ARTICLES

Big-Bang Nucleosynthesis and the Baryon Density of the Universe

Craig J. Copi, David N. Schramm, Michael S. Turner

For almost 30 years, the predictions of big-bang nucleosynthesis have been used to test the big-bang model to within a fraction of a second of the bang. The agreement between the predicted and observed abundances of deuterium, helium-3, helium-4, and lithium-7 confirms the standard cosmology model and allows accurate determination of the baryon density, between 1.7×10^{-31} and 4.1×10^{-31} grams per cubic centimeter (corresponding to about 1 to 15 percent of the critical density). This measurement of the density of ordinary matter is pivotal to the establishment of two dark-matter problems: (i) most of the baryons are dark, and (ii) if the total mass density is greater than about 15 percent of the critical density, as many determinations indicate, the bulk of the dark matter must be "nonbaryonic," composed of elementary particles left from the earliest moments.

The extremely high temperatures of the earliest moments of the universe did not allow nuclei to exist. About 1 s after the big bang, the temperature fell to 10^{10} K, and synthesis of the light elements D, ^{3}He, ^{4}He, and ^{7}Li began. The successful predictions of big-bang nucleosynthesis provide the earliest and most stringent test of the big-bang model and, together with the expansion of the universe and the 2.726 K black-body cosmic background radiation (CBR), provide the fundamental observational basis for the standard cosmology.

In 1948 Gamow, Alpher, and Herman proposed that all of the elements in the periodic table could be produced in the big bang (*1*); it was soon realized that the lack of stable nuclei of mass 5 and 8 and Coulomb repulsion between highly charged nuclei prevent significant nucleosynthesis beyond ^{7}Li. Shortly before the discovery of the CBR, Hoyle and Tayler (*2*) argued that the big bang must produce a large amount of ^{4}He (about 25% by mass) and thus could explain the large ^{4}He abundance observed in many primitive objects.

After the discovery of the CBR in 1965, detailed calculations were carried out and showed that a large amount of ^{4}He and smaller amounts of other light elements were produced in the big bang (*3*). While the explanation of the large primeval abundance of ^{4}He was a great success for the big bang, the prevailing wisdom was that D and ^{7}Li were produced primarily during the T Tauri phase of stellar evolution and so were of no cosmological significance (*4*). Because the amount of ^{4}He produced in the big bang is very insensitive to the cosmic baryon (that is, ordinary matter) density, it was not possible to reach any conclusion regarding the mean density of ordinary matter.

The other light elements are produced in much smaller quantities, their abundances relative to hydrogen ranging from about 10^{-5} for D and ^{3}He to about 10^{-10} for ^{7}Li; therefore, establishing their big-bang origin was more difficult, complicated by the fact that the material we see today has been subjected to more than 10 billion years of astrophysical processing, the details of which are still not completely understood. However, over the past 25 years, the big-bang origin of D, ^{3}He, and ^{7}Li has been established, further testing the model and enabling an accurate determination of the average density of baryons in the universe.

By 1973, it was realized that no viable astrophysical site for the production of deuterium exists; for example, although D can be produced by cosmic-rays, so can ^{7}Li, and producing the observed D would lead to a massive overproduction of ^{7}Li (*5*, *6*). Moreover, because D is so fragile, post–big-bang processes only destroy it; thus, the present deuterium abundance serves as a lower bound to the big-bang production. This argument, together with the strong dependence of big-bang deuterium production on the baryon density, led to the realization that D is an excellent "baryometer" (*5*), and early measurements of the deuterium abundance (*7*, *8*), a few parts in 10^5 relative to hydrogen, established that baryons could not contribute more than about 20% of closure density. This important conclusion still holds today.

The evolution of the ^{3}He abundance is more complicated. Helium-3 is produced in stars as they burn their primeval D before reaching the main sequence and later by the nuclear reactions that cook hydrogen into helium. Some massive stars destroy (or astrate) ^{3}He. However, in 1984 it was shown that the present sum of D + ^{3}He provides an upper limit to their combined big-bang production (*9*), which in turn leads to a lower limit to the baryon density.

Lithium was the last to come into the fold. Stellar processes both destroy and produce ^{7}Li; moreover, the abundance of ^{7}Li varies greatly, from $^7\mathrm{Li/H} \simeq 10^{-9}$ to less than $^7\mathrm{Li/H} \simeq 10^{-12}$. In 1982, Spite and Spite circumvented these difficulties by measuring the ^{7}Li abundance in the oldest stars in our galaxy, metal-poor, population II (pop II) halo stars. They found $^7\mathrm{Li/H} \simeq 10^{-10}$ (*10*), which is consistent with the big-bang prediction. Their results, later strengthened by others (*11*, *12*), established the case for the primeval ^{7}Li abundance.

For the last decade, much effort has been devoted to the critical comparison of the theoretical predictions and inferred primordial abundances of the light elements. The predictions depend on the ratio of baryons to photons (η). [The number of baryons is equal to the number of neutrons plus protons; essentially all the photons are in the CBR. The baryon-to-photon ratio remains constant as the universe expands.] If η is between about 2.5×10^{-10} and 6×10^{-10}, then there is agreement between the predicted and measured abundances of all four light elements (see Fig. 1). This leads to the best determination of the baryon density ρ_B

$$1.7 \times 10^{-31}\ \mathrm{g\ cm^{-3}} \leq \rho_B = \eta n_\gamma m_N \leq 4.1 \times 10^{-31}\ \mathrm{g\ cm^{-3}} \quad (1)$$

where m_N is the mass of a baryon, and the number density of photons, $n_\gamma = 411\ \mathrm{cm^{-3}}$, is known very precisely because the CBR temperature, $T_0 = 2.726 \pm 0.005$ K (*13*), is so well determined. On the other hand, because the critical density

$$\rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G} = 1.88h^2 \times 10^{-29}\ \mathrm{g\ cm^{-3}} \quad (2)$$

(where G is the gravitational constant) depends on the Hubble constant H_0 (for convenience, $h \equiv H_0/100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$), which is still only known to within a factor of 2, the fraction of critical density contributed by baryons Ω_B is much less well known

$$0.009h^{-2} \leq \Omega_B \leq 0.02h^{-2} \quad (3)$$

For a generous range for the Hubble constant, h = 0.4 to 1, baryons contribute

C. J. Copi is with the Department of Physics, University of Chicago, Chicago, IL 60637–1433, and NASA Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510–0500, USA. D. N. Schramm and M. S. Turner are with the Department of Physics, University of Chicago, Chicago, IL 60637–1433; NASA Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510–0500; and the Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637–1433, USA.

between 1 and 15% of closure density.

