2. What is the Origin of the Lightest Elements?

Abstract Although the birth event of our Universe occurred 13.7 billion years ago, it left enough signatures about its details that scientists are quite confident in our understanding of the basic features of that event. The first hints of the Big Bang came from astronomers, as discussed in this chapter. More recently, two incredible experiments, the Supernova Cosmology Project and the Wilkinson Microwave Anisotropy Probe, have determined the parameters that govern our Universe in exquisite detail. One longstanding paradox is also discussed, and shown to be solved by the Big Bang model. Finally, we explore the nuclear reactions that made a few light nuclei in the few minutes that followed the Big Bang. The abundances for these nuclei obtained by observational astronomers are compared to the calculations of the nucleosynthesis that occurred just after the Big Bang.

2.1 The Big Bang

We need to begin our story with the basic constituents of molecules, that is, atoms. So where do the atoms come from? Most of the elements are made in stars. But things are not quite that simple. The elements hydrogen and helium comprise 99% of the mass of the universe that isn't made of exotic stuff (that is, dark matter or dark energy, if you're a physics aficionado), and they were mostly produced in the Big Bang. And the birth event of our Universe is certainly the origin of everything we know, so let's begin our story with a discussion of the Big Bang. That name originated with Fred Hoyle, who actually believed in a "steady state universe," that is, one that didn't have a birth event. Hoyle intended the name as a

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pejorative comment on the model of his competition. Of course, we now know that the name caught on, and the birth event of our Universe is now a well-documented scientific paradigm. Our primary interest will be in Big Bang Nucleosynthesis, BBN, but before we describe that, let's back up a few minutes to the events that preceded BBN.

Thirteen billion seven hundred million years ago an extraordinary event occurred: our Universe was born. This is well documented by many observations, but the Supernova Cosmology Project, SCP, and the Wilkinson Microwave Anisotropy Probe, WMAP, stand out as the modern incarnations of these efforts. The SCP was headed by Saul Perlmutter (who won the 2011 Nobel Prize in physics for his efforts), and WMAP by Charles Bennett.

However, a very prominent forerunner of these occurred in the early twentieth century as a result of astronomical observations by Vesto Slipher and their interpretation by Edwin Hubble. Hubble was an interesting character, noted in his early life more for his athletic prowess than his academic abilities. He once won seven first places in a track meet, and he dabbled in amateur boxing for a time. He also got a law degree before serving in the military, and then getting his Ph.D. Getting back to astronomy, Slipher had noted that the light from some galaxies appeared to be "red shifted," that is, the characteristic wavelengths of the light from those galaxies could be identified as originating from emissions of photons—those particles of light—from atoms of hydrogen, but they were shifted toward longer wavelengths. Since hydrogen is the most abundant element in the Universe, it is appropriate to show some of the characteristic wavelengths that are emitted by hydrogen atoms; no other element emits light at those same wavelengths. These are seen in Figure 2.1.

Figure 2.1 shows the different series (or groups) of emissions of photons when electrons change from one allowed state to another, that is, these are the result of transitions between specific energy levels. The Lyman series results from transitions to the lowest lying energy level, called the ground state. The Balmer series is from transitions to the next highest energy level, called the first excited state. The Paschen series is to the second excited state, and continues beyond the scale to the right. Each series has many more lines, but they pile up at the left most line in each

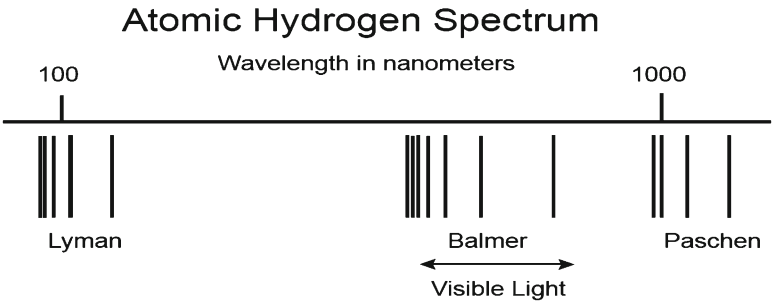

FIGURE 2.1 Characteristic emissions of hydrogen atoms. The electrons in atoms can only exist at well-defined energies which result from well-defined quantum mechanical "states," which are different for the different elements. Transitions between those states produce the characteristic emissions.

series. Those indicated in Figure 2.1 as being in the visible light region would be observed in the laboratory, that is, these are not red shifted. The Lyman series is shifted into the visible part of the spectrum in highly red shifted objects; these are the emission lines that were observed by Slipher.

