The Quark-Hadron Transition and Its Effects On Primordial Nucleosynthesis

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Abstract

In this paper, I discuss the quark-hadron transition in the early universe and analyze how possible inhomogeneities resulting from this phase transition can impact big bang nucleosynthesis. I describe how a possible phase transition could cause inhomogeneities to develop and, after providing a brief description of standard BBN, describe how these inhomogeneities can affect primordial light element abundances. I will then describe how the physics during and after the transition can be constrained by observations.

1 Introduction

Astrophysicists refer to the universe as the “Poor man’s particle accelerator.” This is because energy scales that only exist on earth in large, costly particle accelerators occur naturally in space. Cosmic rays are a standard example of this – currently, it is possible to accelerate particles in a lab up to a few TeV, while cosmic rays are naturally produced in supernovae and other high-energy cosmic events (such as neutron star mergers) that have energies which can exceed 10^8 TeV (10^{20} eV).

Another phenomenon of great interest to particle physicists and astrophysicists alike is the quark-gluon plasma. The theory of quantum chromodynamics and the idea of quark asymptotic freedom leads to the realization that matter must make a phase transition from a hadronic phase to a quark-gluon phase at some point. Theory predicts that this takes place at very high energy (on the order of 100 MeV) and densities on the order of 10^{14} g cm^{-3}. These energies and densities only occur on earth in high-energy hadron colliders such as RHIC. However, the universe provides an excellent testbed for this phenomena in the early universe.

The Big Bang theory of cosmology dictates that the universe is expanding. This means that, if we were to “rewind” the universe, ie, run the evolution of the universe backward in time, we would see the universe get denser and hotter. Molecules would dissociate into atoms, then atoms would ionize, then atomic nuclei would undergo a phase transition into a vapor of protons and neutrons. At high density there will be so many protons and neutrons per unit volume that their constituent quarks will no longer know which nucleon they belong to! At this point quarks will be free to move over distances much greater than the confinement distance of ~ 1 fm. This is referred to as the quark-gluon plasma, and occurs in the early universe a short time after the big bang. If the change of phase between atomic vapor and the quark-gluon plasma is discontinuous so that coexistance of the two phases is possible (ie, a first order phase transition), this can lead to fluctuations in the baryon number density in the early universe. If these fluctuations survive to the epoch of big bang nucleosynthesis (BBN), they can have a strong influence on the predicted light element abundances.

In this paper, I will discuss the physics of the quark-hadron phase transition and the development of baryon inhomogeneities in the early universe. In Section 2 I will briefly describe the physics of the quark-hadron phase transition and baryon diffusion. In Section 3, I will discuss standard big bang nucleosynthesis, and describe how the addition of inhomogeneities changes BBN in Section 4. Finally, I will discuss observational constraints on the possible inhomogeneities in the early universe using light element abundances in Section 5.

2 The Quark-Hadron Phase Transition

Examination of the quark-gadron phase transition using QCD is quite challenging. QCD perturbation theory cannot be used to determine the type of the transition, as all orders of perturbation theory are important. Lattice gauge theory can be used to analyze the transition, though this can be extremely computationally intensive. Results are dependent on the quark masses used in the simulations – the transition could be first or second order, or even a crossover transition (ie, recombination). It is currently impossible to use accurate quark masses (due to quark mass quenching) so we are unable to determine the phase diagram to a high degree of accuracy. However, results suggest that with a light enough strange quark the transition will be first order at high temperatures (100-200 MeV) and low baryon chemical potential (Fodor & Katz 2001, Rajagopal 1999).

A first order phase transition is necessary in order to produce baryon fluctuations. Also, we need the quark-gluon phase to be in coexistance with the hadron phase long enough for baryon transport to produce a disparity in baryon number density across the phase boundary. Coexistence of phases demands the existence of latent heat which must be removed in order to change from the high-temperature quark-gluon phase to the low temperature hadronic phase. The precise value of the latent heat is unknown and depends on the equation of state of both phases at the coexistance temperature, T_c. For the purposes of this paper we will now assume that the transition is first order and examine the consequences.