This fact has two profound implications. First, because "optically" luminous matter (stars and associated material) contributes much less than 1% of the critical density [$\Omega_{LUM} \approx 0.003h^{-1}$ (*14*)], most baryons must be dark, for example, in the form of hot, diffuse gas or "dark stars" that have either exhausted their nuclear fuels (black holes, neutron stars, or white dwarfs) or were not massive enough (less than about $0.08M_\odot$) to ignite them. In clusters of galaxies, most of the baryonic matter seems to be in the form of hot, x-ray–emitting gas. Further, there is now indirect evidence for the existence of dark stars within our galaxy, known as MACHOs (massive astrophysical compact halo objects), detected through their gravitational microlensing of distant stars (*15*).

Second, there is strong—though not yet conclusive—evidence that the average mass density of the universe is significantly greater than 15% of the critical density (*16*). If this is indeed the case, most of the mass density of the universe must be "nonbaryonic," with the most promising possibility being elementary particles left over from the earliest moments of the universe (*17*). Large-scale experiments are underway in laboratories all over the world to directly detect the nonbaryonic dark matter associated with the halo of our own galaxy (*18*).

Big-bang nucleosynthesis is central in defining the dark-matter problems, which touch on almost every aspect of cosmology today. For example, the detection of temperature variations in the CBR by the Cosmic Background Explorer (COBE) satellite was a dramatic confirmation of the general picture that structure in the universe (that is, galaxies, clusters of galaxies, superclusters, voids, and so on) evolved from small density inhomogeneities amplified by gravity. One of the great challenges in cosmology is to formulate a coherent and detailed picture of the formation of structure; the nature of the dark matter is crucial to doing so. At present, the most successful models involve nonbaryonic dark matter; prominent among them are the cold dark matter models, where the nonbaryonic dark matter is composed of slowly moving particles (for example, axions or neutralinos) and the density inhomogeneities arose during a period of inflation (*19*).

Primordial nucleosynthesis also allows us to indirectly study conditions in the early universe, and thereby, to probe fundamental physics in regimes that are beyond the reach of terrestrial laboratories. For example, more than 10 years ago, the overproduction of ^{4}He was used to rule out the existence of more than three light (mass $m_\nu \lesssim 1$ MeV) neutrino species and constrain the existence of other light particle species (*20, 21*). Measurements of the properties of the Z^0 boson made with the Stanford Linear Collider (SLC) at the Stanford Linear Accelerator Center (SLAC) and with the Large Electron Positron (LEP) collider at the European Organization for Nuclear Research (CERN) have since determined that there are just three neutrino species.

The remainder of this article is given to a more detailed assessment of the predictions and observations. We begin with the easier part, a discussion of the theoretical predictions, where the few uncertainties are primarily statistical in nature and easy to quantify. We then move on to the more difficult task, a review of the observations. Here the situation is just the reverse: The uncertainties are dominated by possible systematic errors and interpretational issues. Care and júdgment must be exercised to reach reliable conclusions.

Theoretical Expectations

The assumptions underlying the standard scenario of big-bang nucleosynthesis are few: (i) big-bang cosmological model; (ii) three massless (or very light) neutrino species; (iii) small or vanishing neutrino chemical potentials; (iv) no additional light particle species present in thermal abundance; and (v) spatially uniform baryon-to-photon ratio. In addition, there are "nuclear input parameters": neutron mean lifetime, which sets the rate for all the reactions that interconvert neutrons and protons, and cross sections for the nuclear reactions that lead to the synthesis of the light elements. The network of nuclear reactions for big-bang nucleosynthesis is shown in Fig. 2.

As recently as 10 years ago, the uncertainty in the neutron lifetime was significant. Thanks to beautiful experiments with trapped, ultracold neutrons, it is now known very precisely: $\tau_n = 887 \pm 2$ s (*22*). The other cross sections that are required have been measured in the laboratory at energies appropriate for primordial nucleosynthesis (this is in contrast to stellar nucleosynthesis, where laboratory-measured cross sections must be extrapolated to energies that are not nearly as large). With the exception of ^{7}Li, the uncertainties in cross sections do not result in significant uncertainties in the light-element yields. For ^{7}Li, three important cross sections are still poorly known: $^3He + ^4He \rightarrow ^7Be + \gamma$, $^3H + ^4He \rightarrow ^7Li + \gamma$, and $^7Li + p \rightarrow ^4He + ^4He$.

The theoretical uncertainties can be quantified by Monte-Carlo technique (*23, 24*). We ran a suite of 1000 models with input parameters chosen from the probabil-

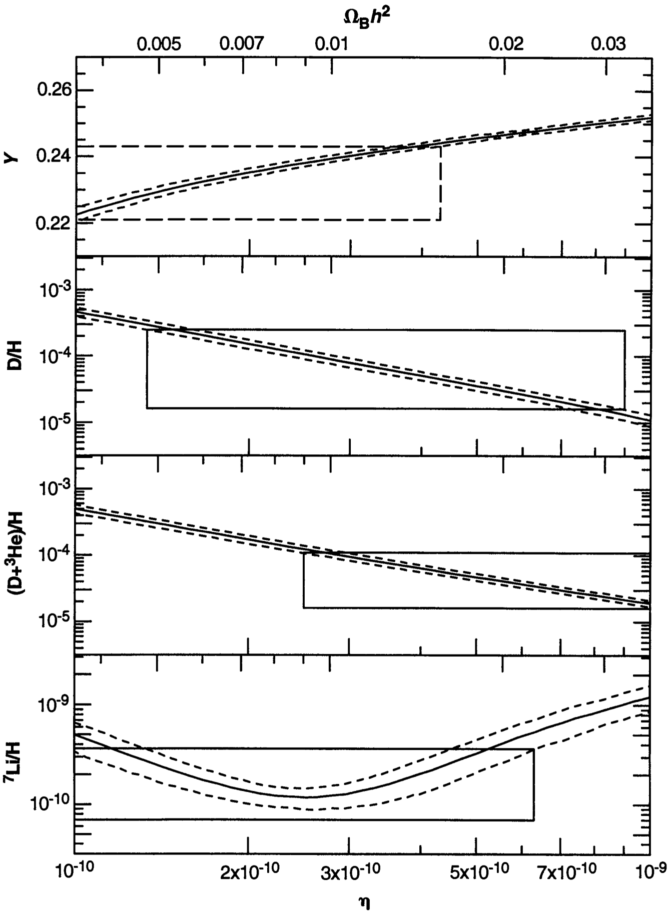

Fig. 1. The predictions of big-bang nucleosynthesis. The dashed curves indicate the 2σ theoretical uncertainties based on our Monte-Carlo analysis. The ^{4}He abundance is given as the mass fraction Y; the other abundances are number relative to hydrogen. The boxes indicate the range of baryon-to-photon ratio consistent with the light-element abundances; the ^{4}He box is broken to remind the reader that ^{4}He has not been used to derive an upper limit to η because of the exponential dependence of such a limit to Y_P. Our concordance range, $2.5 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10}$, derives from D + ^{3}He and ^{7}Li.