We will give a more thorough discussion of wavelength in Chap. 4. For now, we will just observe that "light" is electromagnetic radiation, and that it is characterized by an oscillating electric field and an oscillating magnetic field. The oscillations occur in both space and time. The wavelength is the distance over which a wave repeats itself. Visible light has a wavelength of around 5×10^{-7} m, or 1/2 of one millionth of a meter. The above-mentioned characteristic wavelengths of the light from distant galaxies had to have been a result of a Doppler shift, that is, the fact that the galaxies were moving away from us. This is something that everyone experiences in hearing a train whistle or a police siren: the frequency of the sound is higher (and that means that the wavelength is shorter) when the train or police car is moving toward us, then it drops as it passes us. The same effect applies to light. This ultimately led Hubble to conclude that all galaxies were moving away from all other galaxies in the Universe, that is, that the Universe was expanding. He also concluded from the amount of the red shifts that the more distant the galaxies were, the faster they were receding. This led to "Hubble's law:"

$$v = HR,$$

where v is the velocity of recession between galaxies, R is their separation distance, and H is the constant of proportionality, the Hubble constant. This law is a very simple looking equation, but it has profound consequences: it says that the farther an object is from us the more rapidly it will be receding from us, and this applies to every pair of objects in the Universe! This law prevailed for more than half a century, albeit with a large uncertainty on the value of the Hubble constant.

It's not so easy to envision what this looks like in three dimensions, but if you can for the moment think of our Universe as being just two dimensional, then you can think of it as existing only on the surface of a balloon. If you mark galaxies on the balloon, then blow it up, you will see that every galaxy is receding from every other galaxy. However, I don't know many people who can accurately conceive of this in three dimensions, so if you're having trouble, you're not alone.

Indeed, determination of the Hubble constant led to a major irony of twentieth century science. Two major groups had been performing observations and analyses to determine H. One group, headed by the French astronomer Gerard deVaucoleurs, consistently obtained values around 100 km/s/megaparsec (a parsec is an astronomical unit of distance, and is 3.6 light years, or 3.1×10^{13} [31 trillion] kilometers). The other group, headed by Alan Sandage, an American astronomer, consistently obtained values of around 50 km per second per megaparsec, and the uncertainties on their respective values were much smaller than the differences between them.

In science, when you have two results as discrepant as these, the last thing you would do is average them, since one of them is surely incorrect. Of course, both could be incorrect, and that turned out to be the case here. The modern value for H is 70.5 km per second per megaparsec (WMAP website), close to the average of the Sandage and deVaucoleurs results, and certainly the average of the two results within their uncertainties.

2.2 The Supernova Cosmology Project

However, the SCP found, via very detailed measurements done in the 1990s, that the Hubble constant was not constant! Hubble's law had become so ingrained in astronomy that the red shift of distant objects was used to infer their distance. So if one were to check Hubble's law one would need some independent distance indicator. If you think about making an astronomical observation you will quickly realize that it is easy to locate objects on an up–down and left–right plane, but determining the distance to an object, the third dimension, is trickier. What one needs is a class of objects that always exhibit the same intrinsic brightness, or which produce some other observable quantity that allows determination of the intrinsic brightness. Then the observed brightness allows one to infer the distance to the object, since the observed brightness falls off as the inverse square of the distance to the object. One class of objects in the latter category is Cepheid variables, stars for which their brightness oscillates with a frequency that can be related directly to the intrinsic brightness. So astronomers can measure the frequency of oscillation of a Cepheid, and thus determine its intrinsic brightness. And comparing that to the observed brightness then gives the distance to the star. Unfortunately, Cepheids are not especially bright stars, so some other "standard candle" needed to be found for making measurements at the huge distances that characterize cosmology.

Such objects are Type Ia supernovae. These are extremely bright exploding stars that are all essentially the same mass before they explode, and therefore, since they explode by thermonuclear runaway and blow up the entire star, and the nuclear processes are essentially the same for all Type Ia supernovae, they have nearly identical intrinsic brightness. The SCP utilized Type Ia supernovae for its standard candles.

The simplest description of the Universe would be that it formed in a giant explosion of the entire Universe, and has been expanding, and slowing its rate of expansion, ever since. The reduced rate of expansion would result from the gravitational attraction of all the constituents of the Universe on each other. What the SCP found, however, was that although the Universe is expanding, the expansion was speeding up, not slowing down. This suggests that there is something that acts like a "negative gravity," that is, that it does exactly the opposite of what gravity does. This has been dubbed "dark energy." Its existence actually harks back to Einstein, who included it in his general equations and called it a cosmological constant. He later referred to it as his greatest mistake!

So nearly a century later we have come to realize that, as was often the case, Einstein was way ahead of his time, and way ahead of his fellow scientists. In any event, determining what the dark energy is and understanding why it acts as it does will constitute one of the primary objectives of scientists for at least the next decade.

