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Some Key Questions in Early Universe Cosmology and Big Bang Nucleosynthesis

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For all the interesting possible phenomena which might have occurred during the early universe, there are really only two observational cosmological probes. Of those two, the only probe during the relevant radiation dominated epoch is the yield of light elements during the epoch of big bang nucleosynthesis. The synthesis of light elements occurs in the temperature regime from 10^8 to 10^{10} K and times of about 1 to 10^4 sec into the big bang. The other probe is the spectrum of temperature fluctuations in the CMB which (among other things) contains information of the first quantum fluctuations in the universe, and the details of the distribution and evolution of dark matter, baryonic matter and photons up to the surface of photon last scattering. Here, we emphasize the role of primordial nucleosynthesis in answering some key questions of the big bang and early universe cosmology.

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1. Introduction

The early universe includes the Planck epoch, the birth of space-time, inflation, reheating, a variety of cosmic phase transitions (e.g. supersymmetry breaking, baryogenesis, the electroweak transition, and the QCD transition), the epoch of big bang nucleosynthesis (BBN), and the production of the cosmic microwave background (CMB).

The evolution of the early universe is simply given by the Friedmann equation which describes the the Hubble parameter H in terms of densities ρ, curvature k, the cosmological constant Λ, and the cosmic scale factor a:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\rho - \frac{k}{a^2} - \frac{\Lambda}{3} \;=\; H_0^2\left[\frac{\Omega_\gamma}{a^4} + \Omega_m a^3 + \Omega_k a^2 + \Omega_\Lambda\right] \;, \tag{1.1}$$

where H_0 is the present Hubble parameter, and the various closure contributions from relativistic particles, nonrelativistic matter, curvature, and dark energy are given respectively by $\Omega_\gamma = 8\pi G\rho_\gamma/(3H_0^2)$, $\Omega_m = (8\pi G\rho_m)/(3H_0^2)$, $\Omega_k = -k/(a^2H_0^2)$, and $\Omega_\Lambda = \Lambda/(3H_0^2)$. For most of the big bang only the radiation [Ω_γ term in Eq. (1.1)] is important. There are, however, interesting variants of big bang cosmology where this is not the case. The only direct probe of the radiation dominated epoch is the yield of light elements from BBN in the temperature regime from 10^8 to 10^{10} K and times of about 1 to 10^3 sec. The only other probe is the spectrum of temperature fluctuations in the CMB which contains information of the first quantum fluctuations in the universe, and the details of the distribution and evolution of dark matter, baryonic matter and photons near the surface of photon last scattering.

Light Element Abundances: One of the powers of standard-homogeneous BBN [1, 2] is that all of the light element abundances are determined in terms of a single parameter η_{10} which is the baryon-to-photon ratio in units of 10^{-10}. The crucial test of the standard BBN is, therefore, whether a single value of η_{10} can be found which reproduces all of the observed primordial abundances.

Primordial deuterium is best determined from its absorption line in high redshift Lyman α clouds. The average of measurements of nine absorption-line systems towards various QSOs gives [3, 4] $D/H = 2.87^{+0.22}_{-0.21} \times 10^{-5}$. This would imply an value of $\eta_{10} = 5.7 \pm 0.3$. This is an important result because it is also very close to the value $\Omega_b h^2 = 0.0227 \pm 0.0007$ ($\eta_{10} = 6.00 \pm 0.25$) deduced [5] from the *WMAP* analysis described below.

The primordial lithium abundance is inferred from old low-metallicity halo stars which exhibit an approximately constant ("Spite plateau") lithium abundance as a function of surface temperature. There is, however, some question [6] concerning the depletion of ^{7}Li on the surface of such halo stars and/or during the big bang itself [7]. Here, we adopt the value from [**?**] ^{7}Li$=1.86^{+1.30}_{-1.10} \times 10^{-10}$,

The primordial helium abundance is obtained from extragalactic HII regions in low-metallicity irregular galaxies. There is, however, debate over the extent of systematic errors [9] which could stretch the error to a range of $0.232 \le Y_p \le 0.258$. However, if we adopt a narrow range of helium abundance [10] there is a possible 2-3σ discrepancy between the ^{4}He + ^{7}Li and the D + *WMAP* results [11]. If this dilemma persists it may provide insight into new physics beyond the minimal BBN model, for example, brane-world effects [12], cosmic quintessence [13], time varying constants [14], etc. It has been noted, however [15] that much of the possible discrepancy could be accounted for simply by adopting a shorter neutron decay lifetime [16]. The most recent analysis of [3] concludes that $Y_p = 0.247 \pm 0.002_{stat} \pm 0.004_{syst}$, for which there is concordance between *WMAP* and Y_p.

CMB Observations: The most important parameter from the CMB for BBN is the baryon to photon ratio. The best current fifth year data of the *WMAP*, when combined with the distance measurements from Type Ia supernovae and the Baryon Acoustic Oscillations, gives the following best fit parameters for a ΛCDM model: $\Omega_b = 0.0462 \pm 0.0015$, $\Omega_c = 0.233 \pm 0.013$, $\Omega_\Lambda = 0.721 \pm 0.015$, $h = 0.701 \pm 0.013$ km/s/Mpc, where h is the Hubble parameter in units of 100 km s^{-1} Mpc, and Ω_b, Ω_c are baryonic and cold dark matter contents, respectively. There are still some discrepancies, however, between the best fit cosmology and the data such as a suppression of the lowest multipole moments of the CMB. We have examined [17] whether this might be evidence for a compact topology [18]. However, as of yet, there is no evidence for the signatures of a compact topology either in CMB "circles" or correlated objects [17]. There is also a possible excess of power on the largest multipoles (smallest scales) as measured by *ACBAR* [19] and CBI [20]. We have explored [21, 22] whether this might suggest new physics on small scales.