ity distributions for the various cross sections and neutron mean lifetime (*25*). The 2σ limits for the light-element abundances are shown in Fig. 1 (that is, 950 of the models have predicted abundances in the intervals shown). The predicted ^{4}He abundance is known very accurately, $\Delta Y_P \simeq \pm 0.001$, where Y_P is the mass fraction of ^{4}He produced; the predictions for D and ^{3}He are uncertain by about 10% and 20%, respectively. For ^{7}Li, the theoretical uncertainty is still about 50%. Updated measurements of the key reactions (Fig. 2) will greatly reduce these uncertainties. In particular, a recent measurement of the reaction $^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Li} + \gamma$ (*26*) has reduced the theoretical uncertainty in ^{7}Li to about 25% for $\eta < 3 \times 10^{-10}$.

Many modifications of the standard scenario have been investigated (*27*): additional light particle species; an unstable, massive tau neutrino; decaying particles; variations in the fundamental constants; large neutrino chemical potentials; primeval magnetic fields; and spatial variations in the baryon-to-photon ratio. In most instances, the "nonstandard physics" was introduced for the purpose of using primordial nucleosynthesis to constrain the possible existence of "new physics"; for example, the previously mentioned limit to the number of light neutrino species. In a few cases, there were more pressing motivations.

For example, Witten suggested that the transition from quark-gluon plasma, which existed before about 10^{-5} s, to matter comprised of neutrons, protons, and related particles could involve a strongly first-order phase transition and that the resulting distribution of baryons could be quite inhomogeneous (*28*). This would significantly change the outcome of primordial nucleosynthesis, and it even appeared that such inhomogeneity could relax the bound to Ω_B, perhaps permitting closure density in baryons (*29*).

It is now known that a high level of inhomogeneity upsets the agreement of the predictions with the observations and that smaller levels of inhomogeneity do not significantly change the results (*30, 31*). Further, there is now little motivation from particle physics for a strongly first-order quark-hadron phase transition. At present, the only modification involving the known particles and known physics that leads to significant changes is the possibility that the tau neutrino is unstable and has a mass between 1 and 30 MeV (*32*) (the present laboratory mass limit is about 30 MeV).

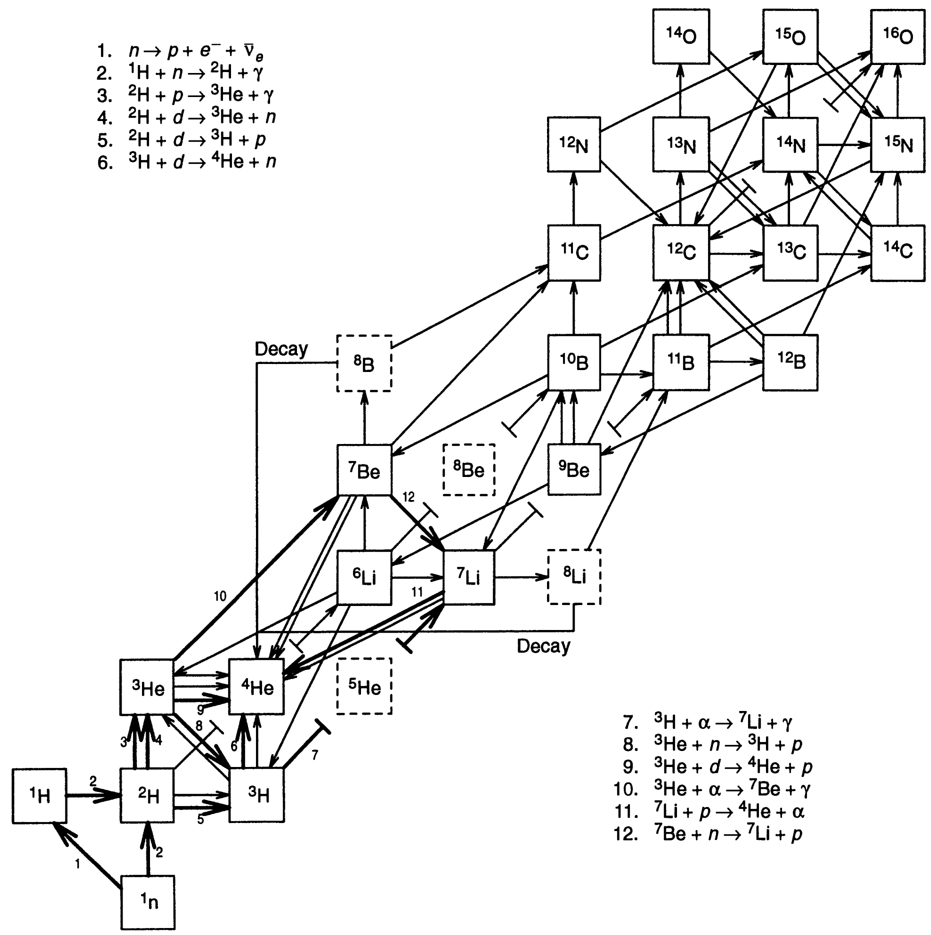

Fig. 2. The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered and have bold arrows. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

Confrontation Between Theory and Observation

In discussing the observed primordial abundances, we emphasize that the abundances are inferred and not measured, because almost without exception, the material that we study today has undergone 10 billion years of chemical evolution (by chemical evolution, astronomers mean the changing chemical abundances in the universe that result from nuclear reactions that take place in ordinary stars, cosmic-ray collisions, stellar explosions, and so on).

Deuterium and helium-3. Because deuterium is the most weakly bound, stable nucleus, it is easy to destroy and difficult to produce. Thus, the deuterium abundance today provides a lower limit to big-bang production. The Apollo Solar Wind Composition experiment, which captured solar-wind particles in foils exposed on the moon, and the subsequent analysis by Geiss and Reeves (*7*) provided the first accurate assessment of the presolar D plus ^{3}He abundance (deuterium present at the time the solar system formed was quickly burnt to ^{3}He as the sun became a star). On the basis of these experiments and studies of the ^{3}He abundance in primitive meteorites (*33*), Geiss deduced a presolar deuterium abundance (*34*)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\odot} = (2.6 \pm 1.0) \times 10^{-5} \qquad (4)$$

This value is consistent with measurements of the deuterium abundance in the local (within a few hundred parsecs) interstellar medium (ISM) made two decades ago with the Copernicus satellite (*8*) and more recently by the Hubble Space Telescope (HST) (*35*)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{HST}} = 1.65^{+0.07}_{-0.18} \times 10^{-5} \qquad (5)$$

That the ISM value is apparently slightly

Table 1. Estimate of systematic errors in the observed ^{4}He abundance.