The early universe is hot and dense, and expands according to Einstein's equations (Peebles 1993; Kolb & Turner 1990). Before the universe cools to T_c, it exists in thermal and chemical equilibrium in a soup consisting of electron and muons, 3 species of neutrinos, light quarks and gluons, and also the antiparticles of all of the species mentioned. Equilibrium is kept by rapid interactions via the electroweak interaction.

When the universe cools to T_c coexistence is possible, but at this temperature the probability of producing a stable "bubble" of hadronic matter in the quark-gluon plasma is quite low. The universe thus supercools (cools to $\mathrm{T} < \mathrm{T}_c$ while still in the high-temperature phase) until the probability of nucleation is favorable. Calculations suggest that the temperature only drops approximately ~ 1 % below T_c before nucleation occurs. (Kapusta 2000). Once nucleation begins, latent heat is released into the system which reheats the the universe to T_c, inhibiting nucleation again.

The universe continues to expand, extracting more latent heat from the quark-gluon plasma, and the hadronic bubbles grow. When roughly 50% of the volume of the universe has been converted to the hadronic phase the bubbles of hadronic matter get so large that they start to collide and merge, leaving the universe with droplets of quark-gluon plasma surrounded by hadronic matter. These droplets then shrink and fragment, and continue to extract more latent heat. This happens until all of the matter in the universe has been converted to the hadronic phase, at which point the universe can continue the process of cooling with expansion.

The process of bubble creation and destruction can lead to the creation of a baryon number inhomogeneity. The development of these fluctuations depends on how baryon number is transported across the phase boundary. It is more likely that a quark/antiquark pair with the proper color charge combination arrives together at the boundary between phases than 3 quarks doing the same. Since mesons (a hadron created from a quark/antiquark pair) do not carry a net baryon number, the relative baryon number density increases in the quark-gluon plasma. Mesons also typically have masses smaller than nucleons, so simple energy arguments show that baryon transport into the hadronic phase is suppressed even more. See Fuller, Mathews & Alcock (1988) and Witten (1984) for more in-depth discussion of baryon transport.

When the hadronic bubbles first form, baryons tend to stay in the quark-gluon phase, so at the end of the transition period the nucleation sites are then typically baryon-poor when compared to the droplets of quark-gluon plasma. As the droplets shrink, baryon transport produces a smooth baryon density distribution which is low in baryon density at the nucleation sites and high at the termination sites. The end result is a universe at a single temperature with an inhomogeneous baryon distribution. More technically, the baryon-to-photon ratio $\eta \equiv (n_b - n_{\bar{b}})/n_\gamma$, a quantity that is critically important to light element abundances in big bang nucleosynthesis, varies in space. If these fluctuations are not wiped out by diffusion they will expand with the universe. At early times baryon diffusion is limited by electron scattering and nucleon-nucleon scattering. The mean free paths of both the neutron and proton at T $\simeq$ 1 MeV is roughly 1 cm, so fluctuations smaller than this are wiped out (Malaney & Mathews 1993). The neutron and proton diffusion is linked via the weak interaction, which keeps the neutron-to-proton ratio in equilibrium. Fluctuations larger than the mean free path persist and remain unchanged until the rate of conversion from neutrons to protons (and vice-versa) become significantly different and until the electrons and positrons annihilate, leaving photons as the dominant scattering source. All of this happens at the beginning of the BBN epoch, so we are led to believe that large fluctuations produced during the quark-hadron transition will persist and remain markedly unchanged until the epoch of big bang nucleosynthesis.

For more information on the quark-hadron phase transition and inhomogenuous BBN, the interested reader is directed to reviews by Witten (1984), Fuller, Mathews & Alcock (1988), Kurki-Suonio, Matzner, Olive & Schramm (1993) and Kapusta (2000). Also, please note that it is possible to generate fluctuations in the baryon-to-photon ratio during the electroweak transition. However, this is outside of the scope of this paper and will not be discussed here.