2. What are the Questions?

The important questions regarding the big bang are something like the following. Highlighted in bold are some intriguing questions which can be addressed using BBN:

1)How did the universe begin? 2)Why are there 3 large dimensions? 3) **What drives inflation?** 4) **Are there observable effects from: supersymmetric particles, string excitations, etc.** 5) **Is there evidence for large extra dimensions?** 6) How does the universe reheat? 7) **How and when was the net baryon number generated?** 8) **When and how was the dark matter generated?** 9) **When and how was the dark energy created?** 10) **Are there observable effects from the Electroweak or QCD transition?** 11) **Is there a primordial magnetic field?**

What drives Inflation?: The simplest explanation for the fact that the universe is so nearly flat today ($\Omega_{tot} = 1.000 \pm 0.011$ [5]) and the near isotropy of CMB almost demands that the universe has gone through a rapid inflation. The traditional view, however, is that some vacuum energy $V(\phi)$ drives inflation due to the existence of a self-interacting scalar field ϕ. That is, the energy density of the cosmic fluid in the early universe becomes $\rho_\phi = \dot{\phi}^2/2 + (\nabla\phi)^2 + V(\phi)$, and the inflaton field ϕ evolves according to a damped harmonic-oscillator-like equation of motion: $\ddot{\phi} + 3H\dot{\phi} - \nabla^2\phi + dV/d\phi = 0$. As the universe expands, H is large and $\dot{\phi}$ becomes small. It is trapped in the slowly varying $V(\phi)$ dominated regime and the scale factor grows exponentially.

The biggest unknown in this paradigm is the form of $V(\phi)$. The simplest form $V(\phi) = (m/2)\phi^2$ may be motivated by the Kahler potential in string theory, however, almost any form for the potential works except a fourth order potential $[V(\phi) = (\lambda/4)\phi^4]$. In [13] we looked at an intriguing form for inflation called *quintessential inflation*. This is an attempt to reduce the inflation potential problem, the baryogenesis question, and the dark energy mystery into a single paradigm which involves non-minimal coupling between matter and gravity as the universe makes a transition from an inflation driving potential to a dark-energy producing quintessence. Big bang nucleosynthesis significantly constrains this paradigm as the non-minimal couplings lead to an excess energy density in gravity waves which alter the results of BBN.

Is there Evidence for Large Extra Dimensions?: In M-theory the universe can be represented by two manifolds separated by a large extra dimension. It is possible that the extra dimension could manifest itself on the dynamics of the universe and BBN [23]. For example, in a Randall-Sundrum II [24] brane-world cosmology, the cosmic expansion for a 3-space embedded in a higher dimensional space can be written [23] as

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} + \frac{\kappa_5^4}{36}\rho^2 + \frac{\mu}{a^4} \ , \tag{2.1}$$

where the four-dimensional gravitational constant $G_{\rm N}$ is related to κ_5 the five-dimensional gravitational constant, i.e. $G_{\rm N} = \kappa_5^4 \lambda / 48\pi$, with λ the intrinsic tension of the brane. The fourth term arises from the imposition of a junction condition for the scale factor on the surface of the brane, and is not likely to be significant. The fifth term, however, scales just like radiation with a constant μ and is called the *dark radiation*. Its magnitude and sign derives from the projection of curvature in higher dimensions onto four-dimensional space-time. Because this dark radiation scales as a^{-4} it can affect both BBN and the CMB. It can significantly improve [23] the fit to BBN abundances and the CMB if μ is negative.

When and how was the dark energy created?: There are a variety of models for the dark energy besides that of a simple cosmological constant. Dark energy is often attributed to a vacuum energy in the form of a "quintessence" scalar field which must be slowly evolving along an effective potential. A quintessence or *k*-essence field is of interest as it can be constrained by both BBN and the CMB [13]. However, the simple coincidence that both of dark matter and dark energy currently contribute comparable mass energy toward the closure of the universe begs the question as to whether they could be different manifestations of the same physical phenomenon. We reviewed our investigations of this in [25] and found that this is possible if the dark matter is inflowing form a higher dimension, or the dark matter generates a cosmic bulk viscosity. It is not yet clear, however, whether an inhomogeneous distribution of dark matter can produce relativistic corrections to the Friedmann equation (1.1) that lead to a dark-energy like term [25].

Is there evidence of supersymmetric matter in the early universe?: Recent observations [26] indicate that ^{6}Li in metal poor stars appears to be primordial and at an abundance a factor of $\sim 10^3$ larger than that expected from BBN. At the same time ^{7}Li is as much as a factor of 3 below the BBN expectation. These two lithium abundance anomalies might be a manifestation of the existence of new unstable particles which decay during and/or after the big bang ([27]).

Several recent papers [28, 29] have also considered heavy negatively charged decaying X^- particles (the supersymmetric partner of the tau) that modify BBN. The heavy X^- particles bind to the nuclei produced in BBN. The massive X^- particles reduce the reaction Coulomb barriers and enhance the thermonuclear reaction rates, extending the duration of BBN to lower temperatures. This can lead to a a large enhancement of the ^{6}Li abundance [29] (for example by the $^4{\rm He}_X(d,X^-)^6{\rm Li}$ reaction, while depleting ^{7}Li.

Is there evidence of a QCD phase transition?: Many papers [2] have considered the possibility that BBN could constrain the details of a first order QCD transition in the early universe. However, recent WMAP limits on the baryon-to-photon ratio imply such tight constraints on the the allowed inhomogeneous big bang parameters and nucleosynthesis [30], that it is probably not possible to have a significant effect on BBN from a primordial QCD transition.

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