PERSPECTIVES: COSMOLOGY

A Census of Cosmic Matter

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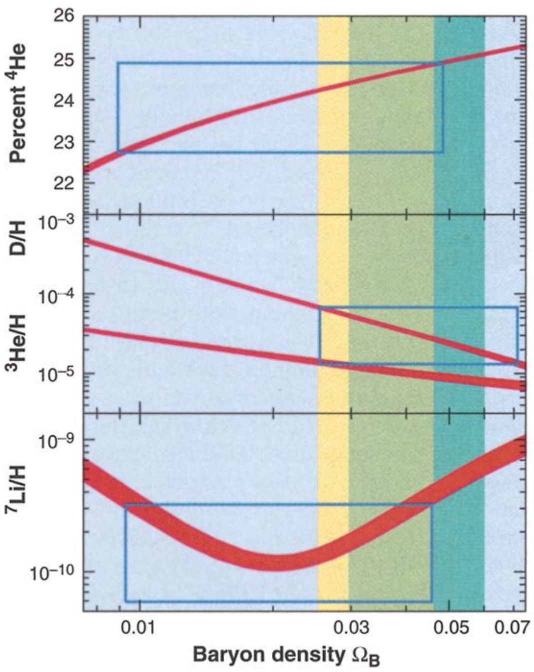
The advent of new, high-precision data is sharpening our view of the past and present universe and firming up our accounting of matter and energy within the universe, with profound implications for our understanding of dark matter and fundamental physics. These advances are made possible by the ability of new data to reveal connections between two pivotal aspects of the early universe: Big Bang nucleosynthesis (BBN) and the cosmic microwave background (CMB).

Both of these phenomena are inevitable consequences of the Big Bang. We observe galaxies receding from us today and infer that the universe is expanding. In the past, therefore, matter in the universe was more concentrated. Extrapolating to very early times, we conclude that the universe was once very dense and very hot. BBN and the CMB follow from applying well-tested principles of atomic and nuclear physics to this hot, dense, and rapidly expanding early universe.

BBN marks a milestone in the cosmic history of ordinary matter—"baryons" in the language of particle physics—which is broadly understood to be anything made of protons, p, and neutrons, n. (This includes the entire periodic table.) BBN took place between 1 s and about 3 min after the Big Bang, when matter was so hot ($>10^9$ K) that not only were atoms ionized into bare nuclei and free electrons, even the nuclei themselves were "ionized" into their constituent neutrons and protons. As the expansion of the universe cooled the plasma, neutrons and protons combined to form bound states, that is, nuclei. These were created via fusion reactions, which first produced deuterium (the np bound state) and then the very stable ^{4}He (2p2n) nucleus.

For three decades (*1*), the likely chemical makeup of baryonic matter after BBN has been carefully calculated. Increasingly sophisticated networks of nuclear reactions have led to ever more precise predictions (*2*), but the main result has remained unchanged: After BBN, the baryons are believed to have consisted of ~76% (by mass) hydrogen and ~24% ^{4}He, with trace amounts of the isotopes deuterium (D), ^{3}He, and ^{7}Li. These abundances depend in different ways on the amount (density) of baryons in the universe (see the figure). For example, ^{4}He makes for an almost density-independent test of the basic BBN framework, whereas deuterium is an excellent probe of the baryon density, Ω_B.

BBN theory thus predicts that 3 min after the Big Bang, the light element abundances were set at uniform levels across the cosmos. We can test this theory by observing the light elements in different astronomical environments. Unfortunately, no one setting allows measurement of all primordial abundances. Luckily, the homogeneous nature of the Big Bang allows us to meaningfully compare abundances from different sites. For example, ^{4}He is observed in nearby dwarf galaxies (*3*, *4*), whereas deuterium is observed in distant protogalactic clouds (*5*). As seen in the figure, theory and observations are in concordance, but only if the baryon density is a fraction Ω_B = 2.6 to 4.6% of the amount needed to keep the universe from expanding forever.



A cosmic census of baryons. The light element abundances predicted by BBN theory are shown in red as a function of cosmic baryon density (expressed as a fraction Ω_B of the "critical" density required to prevent the universe from expanding forever). The observed range of each light element's abundance sets the height of the three boxes. For each element, the observed data range and the theory curves combine to select a domain in Ω_B, shown as the horizontal range of the box. The vertical overlap of the boxes thus gives the range in Ω_B for which BBN theory and observations agree. This is the BBN measurement of cosmic baryons (yellow band). The CMB range for Ω_B (green band) agrees with the BBN result.

BBN theory and light element abundances thus allow us to determine the amount of normal matter in the universe. Because $\Omega_B << 100\%$, we see that the baryon density falls far short of that needed to keep the universe from expanding forever. Furthermore, other means of weighing the universe indicate that the total density of matter in any form is considerably larger, ~30%. Hence, most of the matter in the universe is exotic—not made of protons and neutrons.

This conclusion rests on our knowledge of the total matter content of the universe. A new way to measure both the total and baryonic densities is via the CMB.

Just as BBN was the "nuclear age" of the cosmos, the CMB was created during the "atomic age," when the temperature and particle energies were comparable to atomic energy scales. Before the universe was about 300,000 years old, it was so hot that the atoms were ionized. The universe was therefore filled with free electrons, which readily scatter light, and the cosmos was opaque. When the universe cooled below about 3000 K, the free electrons and ions combined to form neutral atoms and the universe became transparent.

The thermal radiation present at that time, mostly in the form of ultraviolet light, was released and has since traveled freely in all directions, losing energy as the photon wavelengths stretch with the cosmic expansion. Those photons today are in the microwave band (hence their name). Their spectrum is very precisely thermal (blackbody), a powerful indication that matter and radiation in the universe were once in thermal equilibrium.

