drops to that of a gas at a few thousand degrees Kelvin. This means that the density fluctuations, which previously were pressure-driven sound waves, now respond only to gravity, the pressure being completely unimportant at least for fluctuations that contain the masses of even the smallest galaxies. Indeed, the minimum size for gravity to dominate, and thus for the first self-gravitating gas clouds to form, is about a million solar masses. As time proceeds, the clouds build up in mass by clustering together under the action of gravity to form a galaxy and eventually cluster mass clouds. The galaxy mass clouds are able to cool and fragment into stars. One ends up with galaxies and clusters of galaxies, the latter containing large amounts of gas that is too hot to have cooled.

The sound waves leave a remarkable imprint on the CMB. Inflation, or some equivalent theory, generates these waves that just begin to undergo their first compression peak when they enter the horizon. The wavelength simply spans the distance traveled by light since the Big Bang. Such waves that are cresting at last scattering for the first time have the largest amplitude. They produce a peak in the CMB fluctuations at an angular scale corresponding to the horizon scale at last scattering, about 1 degree. Shorter waves that are cresting for the second time at last scattering are amplified less and leave a smaller angular scale peak. Waves undergoing their first rarefaction also leave a peak on an intermediate scale, since rarefactions are measured in quadrature as fluctuations that are either negative or positive, the density field being random. There are a series of peaks predicted to be of decreasing strength until one reaches wavelengths that are so inefficient at scattering the radiation that there are no further fluctuations. It is then said the fluctuations are damped out, and this occurs at a physical scale corresponding to the thickness of the last scattering epoch, the distance a primordial sound wave could travel over the time the universe undergoes the transition from ionized to neutral. This amounts to approximately 30,000 years, so the smallest surviving primary fluctuations are on a scale of about one-tenth of a degree.

A series of peaks have been measured in the CMB temperature fluctuations. The first, second, and third peaks have been detected. The angular position of the peaks is sensitive to the curvature of the universe. If one lived, for example, in an open universe with hyperbolic geometry, the peaks are shifted to smaller angular scales, the universe acting like a giant concave lens. This effect is not observed: the universe is found to be flat to within an accuracy of 10 percent, in terms of the critical energy density, $\Omega_m + \Omega_\Lambda \approx 1$.

The detection of the acoustic peaks is another independent confirmation of the dominance of nonbaryonic dark matter in the universe; the peaks are produced by baryons, scattering by electrons. From their strength, a value $\Omega_b \approx 0.04$ is independently inferred. $\Omega_m \approx 0.3$ is required in order to have enough fluctuation growth in the early universe to make the fluctuations as small as they are observed. From the locations of the peaks, the equation of state is also measured, and one infers from both large-scale structure and cosmic microwave background observations that w is less than approximately -0.5, not far from the value corresponding to the cosmological constant. Hence, an independent confirmation of Λ holds: for the universe to be flat, $\Omega_\Lambda \approx 0.7$. This constitutes the concordance model of the Big Bang.

See also: ASTROPHYSICS; BIG BANG NUCLEOSYNTHESIS; COSMOLOGY; HUBBLE CONSTANT; INFLATION

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Joseph I. Silk

BIG BANG NUCLEOSYNTHESIS

The search for the origin of our universe and its contents, including the Earth and its living organisms, is a fundamental object of human curiosity. Following the discovery by Hubble that the galaxies of the universe all recede from each other, a simple projection back in time allowed Gamow to estimate that the universe must have originated from a very dense and hot condition that allowed the formation of the chemical elements out of more elementary constituents. By turning the problem around to deduce conditions in the early universe, the investigation of Big Bang nucleosynthesis provides one of the most powerful probes of the origin of the universe.