Type of correction	Estimate (%)
Line ratios (including dust absorption)	±2
Emissivities	±2
Collisional excitation and stellar absorption	±1
Neutral helium	+2
Total	+7, −5

lower than the presolar abundance is consistent with slow depletion of deuterium with time because the material in the ISM is about 5 billion years younger than the material from which our solar system was assembled. On the basis of these measurements and their uncertainties, we deduce a firm lower bound to the primordial deuterium abundance

$$\left(\frac{D}{H}\right)_P \geq 1.5 \times 10^{-5} \qquad (6)$$

Because D production decreases rapidly with η, this leads to an upper limit to η of 9×10^{-10}, which is insensitive to the lower bound adopted for D/H. This argument is very robust because it involves the simplest assumption about chemical evolution, that D is destroyed by stellar processing (*6*).

Because deuterium is so easily destroyed, it is not possible to use the ISM deuterium abundance to obtain a lower bound to η. However, an equally useful bound can be derived from the sum of D + ^{3}He. Primordial deuterium either resides in the ISM or has been burnt to ^{3}He (by means of D + $p \rightarrow {}^3$He + γ). A significant fraction of ^{3}He survives stellar processing, and thus, an upper bound to the primordial D + ^{3}He abundance can be inferred from present-day measurements. Yang *et al.* (*9*) derived such a bound assuming the ^{3}He survival fraction g_3 is greater than 25%. [Low-mass stars are net producers of ^{3}He; even massive stars, which burn ^{3}He, eject some ^{3}He in their winds (*36*).] Their argument was improved by taking account of material that has been processed by more than one generation of stars (*21*). Both methods lead to similar upper limits to the primordial D + ^{3}He abundance

$$\left(\frac{D+{}^3He}{H}\right)_P \leq 1.1 \times 10^{-4} \qquad (7)$$

This then leads to a lower bound to η of 2.5×10^{-10}. Like the upper limit to η based on deuterium, it is insensitive to the precise bound to the primeval abundance of D + ^{3}He because D + ^{3}He production varies rapidly with η. Together, D and ^{3}He define a concordance interval (a range of values for which the predicted abundances are consistent with the observed values) of $2.5 \times 10^{-10} \leq \eta \leq 9 \times 10^{-10}$.

The linchpin of the above argument involves the chemical evolution of ^{3}He, which to be sure is more complicated than that of D. The theoretical belief that low-mass stars increase the D + ^{3}He abundance by producing ^{3}He is supported by the observations of Wilson, Rood, and Bania (*37*), who found ^{3}He/H $\approx 10^{-3}$ in planetary nebulae. This much additional ^{3}He production agrees with the value predicted by stellar models (*38*). However, measurements of the ^{3}He abundance by the same method in hot, ionized gas clouds, so called H II regions, vary greatly from ^{3}He/H $\approx 1 \times 10^{-5}$ to 8×10^{-5} (*39*), which suggests that ^{3}He is destroyed by varying degrees (*40*). Although H II regions are one of the few places outside the solar system where the ^{3}He abundance can be measured, they are samples of the cosmos dominated by the effects of massive, young stars, the most efficient destroyers of ^{3}He, and thus, they do not represent "typical samples" of the cosmos so far as ^{3}He is concerned. All this being said, we believe that a ^{3}He survival fraction of 25% or more is a conservative estimate as applied to the solar system ^{3}He abundance.

Helium-4. In two important regards, the primordial ^{4}He abundance is the easiest to measure: It is large, around 24% by mass fraction, and the chemical evolution of ^{4}He is straightforward—stars are net producers of ^{4}He. On the other hand, although the predicted abundance is accurately known, it varies only logarithmically with η, so measuring the ^{4}He abundance with sufficient accuracy to sharply test the big-bang prediction is still challenging.

Because ^{4}He is ubiquitous, its abundance can be measured in many different ways, all of which give values consistent with a primeval mass fraction of around 24%. Because stars produce both helium and other heavier elements (collectively referred to as metals), contamination from stellar production can be minimized in metal-poor samples of the universe. The most accurate determinations of the primeval ^{4}He abundance rely on measurements of the ratio of helium to hydrogen in highly ionized, extragalactic gas clouds (the H II regions) that are metal poor (*41*). Because of the high quality data that exist and the accuracy of abundances desired, systematic errors now dominate the error budget.

Observed line strengths of the recombination radiation of hydrogen and helium are translated into a helium mass fraction by means of theoretical emissivities and modeling of the H II region. In modeling an H II region, spherical symmetry and uniform temperature are assumed, neither of which actually pertains because a typical H II region is heated by a few massive, young stars near its center. Because the ionization potentials for hydrogen and helium are different, corrections must be made for any neutral or doubly ionized helium present. Collisional excitation can be significant but is not easy to estimate accurately. Stellar absorption by the stars heating the H II region can affect the excitation of the hydrogen and helium in the H II region. Absorption by intervening dust can also affect abundance determinations. A recent analysis of the size of the systematic effects (*42*) is summarized in Table 1. A numerical assessment of some of these effects (*43*) suggests that the systematic errors could even be slightly larger.

Even in the most metal-poor H II regions, some of the ^{4}He is produced by stars. Because stars also produce metals, there should be a direct relation between metallicity and stellar-produced ^{4}He. Oxygen, nitrogen, and carbon have all been used as indicators of stellar nucleosynthesis and hence the amount of stellar-produced ^{4}He (*44*). A recent analysis of all the very metal-poor, extragalactic H II regions yields a primordial ^{4}He abundance (*45*)

$$Y_P = 0.232 \pm 0.003 \pm 0.005 \qquad (8)$$

where the statistical error is quoted first and the systematic error appears second (Fig. 3).