The results from the SCP are summarized in Figure 2.2, which plots the "effective m_B," (which is just the observed brightness of

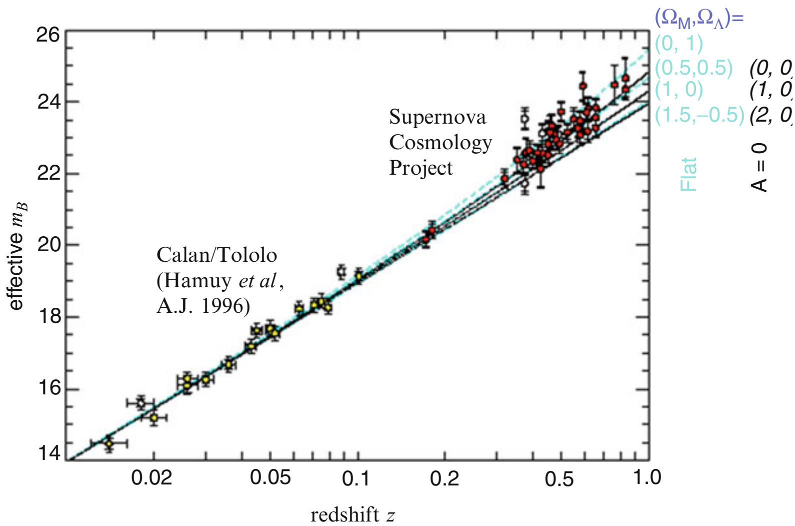

FIGURE 2.2 Hubble diagram, showing effective m_B, the effective peak brightness of the supernovae, versus redshift z, for 42 high-redshift type Ia supernovae from the Supernovae Cosmology Project, and 18 lower-redshift type Ia supernovae from the Calan/Tololo Supernova Survey [1]. Several outliers that were not included in determining the fits to the data are indicated as open circles (although their inclusion did not affect the conclusions). The solid curves are the theoretical effective $m_B(z)$ for a range of cosmological models with zero cosmological constant Ω_Λ and varying energy density of the Universe Ω_M, $(\Omega_M,\Omega_\Lambda) = (0,0)$ on top, (1,0) in the middle, and (2,0) on the bottom. $\Omega_M = 1$ is the critical density of the Universe, as defined in the text. The dashed curves are for a range of cosmological models: $(\Omega_M,\Omega_\Lambda) = (0,1)$ on top, (0.5, 0.5) second from top, (1,0) third from top, and (1.5, –0.5) on the bottom. The high-redshift data are clearly seen to favor a nonzero Ω_Λ. (Reprinted from Boyd [2]. Originally from Perlmutter et al. [3]. Courtesy of IOP Publishing, and of Saul Perlmutter)

each star) on the y-axis versus "redshift" on the x-axis. Redshift is simply related to the "time from Today," or in astronomers' jargon, "lookback time." The scale of the Universe characterizes the expansion of the Universe. The several curves represent the Universal expansion in terms of the different assumptions about the different cosmological parameters that characterize the Universal expansion.

Figure 2.2 shows that the data lie up and to the left of the line labeled (1,0), which is where the data would be if the energy density of the Universe were equal to the "critical value" and the cosmological constant was zero. By critical value we mean that the Universe would continue to expand forever, but slow down at a rate such that it would only stop expanding at infinite time. Thus the data do not favor a scenario in which the Universe is expanding at a decreasing rate resulting only from mutual gravitational attraction. Rather the Universe appears to favor a scenario in which the Universe is expanding, and the expansion *is accelerating*. So the thing to take away from this is that the SCP data do not support the model that had prevailed for more than half a century, but do support a considerably more complicated universe—one that contains stuff that scientists, excepting Einstein (with his cosmological constant), had not imagined previous to the SCP results.

2.3 The Wilkinson Microwave Anisotropy Probe

Although the SCP is probably the most direct way to check the veracity of Hubble's law, it is not the only experiment done to determine cosmological parameters. As mentioned above, the Wilkinson Microwave Anisotropy Probe, WMAP, was the prime example of another class of projects to study cosmology; it was directed toward the 2.7 K (this corresponds to –270.5° Centigrade, 4.9° Rankine, and –454.8° Fahrenheit. This is pretty cold no matter what temperature scale you use!) cosmic microwave background radiation. This is the electromagnetic radiation—the photons—left over from the Big Bang. It was first discovered by accident by Arno Penzias and Robert Wilson, two scientists at Bell Laboratories in New Jersey, as they were trying to develop an extremely sensitive antenna.

