Is The Universal Matter - Antimatter Asymmetry Fine Tuned?

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Abstract

The asymmetry between matter and antimatter (baryons and antibaryons or nucleons and antinucleons, along with their accompanying electrons and positrons) is key to the existence and nature of our Universe. A measure of the matter - antimatter asymmetry of the Universe is provided by the present value of the universal ratio of baryons (baryons minus antibaryons) to photons (or, the ratio of baryons to entropy). The baryon asymmetry parameter is an important physical and cosmological parameter. But how fine tuned is it? A “natural” value for this parameter is zero, corresponding to equal amounts of matter and antimatter. Such a Universe would look nothing like ours and would be unlikely to host stars, planets, or life. Another, also possibly natural, choice for this dimensionless parameter would be of order unity, corresponding to nearly equal amounts (by number) of matter (and essentially no antimatter) and photons in every comoving volume. However, observations suggest that in the Universe we inhabit the value of this parameter is nonzero, but smaller than this natural value by some nine to ten orders of magnitude. In this contribution we review the evidence, observational as well as theoretical, that our Universe does not contain equal amounts of matter and antimatter. An overview is provided of some of the theoretical proposals for extending the standard models of particle physics and cosmology.

*Following the untimely death of Gary Steigman, the second author was brought in to complete this chapter. He has endeavored to adhere as closely as possible to the original format and spirit of the manuscript constructed by the first author.
in order to generate such an asymmetry during the early evolution of the Universe.

Any change in the magnitude of the baryon asymmetry parameter necessarily leads to a universe with physical characteristics different from those in our own. Small changes in this parameter will barely affect cosmic evolution, while large changes might alter the formation of stars and planets and affect the development of life. The degree of fine tuning in the baryon asymmetry parameter is determined by the width of the range over which it can be varied and still allow for the existence of life. Our results suggest that the baryon asymmetry parameter can be varied over a very wide range without impacting the prospects for life; this result is not suggestive of fine tuning.

We note that according to those extensions of the standard models of particle physics and cosmology that allow for a nonzero baryon number, the Universe began with zero baryon number, at a time (temperature) when baryon number was conserved. As the Universe expanded and cooled, baryon number conservation was broken at some high temperature (mass/energy) scale and a nonzero baryon number was created. However, even though baryon nonconservation is strongly suppressed at late times (low temperatures), baryon number is not conserved, so matter (protons, the lightest baryons) might eventually decay, with the baryon number reverting back to zero. Ashes to ashes, dust to dust, the Universe began with zero baryon number and may well end that way.

1 Introduction and Overview

The asymmetry between matter and antimatter (baryons and antibaryons or nucleons and antinucleons, along with their accompanying electrons and positrons) is key to the existence and nature of our Universe. Any causal Lorentz-invariant quantum theory allows for particles to come in particle-antiparticle pairs. The discovery of the antiproton \[1\] in 1955 quickly stimulated serious consideration of the antimatter content of the Universe \[2,3\] and led to constraints on the amount of antimatter based on the astrophysical effects of interacting matter and antimatter \[4\]. At the time, and for many years after, the prevailing view in the physics community was that baryon number (the quantum number that distinguishes baryons and antibaryons) was absolutely conserved, and this assumption led to two differing points of
Either the Universe is and always has been symmetric between matter and antimatter, or the Universe is and always has been asymmetric, with an excess of matter over antimatter that has remained unchanged from the beginning of the expanding Universe (the big bang). Those who believed the Universe to be symmetric between matter and antimatter were undeterred by the fact that that the only antimatter seen up to that time (not counting positrons) was the handful of antiprotons created in collisions at high energy accelerators. Those who believed the Universe to be asymmetric had to come to grips with the dilemma of creating such a Universe if the laws of physics dictated that particles are always created (and destroyed) in pairs and that baryon number is absolutely conserved.

Most ignored this dilemma. Andrei Sakharov [5] did not. To set the stage for Sakharov’s seminal work, it is useful to recall the 1965 discovery of the cosmic microwave background (CMB) radiation [6, 7], which transformed the study of cosmology from philosophy and mathematics to physics and astronomy. It quickly became clear that the discovery of the radiation content of the Universe, along with its observed expansion, ensured that very early in its evolution, when the temperature and densities (both number and energy densities) were very high, collisions among particles would be very rapid and energetic and, at sufficiently high temperatures, particle-antiparticle pairs would be produced (and would annihilate). Sakharov explored the requirements necessary for such high energy collisions in the early Universe to create a matter-antimatter asymmetry if none existed initially. Sakharov’s recipe for cooking a universal baryon asymmetry has three ingredients. One obvious condition is that baryon number cannot be absolutely conserved; baryon number (B) conservation must be violated. Although the standard model of particle physics at the time did not allow for violation of baryon number conservation, the later development of grand unified theories (GUTs) did. Sakharov also noted that the discrete symmetries of parity (P) and charge conjugation (C), replacing particles with antiparticles, or of CP, would need to be broken as well. Current models, in agreement with accelerator data, do allow for P and CP violation. Sakharov’s third ingredient is not from particle physics, but from cosmology, relying on the expansion of the Universe. The third ingredient in the recipe requires that thermodynamic equilibrium not be maintained when the B, P, and CP violating collisions occur in the early Universe. Although at the time of Sakharov’s work there was no evidence that conservation of B and CP were violated, it was already known that parity is not conserved in the weak interactions and that the expansion of the
Universe could possibly provide the required departure from thermodynamic equilibrium. Sakharov set the stage for consideration of a Universe with unequal amounts of matter and antimatter. We will revisit Sakharov’s three conditions for baryogenesis in §4.

In the hot, dense thermal soup of the very early Universe, matter and antimatter (baryons and antibaryons) are as abundant as all the other particles whose mass is less than the temperature. As the Universe expands and cools, particle-antiparticle pairs annihilate, leaving behind only the lightest particles, along with any particle-antiparticle pairs that evaded annihilation in the early Universe or, perhaps, in an asymmetric Universe, an initial matter excess that escaped annihilation. In the late Universe, when the temperature (in energy units) is far below the masses of the unstable particles of the standard model (SM) of particle physics, only photons and the lightest stable (or very long lived) SM particles remain: nucleons (and possibly antinucleons), electrons (and possibly positrons), and the three SM neutrinos. In cosmology it is conventional to refer to all ordinary matter consisting of nucleons and electrons (nuclei, atoms, and molecules), as “baryons” (B) to distinguish it from dark matter (DM). Electrons are not baryons, but their (very small) contribution to the present-day matter density is included in this definition of the baryon density. The photons and neutrinos are often referred to as “radiation”. The matter-antimatter asymmetry is the difference between the numbers of baryons and antibaryons. Since this is an extensive quantity, scaling with the size of the volume considered, it is useful to introduce the ratio (by number) of baryons to photons to quantify the size of any matter-antimatter asymmetry. The ratio of the baryon (minus the antibaryon) and photon number densities, $\eta_B = n_B/n_\gamma$, provides a measure of the matter-antimatter asymmetry of the Universe. However, as the Universe expands and cools, the heavier, unstable SM particles annihilate and decay, increasing the number of photons $N_\gamma$ in a comoving volume $V$, where $N_\gamma = n_\gamma V$, while the baryon number in the same comoving volume is unchanged (at least during those epochs when baryons are conserved). Instead, it is the entropy, $S = sV$, in the comoving volume, not the number of photons, that is conserved as the Universe expands adiabatically. The entropy and the number of photons in a comoving volume are related by $S = 1.8g_sN_\gamma$, where the total entropy is related to the entropy in photons alone by $S \equiv (g_s/2)S_\gamma$.

1Throughout this article the terms baryons, nucleons, ordinary matter, and normal matter are used interchangeably.
and \( S_\gamma = 4/3(\rho_\gamma/T)V = 4/3(\langle E_\gamma \rangle/T)N_\gamma \) and \( \langle E_\gamma \rangle = 2.7 T \). The quantity \( g_s = g_s(T) \) counts the number of degrees of freedom contributing to the entropy at temperature \( T \). For the SM of particle physics, with three families of quarks and leptons, at temperatures above the mass of the heaviest SM particle (the top quark), \( g_s \approx 427/4 \). For temperatures below the electron mass, after the three flavors of weakly interacting neutrinos have decoupled and the photons have been heated relative to the neutrinos by the annihilation of the \( e^\pm \) pairs, \( g_s \rightarrow g_{s0} \approx 43/11 \). As a result, as the Universe cools from above the top quark mass to below the electron mass, the number of photons in a comoving volume increases by a factor of \( \approx 27 \), and the baryon to photon ratio is diluted by this same factor. In an adiabatically expanding Universe (as ours is assumed to be) the entropy in a comoving volume is conserved, along with the net number of baryons minus antibaryons (during those epochs when baryon number nonconservation is strongly suppressed). Therefore, the ratio of baryon number to entropy, \( N_B/S = n_B/s \), provides a measure of the baryon asymmetry whose value is unchanged as the Universe expands and cools. Evaluated in the late Universe, after \( e^\pm \) annihilation is complete, \( s/n_\gamma \rightarrow (s/n_\gamma)_0 = 1.8 g_{s0} \approx 7.0 \), so that \( n_B/s \approx \eta_B/7.0 \). Consistent with most of the published literature, \( \eta_B \) is evaluated here in the late Universe, so that \( \eta_B \equiv \eta_{B0} \equiv (n_B/n_\gamma)_0 \). In the discussion here \( \eta_B \) and \( n_B/s \) will both be referred to as the “baryon asymmetry parameter.”

In a matter-antimatter symmetric Universe the baryon asymmetry parameter \( \eta_B = 0 \). For a quantity that could, in principle, have any value between \(-\infty\) and \(+\infty\), zero might seem to be a “natural” choice.

When is a physical parameter, such as the baryon asymmetry parameter, considered to be fine tuned? The criteria for answering this question, along with a discussion of the degeneracies with other physical parameters, are discussed in §2. In §3 the overwhelming observational and theoretical evidence that our Universe is not matter-antimatter symmetric is reviewed, excluding the natural choice of \( \eta_B = 0 \). Faced with the necessity that a Universe hosting stars, planets, life requires \( \eta_B \neq 0 \), §4 provides an overview of the multitude of particle physics (and cosmology) models proposed to generate a nonzero baryon asymmetry during the early evolution of the Universe. These models are capable of generating a baryon asymmetry that is much smaller

\[ \text{In a Universe with more “matter” than “antimatter”, } \eta_B > 0. \text{ For the opposite case, where } \eta_B < 0, \text{ the definitions of matter and antimatter could be interchanged. Therefore, without loss of generality, it is assumed here that } \eta_B \geq 0. \]
or much larger than that observed in our Universe, suggesting that there might be universes with almost any nonzero values of $\eta_B$. In an asymmetric Universe the quantitative value of the baryon asymmetry parameter plays an important role in primordial nucleosynthesis (big bang nucleosynthesis: BBN), regulating the abundances of the nuclides produced in the early Universe, before any stellar processing. BBN is reviewed for a large range of $\eta_B$ in §5. The degeneracy of the baryon asymmetry parameter with other cosmological parameters is discussed in §6 and a variety of alternate cosmological models allowing for a range of $\eta_B$ values are presented in §7. The criterion used here to judge the viability of alternate cosmological models is whether their universes are capable of hosting stars, planets, and life. Our results and conclusions are summarized in §8.