3 Standard Big Bang Nucleosynthesis

Standard Big Bang nucleosynthesis makes the assumption that the universe is homogeneous and isotropic, with 3 species of massless, non-degenerate neutrinos and their corresponding antineutrinos. Reviews of the physical history of the universe with emphasis on BBN can be found in Kolb & Turner (1990), Smith, Kawano & Malaney (1993), and Olive, Steigman & Walker (2000). Theory tells us that the universe was in thermal equilibrium before the onset of nucleosynthesis (T $\sim 10^{10}$ K, or 1 MeV). As the temperature of the universe falls below 0.8 MeV ($t_{universe} \simeq 1$ second), the weak interaction rate keeping the neutrinos in equilibrium becomes slow compared to the rate of expansion of the universe, so the neutrinos decouple from the primordial plasma and the forward and reverse neutron-proton interconversion rates (mediated by the weak interaction) become different. This is referred to as "weak freeze-out," and the only significant weak interaction remaining is the decay of neutrons into protons. The neutrons and protons leave thermal equilibrium and deviate from their equilibrium ratio $n/p = exp(-Q/k_bT) \sim$

1/6, where Q is the neutron-proton mass difference (Q=1.293 MeV).

At roughly the same time (T $\simeq$ 1 MeV, or $2m_e$) the electrons and positrons annihilate, which heats the photon fluid relative to the decoupled neutrino fluid and serves to inhibit the formation of heavy elements. The nuclear reactions among the light nuclei are still fast enough to keep all species in nuclear statistical equilibrium, though their abundances remain very low compared to those of neutrons and protons. As temperatures continue to fall, production rates for tritium (^{3}H), ^{3}He and ^{4}He become dominant and species start to deviate from their equilibrium values. The abundances of these light nuclei do not grow – instead, they follow the deuterium abundance because the reverse reaction of $p(n,\gamma)d$ prevents significant buildup of any of the elements due to the large number of photons relative to baryons. This is referred to as the "deuterium bottleneck." Once the temperature of the universe falls to $\simeq$ 0.08 MeV ($t_{universe} \sim$ 2 minutes) the deuterium production channel dominates and fusion into higher mass nuclei can occur, though significant quantities of high mass nuclei are not formed in the early universe due to the instability of nuclei with atomic numbers 5 and 8. Shortly after this, the Coulomb repulsion between nuclei becomes strong enough to halt any further charge-induced reactions and brings an end to the epoch of big bang nucleosynthesis. The predicted abundances plotted against η are summarized in Figure 1. It is important to note that the standard BBN model works extremely well in predicting the observed values of the light element abundances, so any modification to the theory will be severely constrained.

4 Inhomogeneous Big Bang Nucleosynthesis

The addition of inhomogeneities to big bang nucleosynthesis produces some very interesting results. Originally, the idea of inhomogeneous BBN was the result of an attempt to allow for a universe with a baryon density equal to the critical density (where the critical density is the density of matter that will make the universe geometrically flat - see Peebles 1990) while still respecting the light element abundance observations. Baryon fluctuations alone will dramatically affect the predicted abundances, which we can determine by averaging the standard BBN results over the density profile of the inhomogeneous baryon gas. We describe this profile with parameters such as the average baryon-to-photon ratio $\overline{\eta}$, the mean separation of fluctuations ℓ, the density contrast between regions of high and low baryon densities R, and the volume fraction of overdense regions f_V.

The mean separation and average baryon-to-photon ratio are left as free parameters, to be constrained from light element observations. The volume fraction f_V varies from 0 to 1, returning to the homogeneous case when it approaches either 0 or 1. The density contrast R varies from 1 to infinity, returning to the homogeneous case when $R = 1$. When $R \to \infty$ the universe becomes patchy, having baryons only in some regions. Many different scenarios have been considered, but for those that are considered to be physically realistic there are some universal results: For values of R greater than $\simeq 20$, results become insensitive to the density contrast and yield similar results to the homogeneous case. In addition, the predicted elemental abundances of deuterium (D, or ^{2}H), ^{3}He and ^{4}He are not terribly different from the standard BBN case, though the theoretical uncertainties become greater. ^{7}Li is much more strongly affected, and the predictions for ^{7}Li generally claim abundances significantly larger than the standard case. (Fuller, Mathews & Alcock 1988)