Penzias and Wilson were unable to eliminate some background noise, despite heroic efforts to do so. Fortunately, down the road a few miles at Princeton University was Robert Dicke, a theoretical cosmologist, who explained to Penzias and Wilson that they had discovered the relics of the radiation produced in the Big Bang. This radiation was very hot at the time of the Big Bang, but as the Universe expanded, the wavelength of the radiation lengthened with the expansion of the Universe. And larger wavelengths mean less energetic radiation. So this radiation is now extremely cold. It should also be noted that George Gamow had predicted that such a background should exist many years earlier. Penzias and Wilson won the Nobel Prize for their discovery. A much more elegant experiment was performed in the late twentieth century by a team lead by Smoot and Mather [4]; they measured the 2.7 K cosmic microwave background radiation in detail. Smoot and Mather were also awarded the Nobel Prize for their efforts.

However, the Smoot–Mather measurement has undergone an incredibly sophisticated improvement with the WMAP, which was designed to measure temperature fluctuations in the background radiation rather than the temperature itself. It turns out that the density in the early Universe was blotchy, and the sizes and densities of the blotches tell us a great deal about the status of the Universe at the time that the electrons were captured on nuclei to form neutral atoms. Prior to this, the electrons had been free because the temperature of the Universe had been too high, and therefore the density of photons with sufficient energy to ionize the atoms was too great, to permit atoms to exist. The measurement of the blotches can provide tests of theories of how the early Universe formed and evolved. WMAP was able to measure the fluctuations to a few parts in a million; an incredible achievement.

A standard mathematical technique was then used to generate the curves that represent the oscillations in the data shown in Figure 2.3. The x-axis is the size scale of the fluctuations on the cosmic microwave background, as indicated, and the y-axis is essentially the magnitude of the fluctuations in the cosmic microwave background radiation at that angular scale. These representations show that the baryon density of the Universe—baryons are the protons and neutrons that comprise the nuclei of the atoms of which we are made—constitute less than 5% of the mass-energy

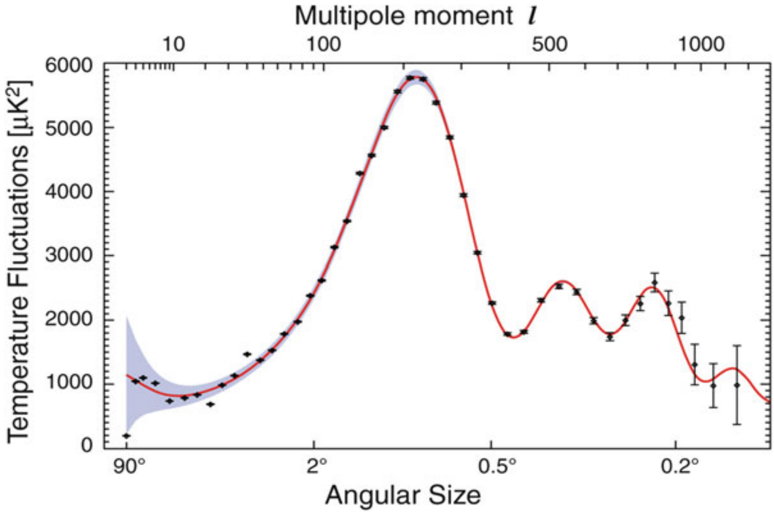

FIGURE 2.3 The *WMAP* angular power spectrum for 7 years of data. The *WMAP* temperature fluctuations are shown in microKelvin (millionths of a Kelvin degree) as a function of the angular size of the fluctuations The best fit Cold Dark Matter with Cosmological Constant model is shown. Author: The WMAP/NASA Science Team. Sponsor: National Aeronautics and Space Administration. (Courtesy of Charles Bennett)

of the Universe. This should produce some level of humility; not only are we not the center of the Universe or even of the Galaxy, we're less than 5% of the stuff from which the Universe is made! This is very accurately determined; the second peak from the left shown in Figure 2.3 is very sensitive to that value.

The WMAP data also showed that 23% of the Universe is dark matter; this is stuff that interacts very weakly with most probes that one might devise to look for it, but does produce a gravitational pull on galaxies, so is obviously present from the motions of galactic constituents. The third peak is especially sensitive to the amount of dark matter. Finally, the dominant component of the Universe's mass-energy, 72% of it, is the dark energy, as determined from both the SCP and the WMAP results. The two experiments also determined that the age of the Universe, to high accuracy, is 13.7 billion years, and the Hubble constant is 70.8 km per second per megaparsec. The original WMAP publication was by Bennett et al. [5], but the most recent results from WMAP at the time this is being written can be found in Jarosik et al. [6].