2 Definition of Fine-Tuning of the Baryon Asymmetry Parameter

How fine-tuned is the baryon asymmetry parameter? Here we will adopt a definition of fine tuning based on the capability of the Universe to harbor life. Clearly, small changes in the asymmetry parameter will have little effect on cosmic evolution. However, large changes in this parameter will have major effects, notably altering the production of elements in the early universe and changing the process of structure formation through the growth of primordial density perturbations. We will see that the former, even in extreme cases, is unlikely to have any effect on the development of life in the Universe, while the latter can have profound effects. In particular, if the process of galaxy and star formation is too inefficient, then there will be no planetary systems to harbor life. One must be cautious, of course, in defining the limits on environments that can support life; our argument will be based on life as we observe it, which exists on planets orbiting stars. It is always possible that more extreme environments might harbor life in ways that we have not considered; for example, Avi Loeb has pointed out that the cosmic microwave background can provide an energy source for life when the universe was only 10 million years old and the temperature of the CMB was between the freezing and boiling points of water [9]. While we will not consider such extreme possibilities here, caution is always advised when defining the conditions needed for the existence of life.
The extent to which the value of $\eta_B$ is fine tuned will depend on how widely it can be varied while still allowing for the existence of life. The issue of the fine-tuning of $\eta_B$ is not, of course, a true-false question: the best we can do is to determine an allowed range for $\eta_B$. The width of this range can then suggest the plausibility (or lack thereof) of the need for special initial conditions or special values for the underlying fundamental parameters that determine $\eta_B$. But the question, “Is the baryon asymmetry parameter fine tuned?” does not have a yes or no answer.

In considering the variation of one or more physical parameters, a choice must be made: do we consider the variation of the baryon asymmetry parameter alone, or do we allow other parameters to vary at the same time? In the latter case changes in the value of one parameter may be compensated, at least in part, by changes in other parameters.

As an example, consider the way in which the relation between the baryon to entropy ratio and the baryon to photon ratio depends on the number of neutrino flavors, as well as on the neutrino decoupling temperature, which depends in turn on the strength of the weak interactions. In an alternate Universe where there are $N_\nu$ flavors of neutrinos, instead of the SM value of $N_\nu = 3$, $g_{s0} = 43/11 + 7(N_\nu - 3)/11 = 43/11(1 + 7(N_\nu - 3)/43)$ and $g_{\rho0} = 3.36 + 0.454(N_\nu - 3) = 3.36(1 + 0.135(N_\nu - 3))$. For these results it has been assumed that when $N_\nu \neq 3$, the usual weak interactions are unchanged and all neutrinos decouple when $T_{\text{dec}} \gg m_e$ (but $T_{\text{dec}} \ll m_\mu$), so that $(T_\nu/T_\gamma)_0 \approx 4/11$. With these caveats, for $N_\nu \neq 3$, the late time entropy per photon is $(s/n_\gamma)_0 \approx 7.0(1 + 7(N_\nu - 3)/43)$ and the relation between $\eta_B$ and $n_B/s$ is changed,

$$\eta_B = (n_B/n_\gamma)_0 \approx 7.0(1 + 7(N_\nu - 3)/43) (n_B/s). \quad (1)$$

For example, in an alternate Universe with only one neutrino flavor ($N_\nu = 1$), $\eta_B \approx 4.7(n_B/s)$, while in one with eight flavors of neutrinos, ($N_\nu = 8$)$^3$, $\eta_B \approx 12.8(n_B/s)$.

In general, allowing multiple parameters to vary simultaneously will weaken the constraints provided when only one of them is varied, an issue that is likely to be an issue with many of the other essays in this volume. For

$^3$For $N_\nu \leq 8$, QCD is asymptotically free, allowing for quark confinement and bound nuclei$^8$. 

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example, consider the atomic energy scale,

$$\epsilon \equiv \mu_H c^2 \alpha^2 = \left( \frac{m_e m_p}{m_e + m_p} \right) e^2 \left( \frac{e^2}{\hbar c} \right)^2,$$

(2)

where $\mu_H$ is the reduced mass of the proton-electron system, and the fine structure constant is $\alpha = e^2/\hbar c \approx 1/137$ (when measured at low energies). For $m_e c^2 \approx 0.51 \text{ MeV}$ and $m_p \approx 0.94 \text{ GeV}$, $\epsilon \approx m_e c^2 \alpha^2 \approx 27 \text{ eV}$. Since $\epsilon$ is not a dimensionless parameter, perhaps it is the dimensionless parameter $\epsilon/\mu_H c^2 = \alpha^2 \approx 5.3 \times 10^{-5}$ that is fundamental. Suppose that $\alpha$ and $\mu_H c^2$ are allowed to change, while the atomic energy scale, $\mu_H c^2 \alpha^2$, is kept unchanged. For example, $m_e$ and $m_p$ might change while $m_e/m_p \ll 1$ might be (nearly) unchanged. Atomic energy levels will be largely unchanged while nuclear energies will be changed. How much freedom is there to change $\alpha$ along with other fundamental parameters (e.g., $m_e$, $m_p$, $m_e/m_p$), while leaving most of “ordinary” atomic and nuclear physics unchanged? This issue of “degeneracy” among physical parameters will rear its head in the subsequent discussion of the fine tuning of the baryon asymmetry of the Universe. When exploring model universes with different values of $\eta_B$, we will keep all other parameters (e.g., $\alpha$, $m_e/m_p$, $N_\nu$, etc.) fixed. However, we need to remain aware that the results presented here can be considerably altered if multiple parameters are simultaneously varied.

3 The Case Against a Symmetric Universe

Over the years, experiments at ever higher energies have confirmed that particles are created (and annihilated) in pairs and that in all collisions studied so far, baryon (and lepton) number is conserved. Perhaps only at the very highest energies, inaccessible to the current terrestrial accelerators, or in searches for proton decay, will nonconservation of baryon (and lepton) number be revealed. However, it is not unreasonable to ask how our present Universe would differ if baryon number were absolutely conserved. A complementary approach is to ask what astrophysical observations can tell us about the amount of antimatter (if any) in gas, stars, galaxies, and clusters of galaxies in the current Universe (e.g., [4]). These two approaches are explored here. The discussion here is based on several earlier papers by the first author (e.g., [10, 11, 12, 13, 14]); the reader is urged to see those papers for details and for many further references.
3.1 The Observational Evidence Against a Symmetric Universe

To paraphrase remarks by the first author in a 1976 review of the status of antimatter in the Universe [12], it is quite easy to determine if an unknown sample is made of matter or antimatter. The most rudimentary detector will suffice. Simply place your sample in the detector and wait. If the detector disappears (annihilates), your sample contained antimatter. Indeed, if you had handled your sample, you would have already known the answer. Astrophysical sources have been repeating this experiment over cosmological times. The first lunar and Venus probes confirmed that the Moon and Venus are made of matter, not antimatter. Indeed, the solar wind, sweeping past the planets of the solar system revealed, by the absence of annihilation gamma rays, that the Sun and the planets, and other solar system bodies are all made of what we have come to define as matter. Were any of the planets made of antimatter, they would be the strongest gamma ray sources in the sky (if they hadn’t already annihilated away). As may be inferred from the discussion below in §3.2, if there were any antimatter in the material (the pre-solar system gas cloud) that collapsed to form the planets and other solid body objects in the solar system, it would have annihilated away long before the solar system formed. The same is true for the stars in our Galaxy. On theoretical grounds, is is highly unlikely that in a Universe some 14 Gyr old, there are any non-negligible amounts of antimatter surviving in our Galaxy.

In a typical nucleon-antinucleon annihilation, $\sim 5-6$ pions are produced. The pions decay to muons, neutrinos, and photons and the muons decay to electrons ($e^\pm$ pairs) and neutrinos. The $e^\pm$ pairs may annihilate in flight or, being tied to local magnetic fields, they may lose energy by Compton emission and annihilate nearly at rest (producing a characteristic 511 keV line) [4]. Photons from matter-antimatter annihilations provide the most sensitive, albeit indirect, probe of the presence of antimatter, mixed with ordinary matter, on galactic and extragalactic scales. In the Galaxy, gas (clouds of atomic or molecular gas) and stars are inevitably mixed. If either contained significant amounts of antimatter, the result would be annihilation, along with the corresponding production of gamma rays. The lifetime against annihilation of an antiparticle (e.g., an antiproton) in the gas in the interstellar medium (ISM) of the Galaxy is very short, $t_{ann} \approx 300$ yr [12]. It is therefore not surprising that observations of galactic gamma ray emission set very strong constraints on the antimatter fraction in the ISM, $f_{ISM} \lesssim 10^{-15}$ [12].
There can be no significant amounts of antimatter in the gas in the Galaxy.

What about antistars? When gas collapses to form stars, the annihilation rate grows as the number density while the collapse rate increases only as the square root of the density. As a result, unless there were no normal matter in the gas that might collapse to form an antistar, the antistar would never form. Setting this aside, let us suppose that antistars had somehow formed in the Galaxy. As the gas in the ISM flowed past these antistars, there would be annihilation, resulting in gamma rays. Using by now outdated (40 year old!) gamma ray data, the first author [12] determined that the absence of gamma rays indicated that the nearest antistar in the Galaxy is at least 30 pc away. This result sets an upper limit on the total number of antistars, \( N \), that could be in the Galaxy: \( N < 10^7 \), a small fraction of all the stars in the Galaxy. Although more recent gamma ray data can refine these bounds, the old data were already sufficiently strong to argue against any significant amounts of antimatter in the Galaxy.