In addition to baryon fluctuation, we must be concerned with the diffusion of baryons from one region to another. As mentioned previously, baryon diffusion has the potential to wipe out the fluctuations caused by inhomogeneous BBN. At energies close to the coexistence temperature T_c electron scattering is the dominant scattering process (the high temperature creating huge numbers of electron/positron pairs), resulting in a small diffusion length. After electron-positron pair annihilation takes place the electron density falls greatly and photon scattering then becomes the dominant diffusion mechanism. Since the neutron has no net charge, a scattering photon must couple to the neutron's magnetic moment, effectively reducing the neutron scattering cross section relative to the proton. This has the net effect of increasing the neutron's mean free path by roughly two orders of magnitude compared to that of the proton and results in different diffusion rates for the two species. At freeze-out the mean free paths for the protons and neutrons are ~ 4 and 135 cm, respectively, which sets the limits for two extreme cases for our inhomogeneous BBN scenario. If the density perturbation separation is much smaller than these diffusion lengths the fluctuations will be completely wiped out and we have the standard BBN scenario. If the average distance between perturbations is much larger than the neutron diffusion length, we have a case where the density profiles do not change due to diffusion.

The most interesting case (for the purposes of this paper) is if the baryon perturbations are of the same order as the diffusion lengths. If so, neutrons will diffuse out of the high density regions, resulting in high density proton-rich regions and low density neutron-rich regions. If the density contrast is too high the proton-rich region burns all of its neutrons during nucleosynthesis and neutrons will flow back to the high density region, effectively returning to the first inhomogeneous case with no diffusion. For more detailed discussion see Malaney & Mathews (1993) and Fuller, Mathews & Alcock (1988).

Neutron diffusion can have a dramatic impact on the nucleosynthetic yields. In the proton-rich region, ^{4}He does not change much because it is proton/neutron symmetric. The dominant nuclear reaction is $D + p \to {}^3$He + γ. With the larger fraction of protons, more deuterium is turned into ^{3}He. If the density is high enough, all of the deuterium is turned into ^{3}He in the proton-rich region, which will in turn be partially burned into ^{7}Be via ^{3}He $+\alpha \to {}^7$Be + γ, increasing the ^{7}Li abundance since ^{7}Be decays into ^{7}Li. Nucleosynthesis in the neutron-rich region is very different. As before, ^{4}He does not change much. The dominant reaction is now $D + n \to {}^3$H + γ, which is a bit weaker than the reaction creating ^{3}He, so a higher density is needed to see significant burning into ^{7}Be. However, deuterium is burned into tritium, which can then be converted to ^{7}Li via ^{3}H + $\alpha \to {}^7$Li + γ. At densities similar to those predicted using the standard BBN case we get similar results from both inhomogeneous and standard BBN. However, by increasing the density one increases the amount of ^{7}Li in both neutron-rich and proton-rich regions. Therefore, using observational constraints on ^{7}Li will place strong limits on inhomogeneous BBN.

5 Observational Results

As seen in Section 4, ^{7}Li can provide a very strong constraint on the parameters of inhomogeneous BBN. Kurki-Suonio, Matzner, Olive & Schramm (1990) consider constraints on inhomogeneous BBN placed by primordial abundance observations. They do so by using these observational limits on abundances to constrain the values of the mean separation ℓ and the baryon-to-photon ratio η.