2.4 Olber's Paradox

There is an interesting argument that shows that the steady state Universe, Fred Hoyle's favorite cosmological theory, can't be correct, or at least has serious problems. This is known as Olber's Paradox. Simply stated, this asks why the night sky isn't bright instead of dark with speckles of starry light? Well, maybe it never occurred to you that the night sky might be bright! Olber's Paradox was promoted in the nineteenth century by astronomer Heinrich Olbers, although the idea behind it was apparently realized as early as the sixteenth century by Kepler.

So why might the night sky be bright? Consider the left-hand side of Figure 2.4, which shows a star seen by observer "O," who is distance d away from it. Suppose now that the same star is distance 2d from the observer; then, since the intensity of the light from the star falls off as $(1/\text{distance})^2$, the star will appear to be 1/4 as bright.

Now consider the right-hand side of Figure 2.4, in which are shown two thin shells of space, each of thickness Δ, one a distance d from the observer and the other a distance 2d from the observer. The observer's telescope will be able to see an angular opening of Θ, which will produce an image of the two disks, the nearer one of diameter Θd, and the more distant one of diameter 2Θd. Thus the nearer disk will have an area proportional to d^2, and the more distant one will have an area proportional to $(2d)^2$ or $4d^2$. So

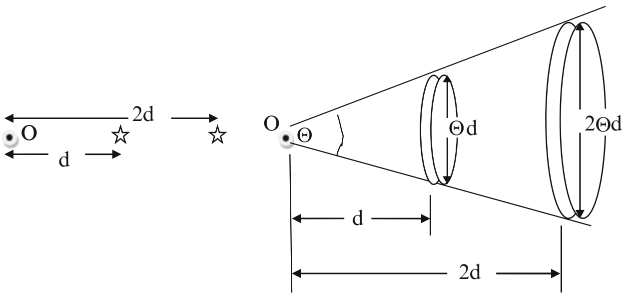

FIGURE 2.4 *Left* Observer "O" in relationship to two stars of the same intrinsic brightness, but the more distant one at twice the distance as the nearer one. *Right* Observer looking through a telescope at two disks that are subtended by the same angle Θ. The disk that is d away has a diameter of Θd, and the one that is 2d away has a diameter of 2Θd.

the volume of the more distant disk, if we now include the third dimension, the Δ, will be four times that of the nearer disk and, assuming that the density of stars is constant, will have four times as many stars as the nearer disk. Each of those stars will appear to have 1/4 of the intensity of the stars in the nearer disk, but there are four times as many of them, so the light from the more distant disk will be exactly equal to that of the nearer disk. If you keep adding disks out to infinity, you should just keep adding to the light seen by the observer, and you will make things bright indeed! Note that I assumed that the Universe was both uniformly populated with stars and that it is infinite. These are assumptions that accompany the Steady State Universe theory.

Okay, so the night sky isn't bright, which means there must be something wrong with the assumptions that went into Olber's Paradox. First, we know that the Universe is not infinite, although it is pretty huge, so that may not resolve the problem. Secondly, the Universe is not static, that is, it is not in a steady state. In fact, we know that it is expanding, and this will increase the wavelengths of the radiation from the distant stars, which also decreases the energy of the photons. In fact, the energies of the light from sufficiently distant stars will be so low as to be irrelevant. Furthermore, the Universe is, in a sense, young, in that the light from distant stars hasn't had time to reach us. And this certainly would not be the case if we had a steady state Universe [6, 7]. So Olber's Paradox really isn't a paradox at all when viewed from the perspective of modern cosmology.

So we know what the baryonic matter is, but we don't know what comprises the dark matter, and we don't have any idea what the dark energy is!

2.5 Big Bang Nucleosynthesis (BBN)

Now, back to our effort to describe what nuclides are synthesized in the Big Bang. What I will do is take you through the nuclear reactions that make the nuclei which were produced in the Big Bang. Along the way we will encounter some physics conservation laws, but I'll explain those also as we proceed. Actually very little was synthesized, due to a couple of nuclear quirks: there are no stable mass 5 or mass 8 nuclides. Mass 5 would be ^{5}He or ^{5}Li, and mass 8 would be ^{8}Be. ^{8}Be is close to being stable, but it is very short lived; it lives 10^{-16} (one ten millionth of one billionth) seconds. The two mass 5 nuclei are much too unstable to live for even a short time. These facts make it virtually impossible to form anything in BBN except ^{2}H, ^{3}He, ^{4}He, and ^{7}Li, and the ^{7}Li is so difficult to produce that its abundance is extremely small. I'll explain what the various nuclides are comprised of below.