Galactic cosmic rays, coming to us from outside of the solar system, provide a valuable direct probe of antimatter in the Galaxy. Whatever the sources of the galactic cosmic rays, the discovery of antinuclei in the cosmic rays would provide direct evidence (a “smoking gun”) for the presence of antimatter in the Galaxy (for more details, but obsolete data, see the discussion in [12]). The antiproton would be the lightest antinucleus, but in high energy collisions between cosmic rays and interstellar gas, some “secondary” antiprotons will be produced. Indeed, antiprotons have been observed in the cosmic rays, but their numbers are consistent with a secondary origin. However, production of more complex antinuclei in high energy cosmic ray - interstellar gas collisions (secondary antinuclei) is strongly suppressed and, to date, no antideuterons [15] or antialpha [16] particles have been detected in the cosmic rays. For example, the 1999 AMS upper bound [16] to the cosmic ray antihelium to helium ratio is \( < 10^{-6} \), providing a strong supplement to the gamma ray data suggesting our Galaxy has no significant amounts of antimatter. The absence of primary antinuclei in the cosmic rays is evidence that the sources of the galactic cosmic rays contain little, if any, antimatter (indeed, if there were some antimatter mixed with a predominant amount of ordinary matter in the cosmic ray sources, they likely would have annihilated over the lifetimes of the sources).

What of external galaxies or extragalactic high luminosity sources such as AGNs or QSOs? If annihilations deposit their energy locally, then the gamma ray flux and the luminosity of an annihilation-powered source are connected
If \( \Phi_\gamma \) is the photon flux from annihilations (photons cm\(^{-2}\) s\(^{-1}\)) and \( \Phi_E \) is the energy flux from the same source (ergs cm\(^{-2}\) s\(^{-1}\)), then \( \Phi_\gamma \gtrsim 10^4 \Phi_E \).

Although annihilation was proposed as a panacea for the energy budgets of QSOs and other high luminosity sources, the detailed emission mechanisms required enormous magnetic fields, compounding the problems of an already stretched energy budget. Steigman and Strittmatter explored whether observations of the annihilation neutrino flux could constrain models of annihilation-driven infrared emission in Seyfert galaxies. For individual sources, it was estimated that the neutrino flux would be at least five orders of magnitude smaller than was observed at the time. The difficulty of detecting the relatively low energy (\( \gtrsim 500 \text{ MeV} \)) neutrinos, combined with improved models for the energy sources in QSOs, Seyferts, etc. have made annihilation neutrinos an unlikely probe.

Moving further away, outside our own galaxy, the strongest constraints come from observations of x-ray emitting clusters of galaxies. Most of the baryons in clusters of galaxies are in the hot intracluster gas. The same collisions between particles in the intracluster gas responsible for producing the observed x-ray emission would result in annihilation gamma rays if some fraction of the gas consisted of antiparticles. The virtue of using x-ray emitting clusters of galaxies is that there is a direct proportionality between the x-ray emission from thermal bremsstrahlung and gamma ray emission from annihilation. This approach leads to bounds on the antimatter fraction (the fraction of antimatter mixed with ordinary matter) on the largest scales in the Universe (\( M \sim 10^{14} - 10^{15} M_\odot, R \sim \text{few Mpc} \)). Using data from 55 x-ray emitting clusters of galaxies in combination with the upper bounds to the gamma ray fluxes, it was found that the antimatter fraction from that sample is limited to \( f < 10^{-6} \). However, even stronger bounds exist for some individual clusters. For the Perseus cluster, \( f < 8 \times 10^{-9} \) and for the Virgo cluster, \( f < 5 \times 10^{-9} \). Perhaps the most interesting upper bound on antimatter on the largest scales comes from colliding clusters. Analysis of the Bullet Cluster gives \( f < 3 \times 10^{-6} \) on the scale \( M \sim 3 \times 10^{15} h^{-1} M_\odot \), where \( h \) is the Hubble parameter in units of 100 km sec\(^{-1}\) Mpc\(^{-1}\).
3.2 The Problem of a Symmetric Universe

Very shortly after the discovery of the CMB [6, 7], Ya. B. Zeldovich [19] and H. Y. Chiu [20], independently, considered the fate of matter and antimatter emerging from the early stages of the evolution of a hot Universe. The result, whose derivation is outlined here, is easily summarized. At high temperatures, above the quark-hadron transition, there are many quark-antiquark pairs and, in a symmetric Universe, there are equal numbers of quarks and antiquarks. As the Universe expands and cools, the quarks (and gluons) are confined into nucleons (neutrons and protons) which, because the strong interaction is strong, are in thermal equilibrium with the cosmic plasma (e.g., photons, neutrinos, and the light leptons and bosons). In this regime the nucleon mass exceeds the temperature so that annihilation of nucleon-antinucleon pairs proceeds on a timescale short compared to the expansion rate of the Universe. But, since \( m \gg T \), creation of new nucleon-antinucleon pairs from collisions in the background plasma is strongly (exponentially) suppressed, so that up to spin-statistics factors of order unity, the ratio of nucleons (and antinucleons) to photons is \( n_N/n_\gamma = n_\bar{N}/n_\gamma = n_{eq}/n_\gamma \propto (m/T)^{3/2} e^{-(m/T)} \ll 1 \). Even though the abundances of nucleons and antinucleons (e.g., relative to photons) are very small, the strong interaction is strong, ensuring that \( n_N \approx n_{eq} \) is maintained down to very low temperatures, \( T \ll m_N \). However, eventually the abundance of the nucleon-antinucleon pairs becomes so small that they no longer can find each other to annihilate (and the creation of new pairs is exponentially suppressed), and the abundance of nucleons (and antinucleons) “freezes out,” at a “relic” abundance \( (n_N/n_\gamma)_0 \). The evolution of the nucleon-antinucleon abundances follows an evolution equation, described next, that accounts for creation, annihilation, and the expansion of the Universe. The solution, presented below, shows that the relic abundance of the nucleon-antinucleon pairs in a symmetric Universe is some nine orders of magnitude smaller than the nucleon abundance observed in our Universe, providing an important nail in the coffin of the symmetric Universe.

As first derived from an argument of detailed balance by Zeldovich [19] and later rediscovered and supported by many textbook derivations based on the Boltzmann equation, the evolution of the abundance of a particle (and its antiparticle) produced and annihilated in pairs, is described by the

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\footnote{It is interesting that Zeldovich’s article was written prior to the discovery of the CMB. As a result, in his review, Zeldovich considered both hot and cold universes.}
standard evolution equation (SEE); see, e.g., \[10, 12, 13, 20, 21, 22, 23, 24\] and references therein. For equal numbers of particles and antiparticles (no asymmetry, zero chemical potential), the SEE may be written as

\[
\frac{1}{V} \left( \frac{dN}{dt} \right) = \frac{dn}{dt} + 3Hn = \langle \sigma v \rangle (n_{eq}^2 - n^2), \tag{3}
\]

where \(N = nV\) is the number of particles (and antiparticles) in a comoving volume \(V\). As the Universe expands and the cosmic scale factor, \(a\), increases, the comoving volume grows as \(V \propto a^3\). In Eq. (3), the number density of particles and antiparticles is \(n\), the total annihilation cross section is \(\langle \sigma v \rangle\), and \(H = a^{-1}(da/dt)\) is the Hubble parameter. The SEE is a form of the Ricatti equation, for which there are no known closed form solutions except in special cases. Although the SEE may be integrated numerically, here the approximate analytic approach first outlined by Zeldovich \[19\] and employed extensively in \[12, 13, 21, 22, 23, 24\] and elsewhere, is followed.

For the approximate analytic solution to the SEE it is convenient to write \(n = (1 + \Delta)n_{eq}\) where, in the nonrelativistic (NR) regime \((T < m)\), \(n_{eq} = (gT^3/(2\pi)^{3/2})x^{3/2}e^{-x}f(x)\), where \(x \equiv m/T\) and \(g = 2\) is the number of spin states of the proton (neutron) and of the antiproton (antineutron). Here \(f(x)\) is an asymptotic series in \(x\) for which \(f(x) \to 1\) as \(x \to \infty\). For the range of \(x\) of interest in tracking the evolution of nucleon-antinucleon pairs, \(f(x) \approx 1\) is a very good approximation. Therefore, the evolution of the equilibrium number density (as a function of \(x\)) in the NR regime is very well described by \(n_{eq} \propto T^3x^{3/2}e^{-x} \propto x^{-3/2}e^{-x}\). Note that since the photon number density varies as \(T^3\), \(n_{eq}/n_\gamma \propto x^{3/2}e^{-x}\) in the NR regime. Instead of following the time evolution of the thermal relic abundance, it is more convenient to track its evolution as a function of \(x\). Neglecting small logarithmic corrections involving derivatives related to the entropy and photon densities, the derivatives with respect to time and \(x\) (or \(T\)) are related by

\[
dt \approx \frac{1}{H} \left( \frac{dx}{x} \right) \approx -\frac{1}{H} \left( \frac{dT}{T} \right), \tag{4}
\]

where \(H = H(T)\) is the Hubble parameter evaluated at temperature \(T\). Now we define the quantity \(g_\rho(T)\) (in analogy to \(g_s\)) by \(g_\rho/2 \equiv \rho/\rho_\gamma\), where \(\rho\) is the total mass/energy density and \(\rho_\gamma\) is the energy density in photons alone. During those epochs in the evolution of the Universe when the energy density is dominated by the contribution from relativistic particles (radiation
dominated: RD), $H \propto \rho_R^{1/2} \propto g_\rho^{1/2} \rho_\gamma \propto g_\rho^{1/2} T^2$. In terms of $\Delta$ and $x$, the SEE may be rewritten as

$$\frac{d(\ln(1+\Delta)N_{eq})}{d(\ln x)} = -\left(\frac{\Gamma_{eq}}{H}\right) y,$$

where $\Gamma_{eq} \equiv \langle \sigma v \rangle n_{eq}$ and $y \equiv \Delta (2 + \Delta)/(1 + \Delta)$.

