mandated by inflation. An excellent treatment of the linear evolution of these perturbations, including the photon, neutrino, baryonic, and dark matter components, is given in Ma and Bertschinger [27]. While it is possible that a cosmological charge asymmetry could manifest itself in exotic forms, these possibilities are unsupported by experiment. This includes searches for fractionally charged particles [24, 28], or a difference between the strength of the proton and electron charges [29]. We therefore consider that if a cosmic charge asymmetry exists, it is due to a difference between the number densities of protons and electrons, following our previous treatment [1].

We choose to work in the conformal Newtonian gauge, defined by the metric

$$ds^{2} = a^{2}(\tau)[-(1+2\psi)d\tau^{2} + (1-2\phi)dx^{i}dx_{i}], \qquad (1)$$

where ϕ and ψ describe the scalar-mode inhomogeneities. Including Coulomb interactions and Thomson/Compton scattering with photons, the evolution equations for the proton and electron fluids become

$$\begin{split} \dot{\delta}_i &= -\theta_i + 3\dot{\phi}, \\ \dot{\theta}_i &= -\frac{\dot{a}}{a}\theta_i + c_s^2 k^2 \delta_i + k^2 \psi \\ &+ \Gamma_i(\theta_\gamma - \theta_i) + \frac{4\pi q_i e a^2}{m_e} (n_p - n_e), \end{split}$$
(2)

where δ_i is defined as the the departure of the local spatial density of species *i* from the overall spatial average (i.e., $\delta_i \equiv \rho_i(x)/\bar{\rho}_i - 1$), and θ_i is defined by $\theta_i \equiv ik^j(v_i)_j$, where v_i is the peculiar velocity of the field δ_i . In equation (2), *i* is *p* for protons and *e* for electrons, n_p and n_e are the local number density of protons and electrons, q_p and q_e are the proton (+*e*) and electron (-*e*) charges, and Γ_i is the (conformal time) rate of momentum transfer due to photon scattering with charged particles,

$$\Gamma_e \equiv \frac{4\bar{\rho}_{\gamma}n_e\sigma_T a}{3\bar{\rho}_e}, \qquad \Gamma_p = \left(\frac{m_e}{m_p}\right)^3 \Gamma_e. \tag{3}$$

The Thomson cross section (σ_T) for electrons is replaced with the Klein-Nishina form for temperatures $T \gtrsim m_e$ [33]. By taking the difference between the density and velocity fields for electrons and protons, a set of evolution equations governing the evolution of a net charge and/or current within a given volume is obtained. The equations for δ_q and θ_q , where $\delta_q \equiv \delta_p - \delta_e$, $\theta_q \equiv \theta_p - \theta_e$, are

$$\delta_q = -\theta_q \tag{4}$$

$$\dot{\theta}_q = -\frac{\dot{a}}{a}\theta_q + c_s^2 k^2 \delta_q - \Gamma_e \left(\theta_\gamma - \theta_b + \theta_q\right) + \omega^2 \delta_q,$$

to linear order, where $\delta_b = (m_p \delta_p + m_e \delta_e)/(m_p + m_e)$ is the baryonic mass density perturbation and $\omega^2 = 4\pi n_e e^2 a^2/m_e$ is the (conformal time) plasma frequency. Note that other types of scattering, such as Rutherford scattering, do not need to be included in equation (4) at this epoch, as the momentum transfer arising from Thomson/Compton scattering is by far the dominant scattering term in the early universe.

In our previous paper [1], we investigated the effects of the source term in equation (4), proportional to $\theta_{\gamma} - \theta_b$, in the absence of any initial charge or current asymmetry. We found that a local charge asymmetry, of order $\delta_q \sim 10^{-34}$ on Mpc scales, is generated near the time of recombination. In this paper, we study the fate of an initial charge (δ_q) or current (θ_q) asymmetry. We note that since equations (4) are linear, these two cases evolve independently of one another. As the rates Γ_e and ω are typically much greater than the expansion rate \dot{a}/a before decoupling, and much greater than the term $c_s^2 k^2$ on all but the smallest scales, the latter terms can be neglected, and equations (4) can be simplified into the single equation

$$\ddot{\delta}_q + \Gamma_e \dot{\delta}_q + \omega^2 \delta_q = 0, \tag{5}$$

where we remind the reader that $\delta_q = -\theta_q$. An initial asymmetry evolves as a damped harmonic oscillator, with slowly varying coefficients. If the coefficients were constant, we would have the usual solution, with two modes,

$$\delta_q = c_1 e^{s_1 \tau} + c_2 e^{s_2 \tau}, \tag{6}$$

where c_1 and c_2 are undetermined constants, and $s_{1,2}$ are the two roots of $s^2 - \Gamma_e s + \omega^2 = 0$,

$$s_{1,2} = -\Gamma_e/2 \pm \sqrt{\Gamma_e^2/4 - \omega^2}.$$
 (7)

For $\Gamma_e/2 > \omega$, the modes are a fast and a slow decay, while for $\Gamma_e/2 < \omega$, there is an oscillation with a damped envelope.

