Matter Domination-Recombination: Coincidence or Consequence?

It is a well known cosmological coincidence that the transition in the expanding universe from radiation domination to matter domination occurs at roughly the same time and temperature as the transition from atoms being ionized to being neutral. It is argued here that this might not be a coincidence at all but a cosmological problem to be solved by super grand unified theories, just as they were used to solve the problem of baryon asymmetry, the horizon problem, and the flatness problem. The solution requires a special relationship between the parity violation of the baryon nonconserving interaction and the fine structure constant.

Over the past decade, grand unified theories (GUTs) and supersymmetry (SUSY) and possibly theories of everything (TOEs) have been successful at explaining away many long-standing cosmological problems. For example, inflation[1] utilized GUTs to explain away the flatness problem, the horizon problem, magnetic monopoles, and rotation, and was able to produce fluctuations which might eventually grow into galaxies. Grand unified theories have also been able to explain baryon asymmetry and provide a quantitative explanation of the baryon-to-photon ratio.[2] It is the purpose of this Comment to bring to the attention of particle theorists another long-standing cosmological problem, one that most cosmologists refer to as "coincidence;" but if we really are on the verge of finding a theory of everything, there should be no coincidences. The coincidence we are speaking of is the fact that in the expanding universe the energy density switches from being dominated by radiation to being dominated by matter at approx-

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imately the same time and temperature as when atoms combine with their electrons and thus switches the universe from being ionized to being neutral. This latter transition is normally referred to as "recombination" although it is actually the first time that matter is ever combined in the history of the universe. Since it is necessary for matter to be both dominant and neutral in order for density fluctuation to grow to form galaxies, clusters of galaxies or even stars, the coincidence of these two transitions is vitally important to an early formation of objects in the universe and thus to our own existence. If these two transitions were greatly separated, the universe might expand sufficiently that the density would be too low to enable gravitational growth of objects in the age of the universe.

To understand why this is generally viewed as a coincidence rather than a consequence of some fundamental physical law, let us note how one calculates the transition from radiation domination to matter domination. In particular note that radiation energy density, ρ_{rad} scales as a fourth power of temperature, T, whereas ρ_{matter} scales as the third power of T. As a result, in the very hot early universe, radiation dominates, and at late times, matter dominates as the temperature cools. The transition can be found by using the present temperature, $T_0 \simeq 3$ K and the baryon-to-photon ratio, η. By using big bang nucleosynthesis[3] we know that the ratio of baryons to photons, η, is approximately 5×10^{-10}. Thus using the mass of baryons ($m_b \sim 1$ GeV) we can see that the transition from radiation dominance to matter dominance occurred at $T \sim 10^4$ K. It is clear that this ratio of the density of matter to the density of radiation is really only dependent on the initial entropy of the universe which is inversely proportional to the baryon-to-photon ratio,[2] generated by the CP violation of the baryon nonconserving interaction. Thus, the reason for the temperature of the transition being $\sim 10^4$ K has to do with the CP violation of the baryon nonconserving interaction which in the standard GUT models is a free parameter.

The epic of recombination is fixed by the ionization potential of an electron bound to hydrogen; this is of course related to the value of the fine structure constant α. The fact that it comes out with a value of a few eV thus occurring also at a temperature of $\sim 10^4$ K (the actual value is 13.6 eV but thermal equilibrium continues down to $\sim KT/10 \sim 1$ eV) appears at least in the standard model to be totally unrelated to the CP violation of baryon non-conserving interactions.

It is interesting that the epic of recombination, red shift $z \simeq 1000$, and the transition from radiation domination to baryons being the dominant matter of the universe occurs also at red shift of about 1000. However, if the universe has a value of $\Omega = 1$, then matter domination actually occurs a bit earlier. We know that if $\Omega = 1$, the bulk of the matter of the universe in not in the form of baryons. From big bang nucleosynthesis,[3] Ω_{baryon} is ~ 0.1. Thus it is actually baryon domination that is roughly concurrent with recombination; it is not matter domination, per se, and is baryon domination that is directly related to the CP violation of baryon nonconserving interactions.

We have seen before that the apparently coincidental cosmological initial value problem might not be coincidental at all; it might be a consequence of some fundamental unified theory. We propose here that in working on these unified theories one should also make sure that the theories remove the coincidence between baryon domination and recombination. In particular, we have seen over the last few years that in order to get inflation to work and satisfy the cosmological problems, theorists have been forced to "fine tune" their GUT models and to choose certain small selected subsets of allowed model space.[4] Perhaps while doing this fine tuning, theorists should also worry about having a model where there is a relationship between the fine structure constant and the CP violation of the baryon conserving interaction so as to have an agreement that makes this transition temperature the same for both recombination and baryon domination.

The temperature at recombination is approximately

$$T_{\mathrm{rec}} \sim \frac{1}{k_B} \frac{(\alpha^2 m_e c^2/2)}{\ln} \left(\frac{s}{k_B n_B \alpha^3}\right) \tag{1}$$

where $(s/k_B n_B)$ is the entropy per baryon in the universe. The temperature when $\rho_b \sim \rho_{\mathrm{rad}}$ is

$$T_{\mathrm{eq}} \sim \frac{m_p c^2}{k_B} \left(\frac{k_B n_B}{s}\right) \tag{2}$$

An estimate for kn_B/s generated by the asymmetric decay of GUT-related particles[5] is

$$\frac{k_B n_B}{s} \sim \frac{1}{7}\frac{N_X}{N}\left(\frac{\alpha_X}{4\pi}\epsilon\right) \tag{3}$$

where N_X/N is the fraction of the available particle states which decay to baryons and $(\alpha_X/4\pi)\epsilon$ is the branching ratio and ϵ is the CP violation of the baryon nonconserving interaction. The condition that $T_{eq} \sim T_{rec}$ implies

$$\frac{\alpha_X}{4\pi}\epsilon \sim \left[\frac{7}{2}\left(\frac{N}{N_X}\frac{m_e}{m_p}\right)\right]\frac{\alpha^2}{|\ln\alpha^5|} \tag{4}$$

We note that in most GUTs $\alpha_X/4\pi \sim 1$; thus, this is equivalent to requiring

$$\epsilon \sim \frac{\alpha^2}{|\ln\alpha^5|} \tag{5}$$

We hope that future models will naturally give us this relationship.

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