For $x \sim O(1)$ ($m \approx T$), $\Delta$ is very small and $n = n_{eq}$ is a very good approximation. As the Universe expands and cools, $x$ increases and $\Delta$ grows exponentially (while $n_{eq}$ decreases exponentially), and the departure from equilibrium grows. Define $x_*$ to be the value of $x$ for which $\Delta(x_*) \equiv \Delta_* \sim O(1)$, so the true abundance, $n_*$, exceeds the equilibrium density, $n_{eq}$, by factor $1 + \Delta_*$ > 1. (A more precise definition of $x_*$ is given below). For $x > x_*$, $\Delta \sim \Delta_*$ and $n/n_{eq} > 1$ increases. In this regime, where $n > n_{eq}$, the SEE simplifies,

$$\frac{dN}{dt} = \langle \sigma v \rangle (n_{eq}^2 - n^2) V \approx -\langle \sigma v \rangle n^2 V = -\langle \sigma v \rangle N^2/V.$$

This equation can be integrated directly from $t = t_*$ (when $T = T_*$ and $x = x_*$) to $t = t_0$ (when $T = T_0 \ll T_*$ and $x \gg x_*$). Replacing the evolution with time (or with $x$) by the evolution with temperature,

$$\frac{dN}{N^2} \approx \frac{\langle \sigma v \rangle dT}{VT},$$

where the Hubble parameter varies as $H \approx H_* (T/T_*)^2$ and the comoving volume increases with decreasing temperature as $V \approx V_* (T_*/T)^3$. Integrating from $T = T_*$ to $T = T_0 \ll T_*$ results in

$$N_0/N_* = [1 + (\Gamma/H)_*]^{-1},$$

where $\Gamma_* = n_* \langle \sigma v \rangle$. For nucleon-antinucleon annihilation, $(\Gamma/H)_* \gg 1$, so that $N_0/N_* \approx (\Gamma/H)_*^{-1} \ll 1$. When $T = T_*$ ($x = x_*$), the number of particles (neutrons or protons) in the comoving volume, $N_*$, may be compared to the number of photons in the same volume, $N_{\gamma*}$,

$$\left(\frac{N}{N_{\gamma*}}\right)_* = \left(\frac{n}{n_{\gamma*}}\right)_* = \left(\frac{H}{n_* \langle \sigma v \rangle}\right)_* \left(\frac{\Gamma}{H}\right)_*.$$

In terms of $x_*$,

$$\left(\frac{H}{n_{\gamma*} \langle \sigma v \rangle}\right)_* = 6.5 \times 10^{-36} g_\rho^{1/2} x_*,$$

(10)
where $m$ is in GeV and $\langle \sigma v \rangle$ is in cm$^3$s$^{-1}$. As the Universe expands and cools from $T = T_*$ to $T = T_0$, the surviving nucleon (and antinucleon) abundance(s) decrease to an asymptotic (“frozen out”) value (ratio to photons) given by,

$$\left( \frac{N}{N_\gamma} \right)_0 = \left( \frac{N}{N_\gamma} \right)_* \left( \frac{N_0}{N_*} \right) \left( \frac{N_{\gamma\gamma}}{N_{\gamma\gamma}} \right)_*,$$

(11)

where, from entropy conservation, $N_{\gamma\gamma}/N_0 = g_{s0}/g_{ss}$. Note that $(N/N_\gamma)_0$ is the frozen out ratio of neutrons or protons to photons (long after annihilation has ceased) and is identical to the ratio of antineutrons or antiprotons to photons. Even though $(N/N_\gamma)_0 \neq 0$, the baryon asymmetry parameter in a symmetric Universe is $\eta_B = 0$. Combining the above equations,

$$\left( \frac{N}{N_\gamma} \right)_0 \approx 2.5 \times 10^{-35} \frac{g_{ps}^{1/2}}{m \langle \sigma v \rangle} \frac{g_{ss}}{g_{ss}} x_*,$$

(12)

where $g_{s0} = 43/11$, corresponding to $N_\nu = 3$, has been adopted. For neutrons or protons (in the approximation here they are assumed to have the same mass, $m \approx 0.94$ GeV), the total (s-wave) annihilation cross section is $\langle \sigma v \rangle \approx 1.5 \times 10^{-15}$ cm$^3$s$^{-1}$, so that

$$(N/N_\gamma)_0 \approx 1.8 \times 10^{-20} (g_{ps}^{1/2}/g_{ss}) x_*.$$

(13)

To find $x_*$ and $T_* = m/x_*$, in order to evaluate $g_{ps} = g_p(T_*)$ and $g_{ss} = g_s(T_*)$, we impose the condition defining $x_*$, that is, when $x = x_*$, $\Delta(x) = \Delta(x_*) \equiv \Delta_*$. Although $\Delta_* \sim O(1)$, a specific choice needs to be made for $\Delta_*$ in order to find the corresponding value of $x_*$ (and it needs to be checked and confirmed that the final result is insensitive to this specific choice). Here, $\Delta_* = 0.618$ (related to the “Golden Mean”) is adopted, so that $y_* = \Delta_*(2 + \Delta_*)/(1 + \Delta_*) = 1$.

It may be verified that $d(\ln(1 + \Delta))/d(\ln x) \ll d(\ln N_{eq})/d(\ln x)$, so that Eq. (5) reduces to

$$-(\Gamma_{eq}/H) y \approx d(\ln N_{eq})/d(\ln x),$$

(14)

---

5Annihilations never really cease. They simply become so rare that they are unable to continue to reduce the relic abundance.

6Even though $T_* \ll m$, the nucleons are moving sufficiently rapidly that Coulomb (Sommerfeld) enhancement of the proton-antiproton annihilation cross section, relative to the neutron-antineutron annihilation cross section, is unimportant.

7For $g_p(T)$ and $g_s(T)$, the results of Laine and Schroeder [25] are used here.
where \( N_{eq} = n_{eq} V \propto VT^3 x^{3/2} e^{-x} \). Generally, \( VT^3 \propto (aT)^3 \approx \text{constant} \), so that the logarithmic derivative of \( VT^3 \), depending on \( d(\ln g_\star)/d(\ln dT) \), may be neglected, further simplifying Eq. (5) to an algebraic equation,

\[
d(\ln N_{eq})/d(\ln x) \approx -(x - 3/2) \approx -(\Gamma_{eq}/H) y.
\]

For \( x = x_\star \), \( \Delta(x_\star) = \Delta_\star = 0.618 \) and \( y = y_\star = 1 \). As a result,

\[
x_\star - 3/2 = (\Gamma_{eq}/H)_\star = n_{eq}\langle \sigma v \rangle/H_\star = A_\star g_{ps}^{-1/2} x_\star^{1/2} e^{-x_\star},
\]

where \( A_\star = 4 \times 10^{34} g m(\sigma v) \); \( g \) is the number of neutron or proton spin states and, as before, the mass \( m \) is in GeV and \( \langle \sigma v \rangle \) is in \( \text{cm}^3/\text{s} \). For \( g = 2 \), \( m = 0.94 \), and \( \langle \sigma v \rangle = 1.5 \times 10^{-15} \), \( A_\star = 1.1 \times 10^{20} \). The transcendental equation for \( x_\star \), Eq. (16), may be solved iteratively. The solution is \( x_\star \approx 43.1 \), corresponding to \( T_\star = m/x_\star \approx 21.8 \text{MeV} \), for which \( g_{ps} \approx 11.5 \) and \( g_{ss} \approx 11.4 \) [25]. Substituting these values into Eq. (13) results in the frozen-out ratios of the surviving numbers of neutrons, protons, antineutrons, and antiprotons to photons,

\[
\left( \frac{n_n}{n_\gamma} \right)_0 = \left( \frac{n_p}{n_\gamma} \right)_0 = \left( \frac{n_n}{n_\gamma} \right)_0 = \left( \frac{n_p}{n_\gamma} \right)_0 \approx 2.3 \times 10^{-19}.
\]

The corresponding nucleon (neutron plus proton) and antinucleon to photon ratios are \( (n_N/n_\gamma)_0 = (n_\bar{N}/n_\gamma)_0 \approx 4.6 \times 10^{-19} \).

Of course, for this symmetric Universe, \( \eta_B \equiv (n_N/n_\gamma)_0 - (n_\bar{N}/n_\gamma)_0 = 0 \). The present mass density of matter (nucleon plus antinucleon) is \( \rho_B = m(n_N + n_\bar{N}) \approx 3.5 \times 10^{-16} \text{GeV cm}^{-3} \), or \( \Omega_B h^2 \approx 3.3 \times 10^{-11} \). In contrast, for our observed asymmetric Universe, where annihilation of any relic antinucleons is very efficient, \( (n_N/n_\gamma)_0 \approx 6.1 \times 10^{-10} \gg (n_\bar{N}/n_\gamma)_0 \approx 0 \) and \( \Omega_B h^2 \approx 0.022 \). In a symmetric Universe the abundance of nucleons surviving annihilation in the early Universe is smaller than the abundance of nucleons in our asymmetric Universe by some nine orders of magnitude.

Notice that when \( T = T_\star \), the ratio of the annihilation rate to the expansion rate is very large, \( (\Gamma/H)_\star \approx (1 + \Delta_\star)(x_\star - 3/2) \approx 67 \gg 1 \). Neither annihilations nor the relic abundances freeze out when \( T = T_\star \). For \( T < T_\star \), annihilations continue to reduce the abundances of nucleons and antinucleons and the ratio of the annihilation rate to the expansion rate, \( \Gamma/H \), continues to decrease. Eventually, for \( T \equiv T_f \approx T_\star/2 \), \( (\Gamma/H)_f = 1 \), and the relic abundances freeze out (although, depending on \( T_f \), the number of photons in the
comoving volume may continue to increase until $T \lesssim m_e$, further reducing the relic baryon to photon ratio). For $T < T_f$, $n_N = n_N = n_{N_f} (T/T_f)^3$. For temperatures even slightly below $T_f$, $(\Gamma/H) \approx H_f/H = (T_f/T)^2 < 1$. Thereafter, the annihilation rate scales as $n\langle \sigma v \rangle \propto T^3$ (for $s$-wave annihilation), while the expansion rate of the Universe scales as $H \propto T^2$ (during radiation dominated epochs in the evolution), so that after freeze out $(T \ll T_f)$, $\Gamma/H \approx T/T_f \ll 1$. During matter dominated epochs in the evolution of the Universe, $H \propto T^{3/2}$, so that $\Gamma/H \propto T^{3/2}$, and it is still the case that $\Gamma/H \ll 1$.

By the same argument, nuclear reactions in this Universe are extremely suppressed by the very low nucleon density. There can be no primordial nucleosynthesis in a symmetric Universe. After freeze out, as the Universe expands and cools, neutrons decay and the Universe is left with protons (and antiprotons) and electrons (and positrons). Note that as the protons and electrons (and antiprotons and positrons) cool and become nonrelativistic, the long-range Coulomb interaction enhances, through Sommerfeld enhancement [27], the annihilation cross section, $\langle \sigma v \rangle \to 2\pi(\alpha c/v)\langle \sigma v \rangle \propto T^{-1/2}$. Even so, the ratio of the annihilation rate to the expansion rate still decreases (as $T^{1/2}$ during RD epochs and as $T$ during MD epochs). Recombination cannot occur in such a low baryon density Universe. In the absence of non-baryonic dark matter, it is unlikely that any collapsed structures (e.g., stars or galaxies) could form in such a low density, ionized Universe. The history (and future) of a symmetric Universe is very bleak. The story barely changes if a symmetric Universe contains non-baryonic dark matter. If, for example, the presence of DM in a symmetric Universe allows collapsed DM structures to form, the relic matter and antimatter would fall into the DM potential wells, increasing their number densities, leading to renewed annihilation, further reducing their already very small abundances. A matter-antimatter symmetric Universe simply bears no resemblance to our Universe.