The constraints given by the authors are as follows: They allow the mass fraction of ^{4}He to range from Y=0.224 to Y=0.254, which are extremely conservative bounds. They assume a lower bound for primordial deuterium of D/H $> 10^{-5}$ by assuming that primordial deuterium was more abundant than observed deuterium abundances in the interstellar medium today since there is no (known) natural astrophysical process to create deuterium, and it is destroyed in stellar interiors. They also consider an upper bound on (D + ^{3}He)/H $< 10^{-4}$ at the BBN epoch, which is currently considered an unreliable bound because the evolution of ^{3}He is sufficiently unknown as to put a large uncertainty in any constraint based upon it. However, the upper bound on (D + ^{3}He)/H is unimportant compared to other constraints, so this does not adversely affect the results. Two ^{7}Li constraints are used. The first is an upper limit from abundance observations of Population I stars (relatively young and metal rich stars) of ^{7}Li/H < 2 x 10^{-9}. The second limit is from Population II stars (older and metal-poor stars), with ^{7}Li/H $<$ 2 x 10^{-10}. These are reasonable bounds because, as with deuterium, there is no astrophysical mechanism for the production of significant quantities of ^{7}Li, and it is destroyed in stellar interiors.

The values of the mean separation ℓ and mean baryon-to-photon ratio $\overline{\eta}$ are severely constrained based upon the observational limits for ^{7}Li from Population II stars. Assuming that the density contrast is R < 100 (recalling that for values of R significantly larger than 20, we obtain the standard BBN case) and that R and f_V have been picked so as to minimize the abundances, they find that the average baryon-to-photon ratio must lie in the range $1.5 \leq \overline{\eta}$ x $10^{10} \leq 7$ and the mean separation must be $\ell \leq 200$ cm at 100 MeV using the ^{7}Li population II constraint only. The authors went out of their way to maximally change the physics that goes into the inhomogeneous BBN case and the results that are found provide constraints on the baryon density similar to those standard BBN provides. Thus, it is impossible to achieve a geometrically flat universe comprised only of baryons that is still consistent with observational constraints. Also, attempts to calculate the mean separation distance all seem to suggest $\ell \simeq 1$ cm at 100 MeV, which is fully consistent with homogeneous BBN, as can be seen from Figure 2 (Kurki-Suonio et. al 1990).

6 Conclusions

We have discussed a mechanism for creating inhomogeneities in the baryon density of the universe at the epoch the quark-hadron transition which could persist until the epoch of big bang nucleosynthesis. However, observational constraints show that reasonable values for the mean separation and baryon density contrast give results consistent with standard BBN. More concrete conclusions from lattice gauge theory are needed in order to determine what order the quark-hadron transition. In addition, results from the MAP and PLANCK satellites will provide us with information on cosmic microwave background anisotropes, which will help to further constrain $\overline{\eta}$ and tighten the limits on the parameters describing inhomogeneous nucleosynthesis.

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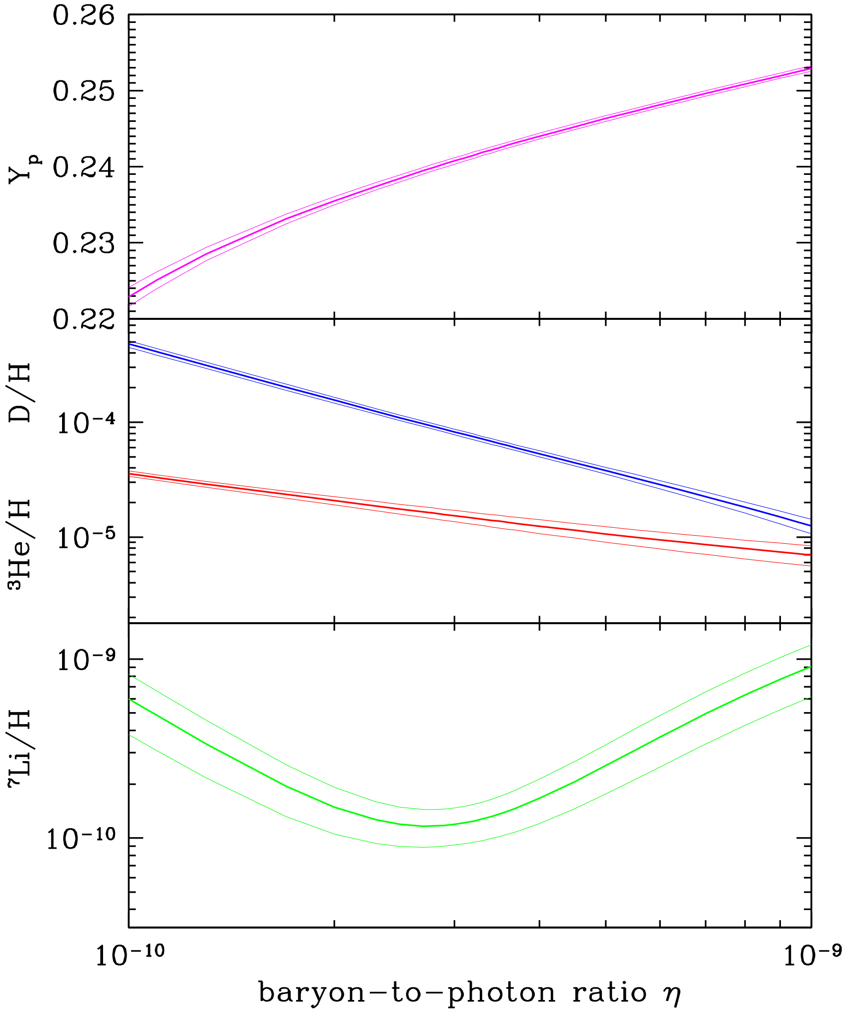