But let's see how these nuclides are made. Seconds after the Big Bang, the only nuclear particles were protons and neutrons. As the Universe was expanding, it was also cooling, but it needed to cool quite a bit before the very first reaction could take place. That reaction is

$$^{1}H + n \rightarrow {}^{2}H + \gamma,$$

where ^{1}H and n refer to the protons and neutrons, ^{2}H is a heavy hydrogen nucleus—a deuteron, comprised of a proton and a neutron, and γ is a gamma-ray, a particle of electromagnetic energy. A gamma-ray is a very energetic form of electromagnetic radiation, that is, a particle of ordinary light; all such particles are called photons. A photon is a necessary component of that reaction in order for it to conserve energy. Energy conservation is a major law in physics. This includes not only the energy of motion, but of mass energy, that is, $E = mc^2$, Einstein's famous equation. So energy conservation says that the sum of the mass energies and the energies of motion of the particles on the left-hand side of the equation must equal those same quantities on the right-hand side. However, the Universe had to cool enough for the photons in the above reaction to lose enough energy that they would not run that reaction backwards, that is, so that they would not destroy ^{2}H as rapidly as it was made.

There are two more conservation laws that we need to attend to in this and all the other reactions that follow. The first is "charge conservation." In the above equation, the proton has a charge of +1 and the neutron has zero charge. On the right hand side, the deuteron also has a charge of +1, and the gamma-ray has zero charge. So each side has a charge of +1, and charge is conserved. If there had been an electron in the equation, its charge would have counted as −1. The other law that must be satisfied is "baryon conservation." For our purposes, baryons are just protons and neutrons and nothing else (there are others, but they occur at higher energies than we will be dealing with, so they won't concern us), so the number of protons and neutrons on the left side of the equation, including those that exist in nuclei that contain both protons and neutrons, has to be equal to that number on the right side. (By the way, baryon conservation is thought by particle physicists to be violated, but only at an incredibly tiny level. For our purposes, baryon conservation applies.) Gamma rays are not baryons, so there isn't a conservation law that affects them, aside from conservation of energy. The deuteron is an unusually loosely bound nucleus. Generally it takes around 8 MeV—million electron volts—a unit of energy that is appropriate to nuclei, to liberate a single proton or neutron from a nucleus, but the deuteron can be broken into its constituent proton and neutron with only 2.2 MeV, a pretty small amount of energy by nuclear standards.

So, the deuteron really was the bottleneck that required the Universe to cool before BBN could begin. However, once ^{2}H began to be formed, BBN began in earnest. There was also a bit of a contest going on. A free neutron is not a stable particle; it decays to a proton, an electron, and a neutrino (technically, an electron antineutrino; we will get to neutrinos later on) with a half-life of just a little over 10 min. So after 10 min you will have only half the neutrons that you had before that period started. However, most of the neutrons will get captured into nuclei, and they are stable in their nuclear homes, provided that the resulting nucleus is stable.

The reactions that convert protons and neutrons into ^{4}He nuclei—comprised of two protons and two neutrons—are as follows:

$$
\begin{aligned}
&{}^2\mathrm{H} + {}^1\mathrm{H} \to {}^3\mathrm{He} + \gamma,\\
&{}^3\mathrm{He} + \mathrm{n} \to {}^4\mathrm{He} + \gamma \text{ or } {}^3\mathrm{He} + {}^2\mathrm{H} \to {}^4\mathrm{He} + {}^1\mathrm{H},\\
&{}^2\mathrm{H} + \mathrm{n} \to {}^3\mathrm{H} + \gamma,\\
&{}^3\mathrm{H} + {}^1\mathrm{H} \to {}^4\mathrm{He} + \gamma \text{ or } {}^3\mathrm{H} + {}^2\mathrm{H} \to {}^4\mathrm{He} + \mathrm{n}.
\end{aligned}
$$

Let me explain in words what is going on in these reactions. In the first of the two sets of equations (the first two lines), a proton is captured onto a deuteron, making ^{3}He (an isotope of helium that has two protons and one neutron) which is then converted to ^{4}He, either with a neutron capture or in a reaction in which a deuteron adds its neutron to the ^3He and releases its proton. In the second set of reactions, a neutron is captured onto a deuteron to make ^3H, a triton (an even heavier isotope of hydrogen than the deuteron, since the triton has a proton and two neutrons), which then gets converted to ^4He either by capturing a proton or in a reaction in which a deuteron drops off its proton and liberates its neutron. Note that each of these reactions conserves baryons.