Even in an asymmetric Universe, during the very early evolution of the Universe when the temperature is very high, the equilibrium abundance of nucleons and antinucleons may be much larger than the relic abundance of nucleons in our Universe, $\eta_B = (n_N/n_\gamma)_0 \approx 6 \times 10^{-10}$. These pairs will annihilate until, at some temperature, $T$, $(n_N/n_\gamma)(g_4(T)/g_{\text{RD}}) \approx 6 \times 10^{-10}$. For lower temperatures, the antinucleons continue to be annihilated but the nucleons, due to the asymmetry, are frozen out. For nucleons (protons plus neutrons), $g = 4$, and their equilibrium abundance relative to photons is
\(n_N/n_\gamma = 0.26 \, g \, x^{3/2} e^{-x} \approx x^{3/2} e^{-x}\), where \(x = m_B/T\) and, prior to BBN, the average mass per baryon is \(m_B \approx 939 \, \text{MeV} [26]\), so that \(x \approx 939/T\), with \(T\) in MeV. Here, we have assumed that \(f(x) \approx 1\). To find \(T\), we need to solve \(\left(\frac{939}{T}\right)^{3/2} \exp\left(-\frac{939}{T}\right) \approx 1.5 \times 10^{-10} g_s(T)\). Using [25] for \(g_s(T)\), the solution is \(T \approx 38 \, \text{MeV}\) \((x \approx 25)\). To avoid the annihilation catastrophe in a symmetric Universe, the baryon asymmetry must have been created when \(T > 38 \, \text{MeV}\) \((\text{or}, \text{when} \, T \gg 38 \, \text{MeV})\). Recall that \(T_* \approx 22 \, \text{MeV}\), so \(T > T_*\), as expected. In the extensions of the standard models of particle physics and cosmology that allow for a baryon asymmetry at low temperatures, the energy/temperature/mass scales are orders of magnitude larger than this conservative estimate.

4 Particle Physics Models for Generating the Universal Matter-Antimatter Asymmetry

It is clear from the preceding two sections that a Universe containing equal abundances of baryons and antibaryons is not the Universe we actually observe. At some point in its evolution, the Universe must have developed an asymmetry between matter and antimatter. How did this asymmetry come about?

One possibility is that the Universe actually began in an asymmetric state, with more baryons and antibaryons. This is, however, a very unsatisfying explanation. Furthermore, if the Universe underwent a period of inflation (i.e., very rapid expansion followed by reheating), then any preexisting net baryon number would have been erased. A more natural explanation is that the Universe began in an initially symmetric state, with equal numbers of baryons and antibaryons, and that it evolved later to produce a net baryon asymmetry.

As we noted in the introduction, Sakharov introduced three conditions necessary to produce a net baryon asymmetry in a Universe that began with zero net baryon number. These Sakharov conditions form the basis of nearly all modern theories of baryogenesis, so we will review them in more detail here. These conditions are:

1. Baryon number violation. This is the most obvious component needed for baryogenesis. If the universe began with zero net baryon number, and
baryon number were conserved, then it would still have zero net baryon number today.

2. C and CP violation. The operator C changes particles into antiparticles and vice versa, while CP also flips all three coordinate axes. A universe that is baryon-antibaryon symmetric is unchanged when C or CP is applied, while the same is not true for a universe with a net baryon excess. Hence, the production of a baryon asymmetry requires C and CP violation.

3. A departure from thermodynamic equilibrium. If baryon and C/CP were violated while thermal equilibrium conditions prevailed, then the chemical potentials for baryons would be driven to zero, and the only possible difference between particle and antiparticle abundances would arise if there were a mass difference between them. But CPT invariance implies that the masses of particles and antiparticles are the same. Hence, Sakharov conditions 1 and 2 allow for a net baryon number to be created only when the particles of interest are out of thermal equilibrium.

While we know the general conditions necessary to generate a baryon asymmetry from an initially symmetric state, we are far from having a single accepted theory of baryogenesis. Here we will outline some of the ideas that have been proposed over the years. For some of the earliest work in this field, see Refs. [28, 29, 30, 31, 32]. For reviews of this topic, see Refs. [33, 34].

Perhaps the simplest class of models (and one of the earliest to be investigated) involves the decay of massive particles. Consider a particle-antiparticle pair, $X$ and $\bar{X}$, that has dropped out of thermal equilibrium in the early Universe, in the sense defined in §3.2. Suppose the $X$ can decay into two different channels, with baryon numbers $B_1$ and $B_2$, respectively, while $\bar{X}$ decays into the corresponding “anti”-channels, with baryon numbers $-B_1$ and $-B_2$, respectively. Invariance under CPT guarantees that the total decay rate for an antiparticle must be equal to the decay rate for the corresponding particle. However, it says nothing about individual branching ratios. So it is possible, for instance, for the branching ratio of $X$ into the channel with baryon number $B_1$ (which we will take to be $r$) to be different from the branching ratio of $\bar{X}$ into the channel with baryon number $-B_1$, which we will call $\bar{r}$. The possibility of such a difference is the key idea underlying this mechanism for baryogenesis. Note that $r \neq \bar{r}$ is only possible if C and CP are violated.
With the branching ratios and baryon numbers defined above, the net baryon number produced from each pair of $X$ and $\bar{X}$ decays is:

$$B = B_1 r + B_2 (1 - r) - B_1 \bar{r} - B_2 (1 - \bar{r}),$$

$$= (B_1 - B_2)(r - \bar{r}).$$

(18)

Eq. (18) illustrates the necessity of the three Sakharov conditions. If C and CP were not violated, we would have $r = \bar{r}$, and the right-hand side of Eq. (18) would be zero. Similarly, the possibility that $X$ can decay into two different channels with different baryon numbers is only possible if $B$ is not conserved; otherwise we would have $B_1 = B_2$ and again the right-hand side of Eq. (18) would be zero. Finally, we assumed out-of-equilibrium conditions in setting up this scenario, i.e., when they decay, $X$ and $\bar{X}$ are not in equilibrium with the thermal background, either through annihilations with each other or through inverse decays. If this were not the case, the particles produced in the $X$ and $\bar{X}$ decays would simply assume thermal equilibrium abundances, which would yield equal baryon and antibaryon densities.

The scenario we have sketched out here is a toy model; for more detailed models see, e.g., Ref. [35]. Models of this sort were first advanced in connection with physics at the GUT (grand-unified) scale, $T \sim 10^{15} - 10^{16}$ GeV. However, these ideas run into trouble if inflation is assumed to occur in the early universe. The reason is that, as we have noted, inflation wipes out any preexisting baryon asymmetry, so that baryogenesis must occur after inflation, and currently-favored models of inflation do not reheat the universe to a temperature as high as the GUT scale.

Another possibility for baryogenesis is the Affleck-Dine mechanism [36]. This model is motivated by supersymmetry, in which all of the particles of the Standard Model have corresponding superpartners with opposite spin statistics (fermions are paired with bosonic superparticles and bosons with fermionic superpartners). The Affleck-Dine mechanism invokes a scalar field that can carry a net baryon number. The field is initially frozen at early times, but begins oscillating when the Hubble parameter drops below its mass. During these oscillations, the scalar field acquires a net baryon number, which is transferred at later times into standard model particles.

Electroweak baryogenesis [37] is based on the idea that the universe underwent an electroweak phase transition at a temperature $T \sim 100$ GeV, when the Higgs field dropped into its vacuum state, giving masses to the quarks, leptons, and gauge bosons. If the electroweak phase transition is
first order, it can temporarily drive the universe out of thermal equilibrium as bubbles of the low-temperature vacuum nucleate, expand, and collide, ultimately occupying all of space. The production of baryons occurs in this out-of-equilibrium state near the walls of these expanding bubbles. Electroweak baryogenesis does require physics beyond the standard model, as the measured Higgs boson mass implies that the phase transition would not be first order in the standard model. This new physics would couple to the Higgs boson, altering its production and decay. Thus, the viability of these models can be tested in the laboratory.

Another proposal goes under the heading of leptogenesis [38]. These models are based on a result by ’t Hooft [39], who showed that even in the Standard Model, baryon number is violated by nonperturbative electroweak processes. These processes conserve $B-L$, but not $B$ and $L$ separately. Furthermore, while the rates for such processes are very low at low temperatures, they can be much higher in the early universe. Leptogenesis then, is the production of a net lepton asymmetry in the early universe, e.g., through massive particle decay as discussed above. Then nonperturbative electroweak effects transfer some of the net lepton number into a net baryon number.

This is by no means an exhaustive list of models for baryogenesis, which remains very much an open and active field of research. At this point we are confident of the ingredients required in any successful model (the Sakharov conditions), and we have a very accurate measure of the desired outcome (the observed baryon asymmetry), but the determination of the correct model for baryogenesis remains an ongoing effort.

5 The Baryon Asymmetry Parameter and Primordial Nucleosynthesis

In the standard model of particle physics and cosmology, the baryon asymmetry parameter plays a key role in BBN, regulating the rates of the nuclear reactions synthesizing (and destroying) the nuclides heavier than hydrogen. BBN in the standard model (SBBN) and in extensions of the SM when various nuclear physics and other parameters are allowed to vary is described in Uzan’s contribution to this volume. Here we are mainly concerned with the BBN predicted primordial (prestellar) abundances of the light nuclides, along with the CNO abundances.
Figure 1: The primordial abundances predicted by SBBN [40] for a large range of the present value of the baryon to photon ratio $\eta_B = (n_B/n_\gamma)_0$. For all abundances (including $^4\text{He}$) the ratio to hydrogen by number is shown. The dashed vertical line indicates the current SM value of $\eta_B \approx 6 \times 10^{-10}$. 

\[ \text{CNO} \]
5.1 Standard BBN

The SBBN predicted abundances, the ratios by number compared to hydrogen, are shown as a function of $\eta_B$ in Figure 1 for a factor of 1000 range in $\eta_B$, for the SM case of $N_\nu = 3$. Agreement between the predicted and the observationally-inferred deuterium abundance and the Planck observations of the CMB power spectrum imply a value of $\eta_B \sim 6 \times 10^{-10}$. This value is shown by the dashed vertical line in Fig. 1. This value of $\eta_B$ also provides good agreement with the primordial $^4\text{He}$ abundance derived from observations. However, it predicts a primordial $^7\text{Li}$ abundance roughly three times larger than the observationally-inferred abundance; this primordial lithium problem remains unresolved at present (see Ref. [41] for a recent review).