The CMB is highly uniform across the sky. It does, however, contain tiny temperature variations from one direction to another. Balloon flights and ground-based experiments at the South Pole have now made first measurements of fluctuations at angles <1° (*6*, *7*). The CMB temperature variations at these small angles encode information about the motion of the baryon-photon

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plasma in response to the gravitational influence of dark matter. They can be mined for a wealth of cosmological parameters, including the baryon density.

The CMB thus provides another independent measurement of the cosmic baryon density, that is, the amount of normal matter in the universe. A comparison between the CMB and the BBN measurements marks a fundamental test of cosmology. Current CMB data are preliminary, but the overlap between the BBN and CMB inventory of baryons (see the figure) indicates agreement between the two values.

The present agreement is remarkable and tantalizing but it is preliminary. New data will soon provide a much stronger test. Space-based missions will make precise measurements of CMB fluctuations and yield baryon density measurements accurate to a few percent. One mission, the Microwave Anisotropy Probe (MAP), launched in July of this year, should be reporting its first results in 2002.

The MAP results will provide profound insights into the baryon density in the universe. If the CMB and BBN results disagree, this could point to unexpected new physics at work in the early universe—or unexpected errors in the BBN and CMB analyses. It is more likely, in my view, that the two will agree, in a beautiful convergence of two lines of cosmological study. If so, then the new CMB results can be combined with BBN to probe the physics of the early universe and the astrophysical evolution of the light elements (*8*). In any case, we are entering a new era in cosmology, which promises to teach us much about the nature of the universe and the matter within it.

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PERSPECTIVES: DEVELOPMENT

Endothelium—Chicken Soup for the Endoderm

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That metaphorical sustenance we call chicken soup is widely acclaimed for its ability to provide nourishment to the sick as well as nutrients for normal growth. In this week's issue, Matsumoto *et al.* on page 559 (*1*) and Lammert *et al.* on page 564 (*2*) establish that endothelial cells, which line the blood vessels (*3*, *4*), and their precursors form the "chicken soup" that sustains the early development of organs (such as the liver and pancreas) that are derived from the embryonic endoderm.

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Matsumoto and colleagues (*1*) studied mice deficient in Flk-1, the receptor for vascular endothelial growth factor (VEGF), which stimulates the formation of new blood vessels (angiogenesis). Mice deficient in Flk-1 lack both mature blood vessels and blood, and die at embryonic day E9.5 to E10.5 (*5*). In Flk-1-deficient embryos, the endoderm destined to become the liver thickens at E9.0 as usual, but surprisingly does not develop into embryonic liver buds. Expression of the genes *albumin*, *transthyretin*, and *Hex*, indicators of liver induction in the developing embryo, seem normal. Unfortunately, because Flk-1–deficient embryos die before the liver is fully formed, the fate of the liver at later stages of development could not be deduced. To address the shortcoming of their mouse model, the authors developed a unique liver explant system in which the liver bud regions of E9.5 embryos were removed and cultured in vitro. Liver buds cultured from either wild-type embryos or heterozygous embryos with only one functional copy of the *flk-1* gene increased in size 15-fold during a 72-hour period, with hepatic cells constituting 20% of the cellular mass. Surprisingly, homozygous embryos with no functional copies of the *flk-1* gene also grew 15-fold (from a smaller starting amount of tissue), but only 5% of their total cellular mass was made up of hepatic cells. Wild-type endodermal explants treated with the angiogenesis inhibitor NK4 (*6*) had growth characteristics mimicking those of the Flk-1–deficient explants, suggesting that early endothelial cells are involved in liver development.

Lammert and colleagues (*2*) took a different tack, examining how endothelium influences the development of the pancreas in both the mouse and the frog *Xenopus*. These investigators blocked formation of the principal blood vessel, the aorta, in *Xenopus* embryos by excising aortic precursor cells. They discovered reduced production of the pancreatic hormone insulin and of two transcription factors, NeuroD and Pax6, which are known to be expressed in the pancreas. The lack of expression of these pancreatic markers indicated that the pancreatic precursor cells had failed to develop. Adjacent structures, such as the gut tube and notochord, were unaffected. These results demonstrate that endothelial cell signals are required for pancreatic cell growth in *Xenopus* embryos (see the figure).

The transcription factor Pdx1 (pancreatic duodenal homeobox 1) is a marker of early pancreatic development in the mouse. Pdx1 is expressed early in development in the region where the pancreas and parts of the duodenum and stomach form, but by birth its expression is restricted to the pancreatic islet cells (*7*). When Lammert and co-workers recombined embryonic mouse aorta with isolated endodermal tissue in vitro, genes encoding both Pdx1 and insulin were expressed, and budlike pancreatic primordia occasionally appeared (*2*). In their most intriguing experiment, Lammert *et al.* created transgenic mice harboring a *Vegf* gene whose expression was driven by the promoter of the *Pdx1* gene. In these transgenic mice, *Vegf* is expressed early in development in those areas where the pancreas, duodenum, and parts of the stomach will form. These animals developed hyperplasia of pancreatic islet tissue and a hypervascularized pancreas. Expression of the *Vegf* transgene in the stomach and duodenum was accompanied by misplaced (ectopic) production of endothelial cells in these areas. Clusters of insulin-producing cells were seen adjacent to the endothelial cells in the stomach and duodenum, tissues that do not normally produce insulin. The Lammert *et al.* work establishes that early endothelial cells participate in development of the pancreas.

Endothelial cells are already known to participate in organ formation later in development. A good example is the interaction of the endocardium (specialized en-

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