Figure 1: Plots are standard BBN abundance predictions with 2σ uncertainties for the mass fractions of ^{4}He and number densities relative to hydrogen for D, ^{3}He & ^{7}Li. Figure courtesy of Richard Cyburt (UIUC Astronomy)

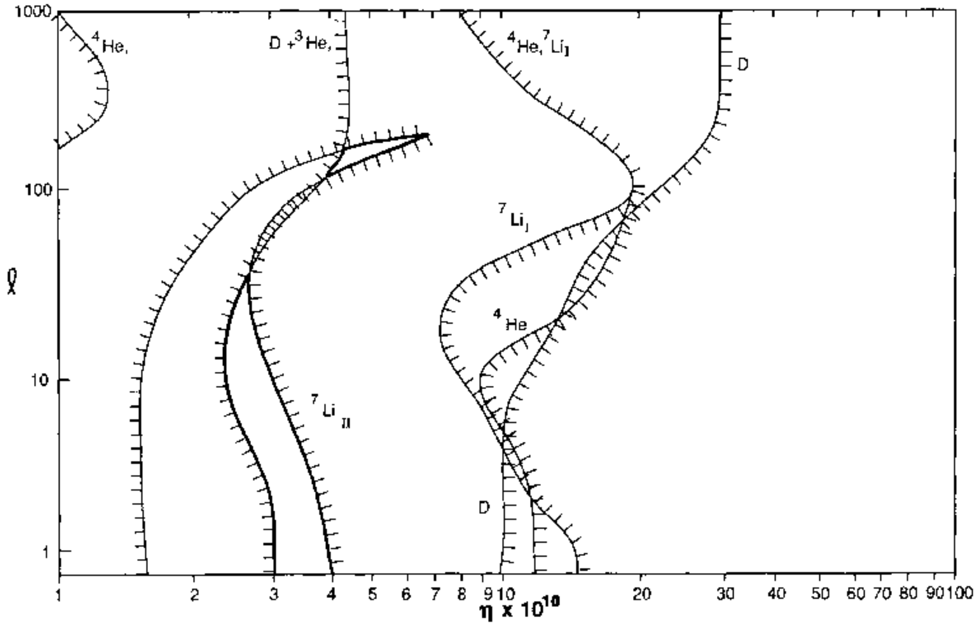

Figure 2: Shows constraints on mean nucleation site separation ℓ and the baryon-to-photon ratio η given reasonable abundance constraints. We are left with a narrow band in η ranging from 2 to 7 and with a maximum ℓ of about 200 cm at T = 100 MeV, using the Population II ^{7}Li constraint. Figure from Kurki-Suonio, Matzner, Olive & Schramm (1990)