To summarize, there is undisputed evidence for a large primeval ^{4}He abundance whose only viable explanation is the big bang and which provides the strongest confirmation of big-bang nucleosynthesis. On the basis of (*45*), we take Y_P = 0.221 to 0.243 as a reasonable estimate for the primeval mass fraction, which allows for a 2σ statistical uncertainty plus a 1σ systematic uncertainty. The 2σ theoretical range is

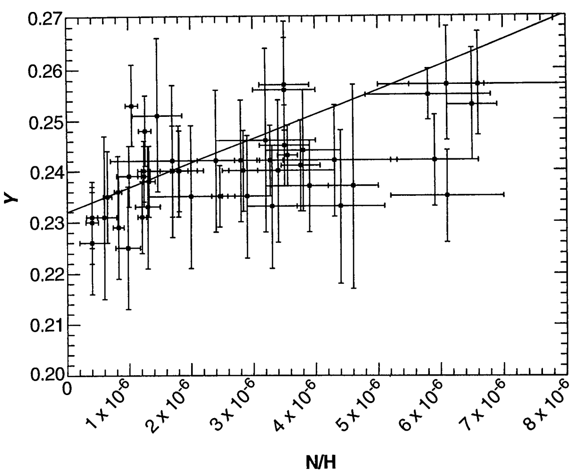

Fig. 3. The ^{4}He mass fraction versus nitrogen abundance for very metal-poor, extragalactic H II regions. The solid line is the best extrapolation to zero metallicity (*45*).

consistent with this provided $0.8 \times 10^{-10} \leq \eta \leq 4 \times 10^{-10}$. However, the uncertainties are dominated by possible systematic errors; allowing for the higher estimate of systematic error in (*42*) (compare with Table 1), a primeval ^{4}He mass fraction as low as 0.21 or as high as 0.25 could not be excluded with certainty. This more extreme range for the primeval ^{4}He abundance is consistent with a much larger interval, $6 \times 10^{-11} \leq \eta \leq 1 \times 10^{-9}$, illustrating the logarithmic dependence of Y_P on η.

Lithium. The study of extremely metal-poor, pop II halo stars provides the bulk of our knowledge about the primeval ^{7}Li abundance. Spite and Spite (*10*) measured the ^{7}Li abundance as a function of metallicity (iron abundance) and surface temperature. They found that the ^{7}Li abundance is flat for surface temperatures greater than about 5600 K (Fig. 4), and further, it is also flat for the stars with the lowest iron abundance (Fig. 5). The first plateau suggests that the stars with the highest surface temperatures are not destroying their ^{7}Li by convection (the depth of the convective zone depends on surface temperature and is shallowest for stars with the highest surface temperatures). The second plateau indicates that any post–big-bang production must be insignificant for the most metal-poor stars because the ^{7}Li abundance does not increase with iron abundance.

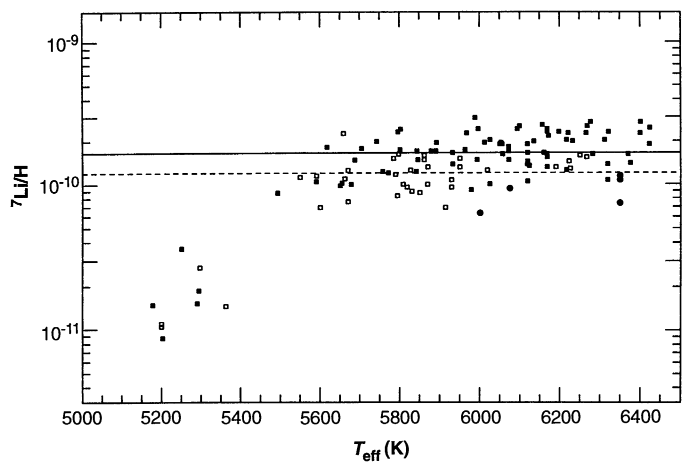

Fig. 4. The ^{7}Li abundance as a function of surface temperature for very metal-poor, pop II halo stars. The decreasing ^{7}Li abundance in the stars with the lowest surface temperatures indicates they have burned some of their ^{7}Li (consistent with the fact that such stars are predicted to have deeper convection zones). The solid and dashed lines indicate the Thorburn (*12*) and Spite and Spite (*10*) plateaus, respectively.

The determination of the plateau value of the ^{7}Li abundance is subject to systematic effects. The effective surface temperatures and assumptions about opacities differ from author to author; both affect the inferred ^{7}Li abundance. These two effects largely explain the difference between the abundance found by Spite and Spite (*10*), $^7\mathrm{Li/H} = 1.1 \times 10^{-10}$, and that derived recently by Thorburn (*12*) from a sample of 90 pop II stars, $^7\mathrm{Li/H} = 1.7 \times 10^{-10}$ (Figs. 4 and 5). Further, Thorburn's data seem to indicate a slight variation of the ^{7}Li abundance with surface temperature, possibly indicating some depletion from a higher primordial value by processes that transport ^{7}Li inward [for example, meridional mixing (*46*)] to regions that have a high enough temperature to burn ^{7}Li. However, the amount of depletion is constrained by the relatively narrow spread in ^{7}Li abundance for a wide range of surface temperatures and metallicities.

The case against significant depletion—and hence for a plateau abundance that reflects the primeval abundance—was further strengthened by the observation of ^{6}Li in two pop II stars (*47*). Big-bang production of ^{6}Li is negligible; the ^{6}Li seen was most likely produced by cosmic-ray processes (along with beryllium and boron, as discussed below). Because ^{6}Li is much more fragile than ^{7}Li and yet still survived with the abundance relative to Be and B expected from cosmic-ray production, depletion of ^{7}Li cannot have been very significant (*48*). These ^{6}Li measurements limit possible ^{7}Li depletion to less than a factor of about 2.

In summary, we infer a primordial ^{7}Li abundance of

$$\left(\frac{^7\mathrm{Li}}{\mathrm{H}}\right)_P = (1.4 \pm 0.3^{+1.8}_{-0.4}) \times 10^{-10} \quad (9)$$

where the central value is the average of the Spite and Spite (*10*) and Thorburn (*12*) determinations, the statistical error is listed first, and the systematic error second. The systematic error consists of ± 0.4 from differences in model atmospheres and $+1.4$ to account for possible depletion. In fixing a range for the primordial ^{7}Li abundance, it is the systematic error that is most important; accordingly, we use the sum of statistical plus systematic error to derive our estimate for the ^{7}Li abundance, $0.7 \times 10^{-10} \leq {}^7\mathrm{Li/H} \leq 3.5 \times 10^{-10}$. Allowing also for the 2σ theoretical uncertainty, the concordance interval is $1 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10}$.