The rates Γ_e and ω in fact vary with expansion, as $\Gamma_e \propto a^{-3}$ and $\omega \propto a^{1/2}$, and so change slowly on the expansion timescale. As a result, the arguments of the exponentials in equation (6) change from $s \tau$ to $\int s d\tau$, as can be seen straightforwardly by changing variables to the logarithm of the asymmetry, $X = -\ln(\delta_q/\delta_0)$, where δ_0 is the initial asymmetry, and its derivative, the damping rate $s = \theta_q/\delta_q$. From equations (4), these quantities satisfy

$$\dot{X} = s, \qquad \dot{s} = -\frac{\dot{a}}{a}s + c_s^2 k^2 + \omega^2 - \Gamma_e s + s^2, \qquad (8)$$

where the rates ω and Γ_e are again much greater than the expansion rate $H = \dot{a}/a$ and the term $c_s^2 k^2$ on cosmological scales. We expect \dot{s} is also small, since the rates Γ_e



FIG. 1: The logarithm of the damping factor $X = -\ln(\delta_q/\delta_0)$ (solid curve) and the normalized damping rate per Hubble time s/H (dashed curves), as a function of redshift. The lower dashed curve represents the slow decay mode, which describes the evolution of an initial charge, while the upper dashed curve illustrates the fast mode, describing the damping of an initial current. After critical damping $(z \approx 10^9)$, the two dashed curves evolve together. For damping rates $s/H \gtrsim 10^5$, any initial charge or current will be completely driven away in less than one Hubble time, which happens for excess charges for values of z between 10^3 and 10^{13} and for currents for $z \gtrsim 10^3$.

and ω vary slowly. In this approximation, the damping rate s is a root of $s^2 - \Gamma_e s + \omega^2 = 0$, as above, and

$$X = \int s \, d\tau = \int da \, \frac{s}{\dot{a}} = \int \frac{da}{a} \, \frac{s}{H}.$$
 (9)

The quantity s/H represents the rate of logarithmic damping per Hubble time, or damping per log expansion factor.

Figure 1 demonstrates dramatically that the damping is so powerful as to wipe out a charge or current asymmetry for a large window around the epoch of critical damping. The figure shows the logarithm of the damping factor for both a charge asymmetry $\delta_q \propto e^{-X}$ and a current $J \propto \theta \propto s e^{-X}$. At early times, an initial charge asymmetry decays according to the slow-decay mode solution of equations (8), while an initial current follows the fast-decay mode. For values of $X \gtrsim 10^2$, an initial charge asymmetry of order 1 is reduced to less than one excess proton or electron per comoving horizon.

The results in Figure 1 indicate that any excess charge created at temperatures above 100 GeV will be entirely wiped out at roughly the electroweak scale, and any electrogenesis that concludes between $T_{\rm EW}$ and $T_{\rm CMB}$ will also be driven away in a time much less than the Hubble time. Furthermore, any relic current created at temperatures $T \gg T_{\rm CMB}$ will be also driven away in a time much less than the Hubble time. We therefore conclude that the evolution of charged particles in the universe, in-

cluding Thomson/Compton scattering and the Coulomb interaction, force the universe to an electrically neutral, current-free state, independent of initial conditions, inflationary remnants, electrogenesis, and phase transitions that may leave charges or currents behind.

The results presented in this paper may have significant implications for scenarios admitting electrogenesis in the early universe. The observational limits on the charge-per-baryon (Δ) of the universe [11, 25, 26] have been used to constrain models admitting electrogenesis in the past. Our results demonstrate that later-time constraints on Δ do not constrain initial values of Δ , as the universe drives away any local charge asymmetries exponentially quickly. Therefore, we also conclude that the $U(1)_{em}$ gauge symmetry may have been broken in the past or may be only approximately exact today, and the observed values of Δ would not be discernably different from zero. Hence, electrogenesis is not constrained at all by observational limits on Δ . Nevertheless, the phenomenological consequences of electrogenesis may leave signatures which can be searches for experimentally. Just as GUT-scale baryogenesis has phenomenological consequences such as proton decay, electrogenesis should also have consequences for particle physics. Each specific model that admits electrogenesis will have its own associated phenomenology. Some consequences of models admitting charge nonconservation have been worked out [30], with various distinct experimental signatures having been (unsuccessfully) searched for [31]. The physical possibilities if either Lorentz invariance or the $U(1)_{em}$ symmetry are broken is quite rich and varied, and deserve further examination.