As seen in Fig. 1, over this large range in the baryon asymmetry parameter, the abundance trends are quite simple: as $\eta_B$ increases, the $^4\text{He}$ abundance increases monotonically, but very slowly ($\sim$ logarithmically); the abundances of $^3\text{He}$, $^6\text{Li}$, and $^6\text{Li}$ are all monotonically decreasing, while the abundances of the CNO nuclides increase. In contrast, the evolution of the abundance of $^7\text{Li}$ is non-monotonic. Starting from very small values of $\eta_B$, as $\eta_B$ increases, the $^7\text{Li}$ abundance first increases (until $\eta_B \sim 3 \times 10^{-11}$), then decreases (until $\eta_B \sim 3 \times 10^{-10}$), and finally increases again (eventually, for even larger values of $\eta_B$, the $^7\text{Li}$ abundance will decrease, being replaced by CNO and heavier nuclides). As $\eta_B$ increases from $10^{-11}$ to $10^{-8}$, $^4\text{He}/\text{H}$ increases by a factor of $\sim 4$, from $^4\text{He}/\text{H} \sim 0.024$ ($Y_P \sim 0.09$) to $^4\text{He}/\text{H} \sim 0.093$ ($Y_P \sim 0.27$) and the deuterium abundance decreases dramatically, from $\text{D}/\text{H} \sim 5 \times 10^{-3}$ to $\text{D}/\text{H} \sim 3 \times 10^{-11}$. Over the same range in $\eta_B$ the $^3\text{He}$ abundance decreases more slowly, from $\sim 10^{-4}$ to $\sim 3 \times 10^{-6}$ and the $^7\text{Li}$ abundance ranges from $\gtrsim 10^{-10}$ to $\lesssim 10^{-8}$, while the abundance of the CNO nuclides increases from $\sim 10^{-18}$ to $\sim 10^{-14}$.

For the value of the baryon asymmetry parameter inferred for the observed Universe, $\eta_B \sim 6 \times 10^{-10}$, $^4\text{He}/\text{H} \sim 0.082$ ($Y_P \sim 0.25$), $\text{D}/\text{H} \sim 2.5 \times 10^{-5}$, $^3\text{He}/\text{H} \sim 1.1 \times 10^{-5}$, $^7\text{Li}/\text{H} \sim 5.4 \times 10^{-10}$, and the abundances of all the other primordial nuclides are $\lesssim 10^{-14}$. For a very wide range in the baryon asymmetry parameter, the gas that will become the first stars in the Universe consists mainly of hydrogen and helium ($^4\text{He}$), with only trace amounts of any other, heavier nuclides. Note, however, that for $\eta_B \gg 10^{-8}$, the primordial abundances of the CNO and heavier nuclides may become non-negligible (see §5.2 below). In the absence of significant CNO (or D) abundances, it is the hydrogen and helium content of the primordial gas that
will most influence the formation, structure, and evolution of the first stars.

5.2 BBN for a Larger Range of Baryon Asymmetries

In the seminal BBN paper of Wagoner, Fowler, and Hoyle (WFH) [42], and in several follow up papers by Wagoner [43], Schramm and Wagoner [44], and Schramm [45], a much larger range in the baryon asymmetry parameter was explored than is shown here in Figure 1. In the WFH paper a range of some eight and a half orders of magnitude was considered, $-12 \lesssim \log \eta_B \lesssim -3.5$, while in the other cited papers the range is five orders of magnitude, $-11 \lesssim \log \eta_B \lesssim -6$. Although the quantitative BBN yields in those papers, based on what are now outdated nuclear and weak interaction rates (especially the much revised neutron lifetime), should be taken with a large grain of salt, the trends of the yields with $\eta_B$ revealed in those papers are likely robust.

For example, over the entire range explored, the helium mass fraction increases (and the hydrogen mass fraction decreases) monotonically with $\eta_B$. Over the same range in $\eta_B$, the D and $^3$He mass fractions decrease monotonically, with the deuterium abundance falling much more rapidly than the $^3$He abundance. The evolution of the $^7$Li mass fraction, $X_7$, is more interesting. At the lowest baryon asymmetries, $X_7$ increases from being negligible at $\log \eta_B \sim -12$ to a local maximum, a hint of which may be seen in Fig. 1 when $\log \eta_B \sim -10.5$. Then, as $\eta_B$ continues to increase, $X_7$ decreases to a local minimum at $\log \eta_B \sim -9.5$, as may be seen in Fig. 1. For $\eta_B \gtrsim 3 \times 10^{-10}$, $X_7$ increases to another local maximum when $\log \eta_B \sim -6$, after which $X_7$ decreases monotonically for all larger values of $\eta_B$. For $\log \eta_B \lesssim -8$, the abundances of the CNO and heavier nuclides are negligible.

As $\eta_B$ continues to increase, so too, do the CNO abundances, surpassing the $^3$He and $^7$Li abundances for $\log \eta_B \gtrsim -6$. However, almost as soon as the CNO nuclides become large enough to be of possible interest, they decrease as $\eta_B$ continues to increase, being replaced by even heavier nuclides. The trend seen at the very highest values of the baryon asymmetry parameter in the WFH paper suggests that at sufficiently high values of $\eta_B$ the iron peak elements might be produced during primordial nucleosynthesis. It is interesting to speculate if even larger baryon to photon ratios might lead to the r-process elements.

As discussed in [42], in determining if the baryon asymmetry parameter is finetuned, we are asking if stars, planets, and life could exist in alternate
universes with different values of $\eta_B$. In this case we need to check if the primordial abundances in alternate universes allow for the cooling and collapse of primordial gas clouds to form the first stars, and if in the course of evolution of those stars, the elements required for life can be synthesized.

6 Relation Between the Baryon Asymmetry Parameter and the Observable Cosmological Parameters

In our present-day Universe, the parameter $\eta_B$ is not a directly observable quantity. Instead, we measure quantities such as the baryon density or the CMB temperature, from which $\eta_B$ can be inferred. In this section we examine the relation between $\eta_B$ and the observable cosmological quantities.

In a matter-antimatter asymmetric Universe such as ours, the baryon asymmetry parameter is related to the contribution of baryons (normal matter) to the total mass density. As a result, the magnitude of the baryon asymmetry plays a role in the evolution of the Universe and in the growth and evolution of structure in it. For the discussion here is it assumed that the Universe is, on average, homogeneous and is expanding isotropically, so that its evolution is described by the “Friedman equation”,

$$\left(\frac{H}{H_0}\right)^2 = \Omega_R \left(\frac{a_0}{a}\right)^4 + \Omega_B \left(\frac{a_0}{a}\right)^3 + \Omega_{DM} \left(\frac{a_0}{a}\right)^3 + \Omega_k \left(\frac{a_0}{a}\right)^2 + \Omega_\Lambda.$$  \hspace{1cm} (19)

In Eq. (19) the subscript 0 indicates the present ($t = t_0$) value of the parameters and $H = a^{-1}(da/dt)$ is the Hubble parameter, quantifying the expansion rate of the Universe, where $a = a(t)$ is the cosmic scale factor. The subscripts, R, B, DM, k, and $\Lambda$ stand, respectively, for the contributions to the total mass/energy density from “radiation” (i.e., massless particles or particles whose total energy (rest mass plus kinetic) far exceeds the rest mass energy), baryons (“normal” or “ordinary” matter), dark matter (non-baryonic matter), curvature, and a cosmological constant. For simplicity,

8For agreement with observations of structure formation and its growth as the Universe evolves, it is assumed that the DM is “cold”, in the sense that for those epochs when deviations from homogeneity occur, the DM particles are moving slowly ($v \ll c$).
we assume here that the observed accelerated expansion of the universe is
driven by a cosmological constant rather than a time-varying dark energy
component. Since the mass densities of baryonic and dark matter evolve the
same way (e.g., $\rho \propto a^{-3}$), it is convenient to introduce a parameter describ-
ing the “matter density”, the total mass density in nonrelativistic particles,
$\Omega_M \equiv \Omega_B + \Omega_{DM}$. At the present epoch ($t = t_0$) a “critical density” of the
Universe may be identified, $\rho_{\text{crit}}(t_0) = 3H_0^2/8\pi G = 1.05 \times 10^{-5}h^2\text{GeV cm}^{-3}$,
where $H_0 \equiv 100h\text{ km s}^{-1}\text{ Mpc}^{-1}$ and $G$ is Newton’s gravitational constant.
Here, and elsewhere, we will often set $c = 1$ and express masses in energy
units. The parameters $\Omega_i$ that appear in Eq. (19) are the ratios of the vari-
ous contributions to the present energy densities, normalized to the present
critical density: $\Omega_i \equiv (\rho_i/\rho_{\text{crit}})0$.

Consider the relation between the baryon asymmetry parameter ($\eta_B$),
the baryon mass density parameter ($\Omega_B$), and the Hubble constant ($H_0$). The
present mass/energy density in ordinary (baryonic) matter is
$\rho_{B0} = m_Bn_{B0} = \Omega_B\rho_{\text{crit}}0 \approx 1.05 \times 10^{-5}\Omega_B h^2\text{GeV cm}^{-3}$. For an average mass per baryon of
$m_B \approx 0.938\text{ MeV}$ [26], the present baryon number density is
$n_{B0} \approx 1.12 \times 10^{-5}\Omega_B h^2\text{ cm}^{-3}$. If the present temperature of the CMB photons is $T_0$ (in de-
grees Kelvin), then the present photon number density is
$n_{\gamma0} \approx 20.3T_0^3\text{ cm}^{-3}$, and the present baryon to photon ratio is
$\eta_B \approx 5.54 \times 10^{-7}(\Omega_B h^2/T_0^3)$, so that
$\eta_B \approx 5.54 \times 10^{-7}(\Omega_B h^2/T_0^3)$ and
$n_{B0}/s \approx 7.87 \times 10^{-8}(\Omega_B h^2/T_0^3)$ (for
three flavors of SM neutrinos). Note that the connection between the baryon
asymmetry parameter ($\eta_B$ or $n_B/s$) and the present mass density in ordinary
matter ($\propto \Omega_B h^2$) depends on the present ($t = t_0$) value of the photon tem-
perature ($T_0$). If the baryon asymmetry parameter were to change by some
factor, the combination $\Omega_B h^2/T_0^3$ would change by the same factor, resulting
in changes to the other universal observables (e.g., $\Omega_B, h, T_0$), separately or
in combination. The baryon asymmetry parameter is degenerate with these
other cosmological parameters. In particular, changes in $\Omega_B$ alone would
change the expansion history of the Universe, as may be seen from the Fried-
man equation. The interconnections (degeneracies) among the cosmological
observables complicates any discussion of the effect on the history and evo-
lution of the Universe resulting from changes to any one of them (e.g., the
baryon asymmetry parameter).