Beryllium and boron. Although the inhomogeneous variant of big-bang nucleosynthesis motivated by a first-order quark-hadron phase transition cannot significantly alter the basic conclusions, an important question remains: Is there an observable signature that can differentiate between the inhomogeneous and the homogeneous models? Regions in inhomogeneous models with high neutron-to-proton ratio could lead to "leakage" beyond mass 5 and mass 8: ^{9}Be, ^{10}B, ^{11}B, and possibly even *r*-process elements (neutron-rich isotopes) (*29*). Unfortunately, detailed studies (*30, 31*) indicate that such leakage is negligible when the D, ^{3}He, ^{4}He, and ^{7}Li abundances are consistent with their observed values. [Other signatures, such as low ^{4}He and high D and ^{7}Li, have been discussed (*31*); but at present, they are inconsistent with the data.]

Recently, both beryllium (*49, 50*) and boron (*51*) have been detected in metal-poor, pop II halo stars. The observations indicate that beryllium and boron abundances increase with metallicity, which is inconsistent with a big-bang origin (*49, 51, 52*) and indicative of post–big-bang origin. The processes that produce the beryllium and boron (and ^{6}Li) seen in younger pop I stars (like our sun) are thought to be cosmic-ray reactions (*53*); these processes are a good candidate for producing the beryllium and boron seen in the pop II stars.

Toward truly primordial abundances. The task of disentangling 10 billion years of galactic chemical evolution is not easy. What are the prospects for determining the light-element abundances in very primitive samples of the universe (that is, in objects seen at very high redshift)?

Gas clouds at high redshift "backlit" by quasars offer the possibility of measuring the deuterium abundance in very old, very distant, and very primitive samples of the cosmos. These clouds, known as quasar absorption line systems, are revealed by the absorption features they produce in quasar spectra: Many are observed to be very metal-poor. Recently, a possible detection of deuterium in a hydrogen cloud at redshift $z = 3.32$ was announced (*54*); if it is deuterium, it corresponds to an abundance

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_P = (1.9 \text{ to } 2.5) \times 10^{-4} \quad (10)$$

There is a significant probability (15% or greater) that the feature seen (the deuterium Lyman α line) arises from the Lyman α line of a smaller hydrogen cloud at slightly lower redshift. Further, the same deuterium feature has been detected in two other hydrogen clouds with high redshifts but with an abundance that is about a factor of 10 smaller. These results are not yet published (*55*).

If we conservatively interpret the published detection as an upper bound to the primordial deuterium abundance, we find the constraint to be $\eta \geq 1.6 \times 10^{-10}$, which is only slightly less stringent than the previous bound based on the production of

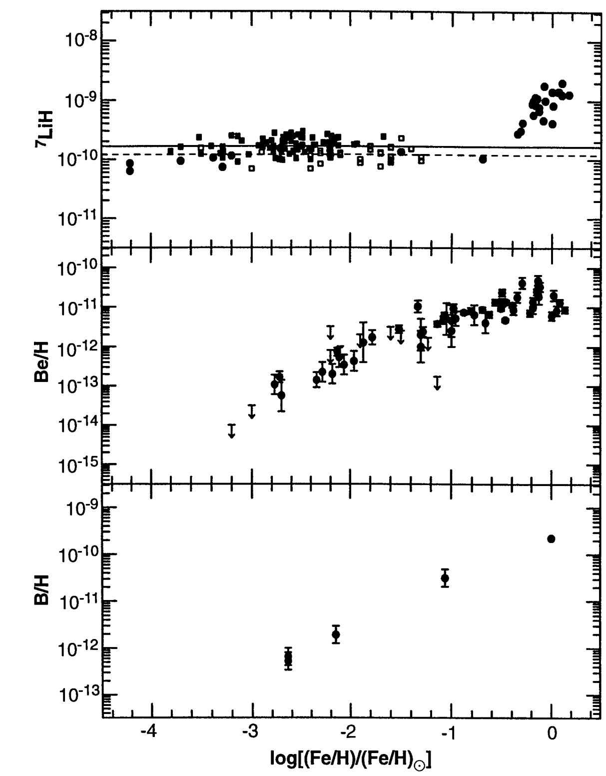

Fig. 5. The ^{7}Li abundance as a function of iron abundance (relative to that seen in the solar system) for stars with surface temperatures greater than 5600 K. The increase in ^{7}Li abundance seen for the stars with higher iron abundance is indicative of additional ^{7}Li from cosmic-ray processes and stellar production. The solid and dashed lines indicate the Thorburn (*12*) and Spite and Spite (*10*) plateaus, respectively. For comparison, the abundances of beryllium and boron in metal-poor, pop II halo stars are also shown (*52*). Unlike the ^{7}Li abundance, the B and Be abundances increase with increasing metal abundance, indicative of significant post–big-bang production.

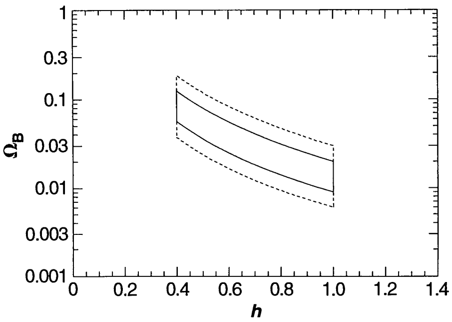

Fig. 6. The fraction of critical density contributed by baryons as a function of the Hubble constant for the reasonable concordance range of baryon-to-photon ratio (solid) and the extreme concordance range (dashed).

D + ^{3}He. If instead we interpret it as a measurement of the primordial deuterium abundance, then the baryon-to-photon ratio has been accurately measured, $\eta \simeq 1.6 \times 10^{-10}$. However, this interpretation is somewhat troubling because $(D/H)_P \approx 2 \times 10^{-4} \gg [(D + {}^3He)H]_\odot \approx 4 \times 10^{-5}$. Because it is almost certain that D is destroyed by burning to ^{3}He, one would expect a much higher D + ^{3}He abundance than has been observed. This could indicate a problem with models of the chemical evolution of ^{3}He or simply in the interpretation of the observation as a deuterium detection (*56*). [The unpublished detections (*55*) are in line with what is expected for the primeval deuterium abundance on the basis of the present D + ^{3}He abundance.] More data of this kind is likely to come soon and clarify the situation.

With regard to ^{3}He, one might hope to determine the ^{3}He abundance in extragalactic H II regions that are very metal-poor. However, present technology is only marginally sufficient to observe ^{3}He in galactic H II regions, so it will likely be some time before extragalactic detections are possible.

The ^{4}He abundance has been measured through its absorption lines in a quasar at redshift $z = 2.72$ (HS1700+6414) (*57*), and very recently, observations made with the refurbished Hubble Space Telescope have revealed the presence of singly ionized ^{4}He in the intergalactic medium (*58*). Although both measurements provide important confirmation of a large, primeval ^{4}He abundance in very primitive samples of the cosmos, they lack the precision necessary to sharply test big-bang nucleosynthesis. Very metal-poor, nearby extragalactic H II regions are likely to continue to be most useful.