That's pretty much all there is to BBN, except that ^7Li (with three protons and four neutrons) can be made in tiny amounts by the two reaction series where e^- is an electron and ν_e is an electron neutrino:

$$^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma, \text{ or}$$
$$^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma, \text{ and then}$$
$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e,$$

On the last line is the reaction by which ^7Be, which is not a stable nucleus (it consists of four protons and three neutrons), ultimately decays to ^7Li by capturing an electron, as indicated. Neutrinos are very important to our story, but not in the context of BBN. However, for the moment it's worth noting that our Sun emits 1.8×10^{38} (100 trillion trillion trillion) neutrinos per second, 8.4×10^{28} (10,000 trillion trillion) of which impinge on one side of the Earth, and virtually all of them pass right on through. If you close your fist, you'll be enclosing a volume that contains several hundred neutrinos. Of course, it's not the same several hundred neutrinos for very long; the neutrinos will pass through your hand with virtually no recognition of your presence.

Solar neutrinos were the source of one of the major scientific puzzles of the twentieth century, that is, why was the rate of detection of Solar neutrinos about one-third of that predicted by the Standard Solar Model (see the website of the late John Bahcall http://www.sns.ias.edu/~jnb/ and Bahcall et al. [8], for many discussions of the Solar neutrino problem and the standard model). The solution to this puzzle required the efforts of many physicists for several decades, and uncovered a profound aspect of neutrinos, that is, they can change from one type—called flavor—to another. We will have more to say about neutrinos later. Finally, note that neutrinos and electrons are not baryons.

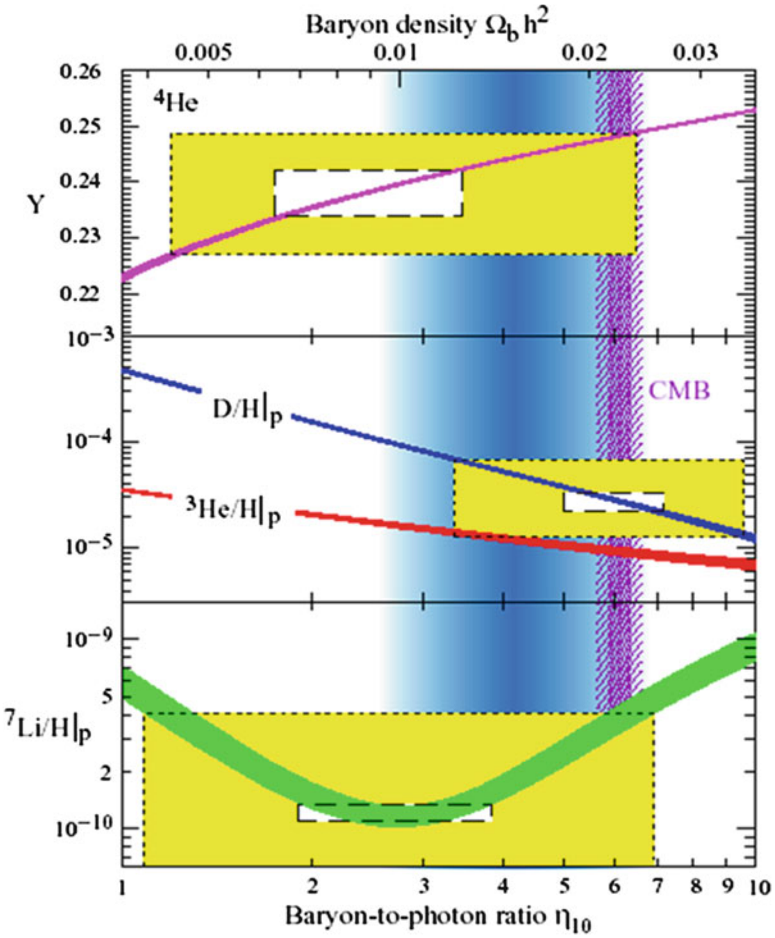

FIGURE 2.5 The abundances of ^{4}He, ^{2}H, ^{3}He, and ^{7}Li as predicted by the standard model of BBN, along with indicated uncertainties in the theoretical predictions. *Boxes* indicate the observed light element abundances (*smaller boxes* 2σ statistical errors, *larger boxes* 2σ statistical and systematic errors added in quadrature). The ^{4}He data are from Fields and Olive [9], the ^{2}H data from Kirkman et al. [10] and Linsky [11], and the ^{7}Li data from Ryan et al. [12] and Pinsonneault et al. [13]. No observations are indicated for ^{3}He, as its primordial value is difficult to obtain. The narrow vertical band along the right side indicates the CMB measured value of the cosmic baryon density. (Reprinted from Boyd [2]. Originally from Fields and Sarkar [14]. Copyright 2004, with permission from Elsevier. Courtesy of Brian Fields)