Also of cosmological importance are the implications for magnetic fields in the early universe. If large-scale currents are truly driven away, as in Figure 1, then not only are magnetic fields generated by a charge asymmetry [22] ruled out, but all magnetogenesis scenarios which rely on a relic current persisting from early times are disfavored as well. This requires careful examination, as the scenarios for magnetic field generation from the QCD [19, 20], electroweak [20, 21], or inflationary [18] phase transitions correctly discuss the growth of instabilities in the hot plasma of the early universe. However, they do not examine whether the currents which are initially generated by the phase transition persist long enough to create such magnetic fields. Our results in Figure 1 illustrate the damping rate for currents per Hubble time, and we find the damping rate to be much quicker than the growth rate of the instabilities given in the literature. If the currents do not persist long enough to create smallscale fields, they will have no opportunity to then be transferred to larger scales [32], creating seeds for the large-scale magnetic fields observed today. Since these currents do not have a source driving them after their creation, the expansion dynamics of the universe ought to damp them away very rapidly. Unless there is some

additional effect which prevents the currents that would give rise to magnetic fields from being driven away, these magnetogenesis scenarios are highly disfavored.

Since our results indicate that initial conditions on δ_a and θ_q are unimportant in the absence of sources, the most significant contribution to a late-time δ_q or θ_q must come from the source contribution in equations (4). After any initial charge is wiped out, δ_q and θ_q evolve according to the dynamics in equations (4), where the source term, $\Gamma_e(\theta_{\gamma} - \theta_b)$, determines δ_q . Results from our previous work [1] indicate that the typical charge-per-baryon on the scale of the present horizon is $|\Delta| \sim 10^{-46} e$, a result that ought to be valid since the present horizon is still in the linear regime of structure formation. Strictly, these calculations apply to asymmetries within the horizon and at finite Fourier wavenumber k. The asymmetry must be within the horizon for its dynamics to evolve according to our analysis due to causality; thus our results are definitely valid for all wavenumbers k from the moment they first enter the horizon. We also consider a naïve (and not rigorous) extrapolation to superhorizon ks. The dependence of our results on k is unimportant and vanishes as $k \to 0$. Thus, it appears that even a global charge asymmetry may be driven to zero. At first glance, this may seem to violate the principle of charge conservation, but we recall that currents carry away excess charge while still satisfying the continuity equation. An intuitive picture is to consider an expanding universe containing homogeneous proton and electron fluids free to expand at different rates. In the Newtonian limit, with spherical symmetry, an excess of positive charge increases the expansion rate for protons and decreases the expansion rate for electrons, and the total charge in a given volume can decrease even though charge is locally conserved. This construct does not work in detail, as different expansion rates require a radial flow of protons relative to electrons, and such a universe could be isotropic about only one center. The flow may also require relativistic velocities. However, the mechanism can apply on arbitrarily large finite scales, and to reduce a charge asymmetry of order the mass density inhomogeneity (10^{-5}) over the scale of the horizon requires a relative velocity of $\mathcal{O}(\text{km/s})$, or a bulk fluid displacement of $\leq 1 \,\mathrm{Mpc}$.

Finally, although our calculations have accounted for high-energy effects in electron-photon scattering [33], we have not done this for protons. We note that protons were dissociated into a quark-gluon plasma at temperatures above the $\Lambda_{\rm QCD}$ scale, resulting in different scattering rates and momentum transfer at these energies. Furthermore, we have not taken into account possible shielding effects on cosmological scales, which, if present, could cause the effective Coulomb force to fall off faster than $1/r^2$ for sufficiently large distances. Inclusion of these effects may be needed to extract the exact behavioral details of δ_q and θ_q at high energies.

The overall conclusion which can be drawn from this

work is that any relic charge or current created on subhorizon scales in the early universe (at temperatures $T \gg 1 \,\mathrm{eV}$) is driven away by cosmological dynamics. This indicates that a net charge or current of any magnitude could be generated at the QCD phase transition, the electroweak scale, the time of Higgs symmetry breaking, the time of supersymmetry breaking, the end of inflation, or the grand unification scale, and the universe would not be discernibly different from a universe that was electrically neutral and current-free at all times. This disfavors many scenarios for the generation of seed magnetic fields, which rely on the survival and sustainability of currents at early times. The possibility that the universe underwent electrogenesis at some point is intriguing and rich with possibility, and present observations of electric charge neutrality do not preclude the possibility that the universe (or a portion of it) was charged in the past. Although the phenomenological consequences of electrogenesis have been elusive thus far, evidence for its existence would profoundly alter our cosmological picture of the universe.

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