It seems very unlikely that the ^{7}Li abundance can be measured in high-redshift objects, or even in extragalactic stars. On the other hand, the data at hand present a good case for having determined the ^{7}Li abundance in the oldest stars in our galaxy.

Implications and Future Directions

The light-element abundance data are not yet good enough to single out a value for the baryon-to-photon ratio. They are good enough to delineate a very narrow concordance interval where the predicted abundances of all four light elements are consistent with their measured values.

The lower limit to the concordance interval hinges on the D + ^{3}He abundance. Based on our understanding of the difficulty of efficiently destroying ^{3}He, $\eta = 2.5 \times 10^{-10}$ stands as a reliable lower bound. This lower bound is buttressed by both ^{7}Li—for $\eta \leq 1 \times 10^{-10}$, the predicted ^{7}Li abundance rises above 3.5×10^{-10}—and by the upper limit to the primitive deuterium abundance discussed above—for $\eta \leq 1.6 \times 10^{-10}$, D/H exceeds 2.5×10^{-4}.

The upper limit to the concordance interval derives from ^{4}He, ^{7}Li, and D, with the stringency of the limits in that order but the reliability in the reverse order. If the primordial mass fraction of ^{4}He is no larger than 0.243 (*45*), then η must be less than 4×10^{-10}. But if, owing to systematic error, Y_P is as large as 0.25, then η could be as large as 1×10^{-9}. The logarithmic dependence of the ^{4}He mass fraction on η makes it a very poor baryometer.

The uncertainty in our upper bound to ^{7}Li, ^{7}Li/H $\leq 3.5 \times 10^{-10}$, is primarily systematic error associated with possible ^{7}Li depletion in metal-poor, pop II stars. Our upper bound to ^{7}Li implies $\eta \leq 6 \times 10^{-10}$. On the other hand, because the strongest argument against very significant depletion of ^{7}Li in metal-poor, pop II stars is the observation of ^{6}Li, which has only been seen in two stars, very significant depletion of ^{7}Li cannot be ruled out. Taking as an extreme upper limit ^{7}Li/H $\approx 6 \times 10^{-10}$, corresponding to a depletion by a factor of 4, η could be as large as 9×10^{-10} (*59*).

The primordial deuterium abundance must be larger than what is seen today: D/H $\geq 1.5 \times 10^{-5}$. This implies an upper bound to η of 9×10^{-10}. Because there is no viable astrophysical site for deuterium, it is difficult to get around this bound.

It is not possible to specify 2σ and 3σ concordance intervals because the dominant uncertainties, primarily in the inferred abundances, are not Gaussian statistical errors. Instead, we specify a "reasonable" and an "extreme" concordance interval for the baryon-to-photon ratio. For the reasonable interval, we take 2.5×10^{-10} to 6×10^{-10}, supported from below by D + ^{3}He overproduction and above by ^{7}Li overproduction. [This concordance interval is essentially the same as that derived in 1984 by Yang *et al.* (*9*), slightly less restrictive than that of Walker *et al.* (*21*), who did not allow for systematic error in the ^{7}Li abundance, and very much less restrictive than those of Smith *et al.* (*23*) and Kernan and Krauss (*24*), who both based their upper limit to η on ^{4}He.]

In setting our extreme range, we take

note of our less than perfect understanding of the chemical evolution of the universe during the 15 billion years or so since primordial nucleosynthesis, as well as other possible systematic errors. Though there is little reason to believe that ^{3}He could be astrated significantly or that the primeval ^{7}Li abundance differs significantly from that seen in halo pop II stars, we base our extreme concordance range, $\eta = 1.6 \times 10^{-10}$ to 9×10^{-10}, solely on deuterium.

From these concordance intervals, we can bound the baryonic fraction of critical density, albeit at the expense of additional dependence on the Hubble constant: For the reasonable estimate, $2.5 \times 10^{-10} \leq \eta \leq 6 \times 10^{-10}$, we get $0.009 \leq 0.009h^{-2} \leq \Omega_B \leq 0.02h^{-2} \leq 0.14$; for the extreme estimate, $1.6 \times 10^{-10} \leq \eta \leq 9 \times 10^{-10}$, we get $0.006 \leq 0.006h^{-2} \leq \Omega_B \leq 0.03h^{-2} \leq 0.21$, where the outer limits to Ω_B allow for $0.4 \leq h \leq 1$ (Fig. 6).

The implications of these big-bang nucleosynthesis bounds for cosmology are manifold and very significant. First and foremost, the nucleosynthesis determination of the baryonic fraction of critical density, taken together with the observational data that indicate that luminous matter contributes much less than 1% of critical density and that the total mass density is greater than 14% of critical density, makes the case for the two dark matter problems: (i) Most of the baryons are dark, and (ii) most of the mass density in the universe exists in the form of nonbaryonic dark matter. Dark matter is one, if not the most, pressing issue in both cosmology and particle physics today. Detecting nonbaryonic dark matter could provide the first evidence for theories that unify the forces of nature, and the composition of the dark matter is crucial to understanding how structure formed in the universe.

Next, we mention an important and topical use of the relatively well known baryon density. From measurements of the ratio of total mass to baryonic mass in clusters of galaxies, the total mass density in the universe can be estimated as

$$\Omega_0 = \frac{M_{tot}(\text{cluster})}{M_B(\text{cluster})}\Omega_B \qquad (11)$$

Clusters of galaxies are used because they are probably large enough to provide a "fair sample" of the universal mix of matter and their x-ray emission allows a determination of both the total mass and baryonic mass. White *et al.* (60) inferred a total mass–to–baryonic mass ratio of $(20\pm5)h^{3/2}$ for the Coma cluster, which leads to the estimate $\Omega_0 \simeq 0.15h^{-1/2}$ to $0.5h^{-1/2}$. If h is near the lower extreme of current measurements, this determination of Ω_0 lends some support to both nonbaryonic dark matter and the theoretically attractive notion of a flat universe (that is, $\Omega_0 = 1$). However, there are still important systematic sources of error and a key assumption associated with this method. The key assumption is that the baryons are either in stars (visible matter) or hot, x-ray–emitting gas (by a wide margin, the baryons in the hot gas outweigh those in stars). If there is a large amount of baryonic matter hidden in dark stars, then M_{tot}/M_B would be smaller. On the other hand, essentially all systematic errors go in the direction of increasing M_{tot}/M_B. If the hot gas is partially supported by magnetic fields or bulk motion of the gas, then M_{tot} is larger. If the hot gas is clumpy, then the gas mass is smaller.