The abundances of the nuclides made in BBN and the predicted abundances are shown in Figure 2.5, where they are plotted as a function of the "baryon to photon ratio," or baryonic density fraction of the Universe. Prior to WMAP, that ratio was not well known, so it was customary to plot the BBN abundances as a function of that density as a way of determining its value. The vertical region labeled "CMB" in Figure 2.5 gives the WMAP value, which is seen to pass right through the preferred "D/H|p" or ^{2}H to ^{1}H ratio, region. It misses the preferred ^{4}He region, but just overlaps it if one includes all the uncertainties, both statistical and systematic (2σ means that the boxes extend to the 95.4% confidence level, that is, there is only a 4.6% chance that the value of any measurement will lie outside the indicated error boxes). The agreement with ^{4}He is important because nearly all of the neutrons that existed in the early Universe are predicted to end up in ^{4}He nuclei, so its Big Bang value represents the result of a simple prediction. However, astronomers are confident that they have observed ^{2}H in environments that come close to representing the Big Bang abundances, so its value is thought to reflect the Big Bang value. And its predicted value is in excellent agreement with the observed value at precisely the WMAP baryon density. ^{3}He is both made and destroyed in stars, so its BBN value has a greater uncertainty than those of the other BBN nuclides, therefore its BBN value is not usually included as part of the success/failure criteria of BBN theory.

This brings us to ^{7}Li. At low baryon density it is mostly made by the $^{3}\mathrm{H}+{}^{4}\mathrm{He}\rightarrow{}^{7}\mathrm{Li}+\gamma$ reaction, whereas at higher baryonic density mass **7** nuclei are mostly made by the $^{3}\mathrm{He}+{}^{4}\mathrm{He}\rightarrow{}^{7}\mathrm{Be}+\gamma$ reaction, and the ^{7}Be subsequently captures an electron to make ^{7}Li. The mass **7** nuclide production from the former reaction falls off as the baryonic density increases before the latter reaction fully takes over, which is what produces the dip in the ^{7}Li abundance curve. The bottom of the dip is just about what is observed for the Big Bang ^{7}Li abundance. Unfortunately, the CMB value is at a higher baryonic density, and the ^{7}Li abundance at that value is about a factor of 3 above the observed value. The resolution of this discrepancy has been the subject of an enormous amount of research; this is an ongoing research topic for many cosmologists and astronomers.

So how is one to solve the lithium problem? Recent studies [15–17] have looked at possible nuclear reaction solutions, that is, reactions that might contribute to BBN, but which are not well characterized in the BBN computer codes. One particularly interesting aspect of these studies is that, since ^{7}Be is the source of most of the ultimate ^{7}Li abundance during BBN, reactions that might destroy ^{7}Be would mitigate the discrepancy between observation and theory. (Incidentally, there are potentially a lot more reactions that could occur than are indicated above!) All of the above reaction studies identified the $^{7}Be + ^{2}H$ reactions as the most promising candidate for a nuclear physics solution, although one of the studies [15] argued that it could not contribute as would be needed in order to reduce the ultimate ^{7}Li abundance by the required factor of 3. The curious feature of this reaction is that it involves a nucleus, ^{7}Be, that has a half-life of 54 days, making it an extremely difficult nucleus on which to study nuclear reactions. However, an experiment has recently been performed with a ^{7}Be beam [18]; the result was that any reactions involving ^{7}Be and ^{2}H could not resolve the lithium problem.

Are there other possibilities that might resolve the problem? One suggestion that has been studied by several authors [19–21] involves the existence of a short lived particle in the early universe that could have become bound to the nuclei that were formed in BBN. The reason that BBN ceases when it does is that the temperature drops to a point at which the nuclides cannot overcome the Coulomb barriers that they must overcome in order to react. (A Coulomb barrier is the electrostatic barrier that exists between two positively charged particles.) However, assuming the short-lived particle was negatively charged, it would reduce the Coulomb barrier as soon as the Universe cooled to the point at which it could be captured into the nuclei that existed at that time, and thus would permit a short resurgence of nucleosynthesis. In so doing, it was found that the ^{7}Li abundance problem could be solved. Of course, if such a particle does exist, it should be produced in the high energy particle accelerators that exist around the world, but has not been seen yet.

To summarize, the current upshot of BBN is that the predicted abundances of ^{2}H and ^{4}He are in good agreement with those observed in stars or other environments that astronomers have identified as representing early Universe abundances. The agreement with ^{7}Li is poor; the predicted value is about a factor of 3 higher than what is observed.

However, we can't make people out of hydrogen and helium, although some politicians are thought to be comprised primarily of gas, but for the rest of us, we need other atoms like carbon and oxygen. These are made in stars, which is the subject of the next chapter.

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