\footnote{In the post-BBN Universe, when the baryons are mainly protons and alpha particles
(hydrogen and helium), the average mass per baryon depends on the helium abundance
(mass fraction, $Y_P$). For $Y_P \approx 0.25$, $m_B \approx 938.112 + 6.683(Y_P - 0.250)\text{MeV}$ [26].}
If the Friedman equation, Eq. (19), is evaluated at present \((t = t_0)\), when \(H = H_0\), there is one condition on the five parameters,

\[
1 = \Omega_R + \Omega_B + \Omega_{DM} + \Omega_k + \Omega_\Lambda = \Omega_R + \Omega_M + \Omega_k + \Omega_\Lambda,
\]

leaving four free parameters. For our observed Universe \(\Omega_k \ll 1\) and \(\Omega_R \ll 1\), so that \(\Omega_B + \Omega_{DM} + \Omega_\Lambda \approx 1\). There are still three parameters and only one constraint, leaving two free parameters. By writing \(\Omega_M = \Omega_B + \Omega_{DM}\), it might appear that there are only two parameters and one constraint, \(\Omega_M + \Omega_\Lambda \approx 1\). However, the ratio \(\Omega_B/\Omega_{DM}\) remains a free parameter, so there are still three parameters with one constraint among them.

In the next section we will consider how the evolution of the universe changes when \(\eta_B\) differs from its observed value. While our intention is to keep all of the other cosmological parameters constant, there remains an ambiguity in the way we treat them. Note that \(\eta_B\) is a dimensionless ratio of two quantities, the baryon and photon number densities. When we alter this quantity, we can consider two different possibilities: (1) changing \(n_B\) relative to the other cosmological parameters, while leaving \(n_\gamma\) unchanged relative to these parameters, or (2) keeping \(n_B\) fixed while changing \(n_\gamma\) relative to the other cosmological parameters. While each of these possibilities produces a change in \(\eta_B\), they differ in their treatment of the way that \(n_B\) and \(n_\gamma\) change relative to the other cosmological quantities of interest. (Of course, these are only the two simplest possibilities; one could consider allowing the ratios of both \(n_B\) and \(n_\gamma\) relative to the other cosmological parameters to change, but by different amounts, thus changing \(\eta_B\) as well).

Which of the two approaches spelled out in the previous paragraph is the correct one? Absent a particular model for a different universe with a different value of \(\eta_B\), it is impossible to say. However, the first possibility seems the more natural one. If we assume that baryogenesis is independent of the processes that led to dark matter or dark energy, then tweaking the model for baryogenesis will alter \(n_B\) by the same factor relative to all of the other cosmological parameters of interest. This is the case we will consider in detail.

Let \(F\) be the ratio of the value of \(\eta_B\) in some hypothetical Universe relative to its value in our Universe; our goal will be to understand what constraints, if any, can be placed on \(F\). We will use a tilde to denote physical quantities in a hypothetical universe in which \(\eta_B\) has changed, and quantities without a tilde will denote the corresponding values of these quantities in our universe,
so that
\[ \tilde{\eta}_B = F \eta_B. \]  
(21)

In case (1) discussed above, the ratios \( \rho_B/\rho_{DM} \), \( \rho_B/\rho_\Lambda \), and \( n_B/n_\nu \) change in proportion to the change in \( \eta_B \), while \( n_\gamma/\rho_{DM} \), \( n_\gamma/\rho_\Lambda \), and \( n_\nu/n_\gamma \) remain the same. Thus, we have
\[
\begin{align*}
\tilde{\rho}_B/\tilde{\rho}_{DM} &= F \rho_B/\rho_{DM}, \\
\tilde{\rho}_B/\tilde{\rho}_\Lambda &= F \rho_B/\rho_\Lambda, \\
\tilde{n}_B/\tilde{n}_\nu &= F n_B/n_\nu.
\end{align*}
\]  
(22) \hspace{1cm} (23) \hspace{1cm} (24)

Of course, there are other possibilities that we will not explore here. In an alternate universe with a late production of entropy, \( n_B \) would remain unchanged, while the ratio of \( n_\gamma \) to all of the other cosmological parameters would be altered. Alternately, if baryogenesis were linked to the process that produced dark matter (as it is in some models), one might consider the possibility of changing \( \eta_B \) while leaving \( \rho_B/\rho_{DM} \) fixed. Nonetheless, we feel that the model spelled out in Eqs. (22) - (24) is the most natural way in which to modify \( \eta_B \), and this is the case we will now attempt to constrain.

7 Alternate Universes with Different Baryon Asymmetry Parameters

Changing \( \eta_B \) alters the evolution of the universe in two ways: it changes BBN, and it alters the processes that give rise to structure formation and ultimately yield stars and planets. We will consider both effects in turn.

First, consider our Universe at present. Our Universe is very well described by a \( \Lambda \)CDM cosmological model with \( \Omega_k \approx 0 \), \( \Omega_R \ll 1 \), and \( \Omega_B < \Omega_{DM} < \Omega_\Lambda \) (\( \Omega_B + \Omega_{DM} + \Omega_\Lambda \approx 1 \)). For our observed Universe, a good approximation to the 2015 Planck CMB observations is \( \Omega_\Lambda \approx 0.7 \), \( \Omega_M \approx 0.3 \), \( \Omega_B \approx 0.05 \), \( \Omega_{DM} \approx 0.25 \). For a \( \Lambda \)CDM cosmology with \( \Omega_\Lambda \approx 0.7 \), \( H_0 t_0 \approx 0.96 \), so that for \( H_0 \approx 68 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( t_0 \approx 13.8 \text{ Gyr} \). For the present CMB temperature, the Fixsen et al. [47] result may be approximated by \( T_0 \approx 2.7 \text{ K} \), corresponding to a CMB photon number density \( n_{\gamma 0} \approx 400 \text{ cm}^{-3} \) (compared to the more accurate results, \( T_0 = 2.7255 \text{ K} \) and \( n_{\gamma 0} \approx 411 \text{ cm}^{-3} \)).
7.1 Effect on BBN

What happens to BBN when we allow for extreme variations in $\eta_B$? As noted earlier, the most important effect of increasing $\eta_B$ is to increase the primordial $^4$He mass fraction at the expense of hydrogen. One might imagine that a universe in which stellar evolution begins with almost pure $^4$He might be less hospitable to life. For example, Hall et al. [48] pointed out that in such a universe, halo cooling takes longer, stellar lifetimes are reduced, and there is less hydrogen to support organic chemistry. (The calculations in Ref. [48] are focused on variations in the weak scale, rather than the magnitude of the baryon asymmetry). However, even extreme increases in $\eta_B$ do not produce primordial $^4$He mass fractions close to 100%. For example, a value of $\eta_B$ as large as $10^{-3}$ (more than six orders of magnitude larger than the observed value) yields a $^4$He mass fraction of only 0.4 [49].

Large values of $\eta_B$ also open up the possibility of producing heavier elements in BBN. Consider first the CNO elements. In standard BBN, these are produced in very small amounts, with abundances relative to hydrogen of $\text{CNO}/\text{H} \sim 10^{-15} - 10^{-14}$ [50]. However, the abundances of these elements are an increasing function of $\eta_B$, peaking at $\text{CNO}/\text{H} \sim 10^{-8}$ for $\eta_B \sim 10^{-5}$, and decreasing for larger values of $\eta_B$ [42]. Even a small primordial abundance of $\text{CNO}/\text{H}$ could affect the evolution of the first generation of stars, as noted in Ref. [51]; this evolution begins to change when $\text{CNO}/\text{H}$ increases above $10^{-11}$. Nonetheless, it seems unlikely that such a change would affect the ability of the Universe to harbor life. For $\eta_B > 10^{-5}$, the abundance of the CNO elements begins to decrease, as the nuclei are converted into even heavier elements [42, 49]. However, even extreme increases in the value of $\eta_B$ result in only trace amounts of such heavy elements. In terms of models that can support life, it does not appear that BBN provides a useful upper bound on $\eta_B$, and certainly not a bound competitive with arguments from structure/galaxy/star formation.

Now consider BBN in the limit of very low values for $\eta_B$. In this limit, the $^4$He abundance becomes negligible, while $^2$H increases, reaching a peak abundance of order $\text{D}/\text{H} \sim 10^{-2}$ when $\eta_B \sim 2 \times 10^{-12}$. For smaller values of $\eta_B$, even the deuterium abundance decreases as $\eta_B$ is reduced, yielding, in the limit $\eta_B \to 0$, a primordial Universe consisting essentially of pure hydrogen. The reduction in primordial helium for small values of $\eta_B$ is likely to reduce the cooling of galaxies that results from the collisional excitation of ionized helium, but this is unlikely to have a major impact [48].
the other hand, a significantly larger abundance of deuterium would lead to enhanced molecular cooling through an increase in the HD abundance [52]. While interesting, this is also unlikely to affect the prospects for a life-bearing universe.

Our conclusion then, is that BBN provides essentially no constraints on Universes with different values of $\eta_B$. The formation of stars and planets and the development of life is nearly completely insensitive to variations in the primordial element abundances, at least within the ranges of $\eta_B$ that we have considered here.

7.2 Effect on Large Scale Structure: the Linear Regime

In the standard model for structure formation, small initial fluctuations in the density are imprinted on the matter and radiation by inflation or some other process early in the evolution of the universe. When the universe is radiation-dominated, these fluctuations cannot grow inside of the horizon; subhorizon fluctuations begin to grow once matter dominates the radiation. If $\delta \rho/\rho$ represents the magnitude of the fluctuation in the matter density relative to the mean matter density, then after matter domination begins, $\delta \rho/\rho$ grows proportional to the scale factor $a$,

$$\delta \rho/\rho \propto a.$$  \hspace{1cm} (25)

Eq. (25) applies only as long as $\delta \rho/\rho \ll 1$; in this case the density fluctuations are said to be in the linear regime. Once $\delta \rho/\rho > 1$, the Universe enters the nonlinear regime, and the analytic solution given by Eq. (25) no longer applies. Numerical simulations are necessary to evolve the density field further forward in time. In the nonlinear regime, the fluctuations in the matter density grow much more rapidly, and the dark matter ultimately collapses into halos.