Although our primary concern here is the baryon density of the universe, big-bang nucleosynthesis also places an important constraint on the number of light particle species present around the time of nucleosynthesis, quantified as the equivalent number of neutrino species, N_ν. This limit arises because more species lead to additional ^{4}He production (*20*). The limit to N_ν relies on a lower limit to η and an upper limit to Y_P. With the D + ^{3}He lower bound ($\eta \geq 2.5 \times 10^{-10}$) and our reasonable upper limit to ^{4}He ($Y_P \leq 0.243$), it follows that $N_\nu \leq 3.3$. Unlike the upper bound to η, this limit is only weakly dependent on Y_P, $N_\nu \lesssim 3.3 + (Y_P^{max} - 0.243)/0.012$.

We believe that primordial nucleosynthesis will continue to be the best method for determining the mean baryon density and that deuterium will prove to be the ultimate baryometer. Prospects for measuring its primeval abundance in high-redshift, metal-poor gas clouds are good, and a handful of such measurements could establish the primeval D abundance to a precision of 10%, and in turn, the baryon density to better than 5%. Because ^{4}He production depends so weakly on the baryon-to-photon ratio and because of lingering systematic uncertainties associated with ^{7}Li, both ^{4}He and ^{7}Li are destined to play supporting roles, albeit important ones. It is both ironic and satisfying that after 20 years, deuterium is still the best baryometer.

More than 40 years have passed since Gamow's introduction of the notion of cosmological nucleosynthesis, and 30 years have passed since the CBR was discovered. Two decades of careful comparison of theory with observation has made primordial nucleosynthesis the earliest and most important test of the standard cosmology and has led to the best measurement of the density of ordinary matter in the universe.

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Prospects for Larger or More Frequent Earthquakes in the Los Angeles Metropolitan Region

James F. Dolan,* Kerry Sieh, Thomas K. Rockwell, Robert S. Yeats, John Shaw, John Suppe, Gary J. Huftile, Eldon M. Gath

Far too few moderate earthquakes have occurred within the Los Angeles, California, metropolitan region during the 200-year-long historic period to account for observed strain accumulation, indicating that the historic era represents either a lull between clusters of moderate earthquakes or part of a centuries-long interseismic period between much larger (moment magnitude, M_w, 7.2 to 7.6) events. Geologic slip rates and relations between moment magnitude, average coseismic slip, and rupture area show that either of these hypotheses is possible, but that the latter is the more plausible of the two. The average time between M_w 7.2 to 7.6 earthquakes from a combination of six fault systems within the metropolitan area was estimated to be about 140 years.

Californians have long anticipated the recurrence of the "Big One," a great earthquake (M ~ 8) emanating from a long section of the San Andreas fault (SAF), such as occurred in 1857 and 1906. Consequently, earthquake hazard assessment and preparedness in southern California has historically focused primarily on the SAF and its various strike-slip branches (Fig. 1) (*1*, *2*). In the past decade, however, several moderate earthquakes have occurred on faults beneath the Los Angeles metropolitan area. Moderate to large earthquakes (M_w 6.5 to 7.5) on these faults could potentially cause even more damage than a much larger earthquake on the more distant SAF. This was dramatically demonstrated by the 1994 M_w 6.7 Northridge earthquake, the second most expensive natural disaster in U.S. history (after Hurricane Andrew) (*3*).

The Los Angeles region is geologically complex, and almost 100 active faults have been identified in the area (*4–8*). Because of their size and proximity to major population centers, six major fault systems are of particular concern (*9–12*).

1) The Sierra Madre–Cucamonga system extends for 100 km along the northern edge of the densely populated San Fernando and San Gabriel valleys (*13*, *14*). The westernmost 19 km of the north-dipping Sierra Madre fault zone (including the San Fernando fault) ruptured during the 1971 M_w 6.7 Sylmar earthquake, which claimed 64 lives and caused $558 million in damage (1971 dollars; ~$2 billion in 1994 dollars) (*15*).

2) The Los Angeles basin fault system comprises two major blind thrust fault ramps (Elysian Park and Compton ramps) that are connected by a mid-basin flat fault segment (*7*; *16*). The Whittier fault (*17*) and the northern Newport-Inglewood fault zone (*4*, *7*) may represent partitioned strike-slip faults above the blind thrust faults. This system underlies the most densely urbanized part of the region, including downtown Los Angeles.

3) The Santa Monica Mountains fault system, which extends for 90 km from near downtown Los Angeles westward along the Malibu Coast, consists of a large blind thrust ramp and the surficial Hollywood–Santa Monica–Malibu Coast subsystem, which we interpret as a set of predominantly left-lateral strike-slip faults (*4*, *5*, *16*, *18–20*).

4) The Oak Ridge fault system is a major south-dipping thrust system that extends for more than 70 km from just east of Ventura to at least the eastern end of the Santa Clarita River Valley (*21*, *22*). A previously unrecognized, blind eastern extension of this system appears to have been responsible for the 17 January 1994 M_w 6.7 Northridge earthquake (*8*).

5) The San Cayetano fault, which dips moderately northward, extends for 40 km along the northern boundary of the oil-rich Ventura basin (*23*). The eastern part of this fault exhibits one of the highest slip rates in the region (7.5 to 10.4 mm year^{-1}) (*23*).

6) The Palos Verdes fault, which is best known from its onshore extent along the northeastern edge of the Palos Verdes Peninsula in the southwestern part of the Los Angeles basin, also extends as a submarine feature for more than 50 km to the south of the peninsula (*24*). Recent studies indicate that the Palos Verdes fault is slipping at a rate of approximately 3 mm year^{-1} (*25*).

The large number of damaging, moderate ($4.8 \leq M_w \leq 6.7$) earthquakes that have occurred in the Los Angeles region

J. F. Dolan and K. Sieh are with the Seismological Laboratory 252-21, California Institute of Technology, Pasadena, CA 91125, USA. T. K. Rockwell is with the Department of Geological Sciences, San Diego State University, San Diego, CA 92182, USA. R. S. Yeats and G. J. Huftile are with the Department of Geological Sciences, Oregon State University, Corvallis, OR 97331, USA. J. Shaw is with the E&P Technology Department, Texaco, Houston, TX 77042, USA. J. Suppe is with the Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544, USA. E. M. Gath is with Leighton and Associates, Irvine, CA 92714, USA. All authors are with the Earthquake Geology Group at the Southern California Earthquake Center, University of Southern California, Los Angeles, CA 90089, USA.

*To whom correspondence should be addressed.