This process applies in a straightforward way only to dark matter, which is collisionless. The baryons evolve in a more complicated way. At high temperatures ($T \gg 10^3$ K) the matter is ionized, and the cross section for scattering off of photons is very high. Thus, the baryons are frozen to the radiation background and baryonic density perturbations cannot grow. As the temperature drops, the electrons become bound to the protons and to the primordial helium nuclei in a process known as recombination.\footnote{Note that this term is a bit misleading, as the electrons and atomic nuclei were never “combined” to begin with.} At this point,
the density perturbations in the baryons can begin to grow along with the dark matter perturbations. A further complication is that in the nonlinear regime, the baryonic matter, unlike the dark matter, is not pressureless and can also radiate away energy in the form of photons. Thus, at late times the baryons evolve very differently than the dark matter. The end result is that the baryons ultimately bind into fairly compact disks or ellipsoids (galaxies), fragment into stars, and form planets, while the dark matter remains in the form of diffuse halos surrounding the galaxies.

In considering the effect of changing $\eta_B$, we must therefore consider the change in two key parameters: the redshift of equal matter and radiation, and the redshift at which recombination occurs. However, redshifts are defined relative to the present day, so they are not particularly useful in determining whether a modified universe can support life, as we are not restricting life to form at redshift zero as it does in our Universe. Instead, we should examine the temperature of equal matter and radiation and the temperature of recombination. In our Universe, the temperature of equal matter and radiation, $T_{eq}$, is given in terms of the present-day temperature, $T_0$, by $T_{eq} = T_0 (\rho_M/\rho_\gamma)_0$. For the parameter values given at the beginning of this section, we obtain $T_{eq} = 9000$ K. How does this change when $\eta_B$ is altered? To determine this, note that the redshift of equal matter and radiation is given by this ratio of present-day densities:

$$1 + z_{eq} = \left( \frac{\rho_{DM} + \rho_B}{\rho_\gamma + \rho_\nu} \right)_0.$$  \hspace{1cm} (26)

Here we are ignoring the fact that the neutrinos can become nonrelativistic at very late times. Then we have:

$$1 + \tilde{z}_{eq} = \left( \frac{\rho_{DM} + F \rho_B}{\rho_\gamma + \rho_\nu} \right)_0.$$  \hspace{1cm} (27)

Using the values for the cosmological parameters above, we can trace out the effect of $F$ on $T_{eq}$. We have $\rho_{DM}/\rho_B \approx 5$. Thus, $z_{eq}$ changes little for $F \lesssim 5$, while for $F \gtrsim 5$, we have $(1 + \tilde{z}_{eq}) = (F/5)(1 + z_{eq})$. Then we have:

$$\tilde{T}_{eq} \approx T_{eq} \text{ (} F \lesssim 5 \text{)},$$  \hspace{1cm} (28)

$$\tilde{T}_{eq} \approx \frac{F}{5} T_{eq} \text{ (} F \gtrsim 5 \text{).}$$  \hspace{1cm} (29)

Now consider the effect of altering $\eta_B$ on the recombination temperature $T_{rec}$. While recombination is a gradual process and does not occur suddenly
at a single temperature, for the purposes of this study it will be sufficient to
take $T_{\text{rec}} \approx 3000$ K. The process of recombination depends primarily on the
ratio of the photon temperature to the binding energy of hydrogen, but there
is also a residual dependence on $\eta_B$. This dependence comes about because
$\eta_B^{-1}$ determines the number of photons per hydrogen atom; an increase in this
number makes it easier for photons to ionize the hydrogen, delaying recombi-
nation, while the reverse is true if the number of photons per hydrogen atom
decreases. However, the temperature at which a given ionization fraction is
reached varies roughly logarithmically with $\eta_B$. This is a much smaller effect
than the change in $T_{\text{eq}}$ with $\eta_B$, so we will ignore it in what follows and take
the recombination temperature to be roughly insensitive to changes in $\eta_B$.

Now we can investigate the effect of changing $\eta_B$ on large-scale structure
in the linear regime. We will not consider any possible changes in the mag-
nitude of the primordial density fluctuations; we will assume that these are
unaltered. We see that neither of the parameters affecting large-scale struc-
ture are modified if $F \ll 1$, so the process of structure formation, at least
in the linear regime, proceeds in the same way as in our Universe. The den-
sity of baryons relative to dark matter will be much lower, leading to fewer
galaxies per dark matter halo, but this by itself does not seem to be a barrier
to the formation of stars and planets. In the opposite limit ($F \gg 1$), the
universe will become matter dominated early on, but baryonic structure
formation will not occur until the temperature drops down to $T_{\text{rec}}$, which is
essentially unchanged from its current value. So in this case, too, we expect
little change to the process of structure formation.

7.3 Effect on Large-Scale Structure: the Nonlinear Regime

Linear perturbation growth allows density perturbations to grow until $\delta \rho/\rho \sim
1$, but it is the subsequent nonlinear perturbation growth that directly pro-
duces galaxies, stars, and planets. Unfortunately, nonlinear perturbation
growth is more difficult to characterize for two reasons. First, it cannot be
solved analytically and requires quite detailed numerical simulations. Sec-
ond, nonlinear baryonic physics is quite a bit more complex than the behavior
of collisionless dark matter and can be difficult to simulate, even numerically.
In the absence of large-scale computer simulations of alternate universes with
different values of $\eta_B$, the limits discussed here should be treated with some
skepticism.

Tegmark et al. [53] have examined systematically the effects on struc-
ture formation of altering the baryon/dark matter density ratio, which, by assumption, is the same as the change in the baryon/photon ratio. Consider first the lower bound on $\Omega_B/\Omega_M$. Tegmark et al. argued that one can derive a lower bound based on the requirement that the collapsing baryon disks be able to fragment and form stars. If the baryon to dark matter ratio becomes too small, then the baryonic matter is insufficiently self-gravitating to allow fragmentation to occur. The limit derived in Ref. [53] is $\Omega_B/\Omega_M \gtrsim 1/300$, which corresponds to the lower bound $\tilde{\eta}_B > 1 \times 10^{-11}$.

In the absence of detailed numerical simulations, this bound should be treated with caution. More conservative lower bounds on $\eta_B$ were derived by Rahvar [54]. Star formation is significantly suppressed at very low $\eta_B$ simply because there are not enough baryons around to form stars. The requirement that at least one star forms per galactic-sized halo mass gives $\tilde{\eta}_B > 10^{-22}$. One can be even more conservative and require at least one star in the observable universe; this requires $\tilde{\eta}_B > 10^{-34}$ [54].

Tegmark et al. also derived an upper bound on $\tilde{\eta}_B$ from Silk damping (also called diffusion damping). Silk damping arises near the epoch of recombination from the diffusion of photons out of overdense (hotter) regions near the epoch of recombination. As the photons diffuse, they scatter off of charged particles and drag the baryons along with them, which tends to erase the baryonic density perturbations. Tegmark et al. argue that if the dark matter density were lower than the baryon density at recombination, Silk damping would tend to erase all fluctuations on galaxy-sized scales. Thus, they derive the limit [53] $\Omega_B/\Omega_{DM} \lesssim 1$, corresponding to $\eta_B < 3 \times 10^{-9}$. Again, this limit should be treated with some caution; before the discovery of dark matter, cosmologists did not consider purely baryonic models to be ruled out by an absence of structure formation!

In summary, our results in this section do not point toward significant fine tuning of the baryon asymmetry parameter, $\eta_B$. Element production in the early universe provides essentially no limits on changes to $\eta_B$ from the point of view of the habitability of the Universe, while limits from structure formation are either very weak, very speculative, or both.

8 Summary and Conclusions

For a dimensionless physical parameter such as the baryon asymmetry parameter, $\eta_B$, that could take on any value from $-\infty$ to $+\infty$ (or, allowing for
a swap in the definition of matter and antimatter, from 0 to \( \infty \)), zero might seem the most natural choice. However, the value of \( \eta_B = 0 \) corresponds to a symmetric Universe, a Universe with equal amounts of matter (baryons) and antimatter (antibaryons), which is inconsistent with what we actually observe. An overview of the problem was provided in §1, where \( \eta_B \) was defined and its relation to the baryon to entropy ratio was discussed. To address the question of whether a nonzero value for \( \eta_B \) is, or is not, fine tuned, some ground rules are required. These were outlined in §2. We evaluate fine-tuning in terms of the ability of the Universe to produce stars, planets, and, ultimately, life. As reviewed in §3, our Universe cannot be symmetric; observations strongly indicate that \( \eta_B \neq 0 \).

An overview of the models that have been proposed to account for \( \eta_B \neq 0 \) was offered in §4. The variety of models in the literature suggests that virtually any value of \( \eta_B \), including the other “natural” value of \( \eta_B \approx O(1) \), could be “predicted.” The observations most sensitive to \( \eta_B \) are the abundances of the elements produced during BBN. The dependence of BBN on \( \eta_B \) was reviewed in §5, revealing that while the precise abundances vary significantly with \( \eta_B \), over a very large range in \( \eta_B \) only hydrogen and helium (\(^4\)He) emerge from the early evolution of the Universe with significant abundances. The connection between \( \eta_B \) and a variety of other cosmological parameters was discussed in §6, and the effect of changing \( \eta_B \) on the evolution of the Universe was examined in §7. While large changes in \( \eta_B \) affect both primordial element production and the formation of galaxies and stars, it is only the latter that allows us to suggest limits on the allowed range for \( \eta_B \). Our results indicate that universes with values of the baryon asymmetry parameter that differ significantly from our own can form galaxies and stars (whose evolution can produce the heavy elements necessary for life), and planets, capable of hosting life. Thus, the value of \( \eta_B \) can be varied by many orders of magnitude without strongly affecting the habitability of the Universe, a result that is not suggestive of fine-tuning.

It is likely that our Universe began with no baryon asymmetry (equal amounts of matter and antimatter), so that the initial baryon asymmetry parameter had its “natural” value of zero. For a Universe like our own, conservation of baryon number, an exact symmetry at very high temperatures, needed to be violated at some mass/energy scale in the very early Universe. Processes such as those described in §4, which must include baryon number nonconservation, resulted in the baryon asymmetry observed in our Universe and in those alternate universes discussed here. However, the baryon non-
conservation required at high mass/energy scales might also lead to nonzero (even if exponentially suppressed) baryon nonconservation at very late times in the evolution of the Universe. If this were the case, then eventually, in a Universe that lives long enough, protons might decay (diamonds are not forever!), so that the baryon number of the Universe (as well as the lepton number) would revert back to its natural value of zero. Ashes to ashes, dust to dust.

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