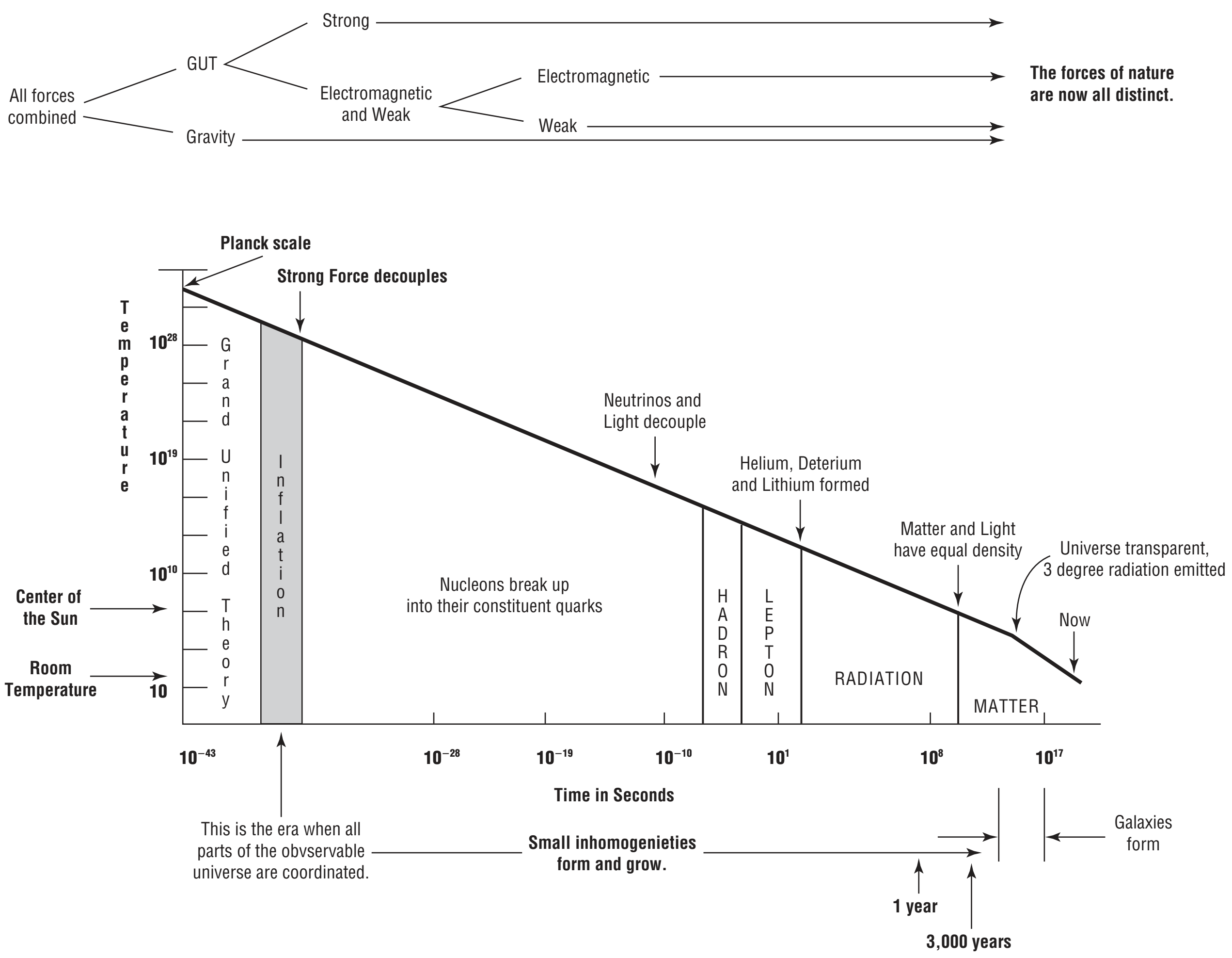
In Big Bang models there is a time of precisely zero when the scale of the universe becomes zero. Although this zero point itself is outside the domain of the physical model, arbitrarily small times near but not equal to zero are within the scope of the model. For these earliest times the density of matter and energy as well as the temperature become arbitrarily high. The words "arbitrarily near zero" mean that there can be as many zeros between the decimal point and the first nonzero number as one may sensibly describe. With time measured in seconds, the limit of physical theories is now at what is called Planck time, with forty-two zeros preceding the first digit. Quantifying the evolution of the universe from this early time until the present is a central goal of modern cosmology.

The fundamental forces of nature in the present universe include gravity, which binds matter into planets; the weak interaction, which allows the creation of electrons and neutrinos when a neutron decays into a proton; the electromagnetic force, which binds electrons and atomic nuclei into atoms and molecules as well as the creation of photons from moving electrons; and the strong force, which holds together nuclei. Associated with these forces are different classes of particles. The strongly interacting particles are composed of two or three quarks and are known as hadrons. The weakly interacting particles are known as leptons and include the electrons, muons, tau particles, and their associated neutrinos. The hadrons include the baryon subgroup that includes protons and neutrons.

At high density and temperature, the universe is filled with particles of many unfamiliar types. With the extreme temperature and energy, the forces of nature lose some of their distinct properties and combine into a more unified form called a Grand Unified Theory (GUT) or still further a theory of everything (TOE) if gravity is included. So far combinations beyond weak forces and electromagnetic fields are only a goal of particle physics and cosmology. As the expansion continues, more familiar particles like protons, neutrons, electrons, and photons begin to appear. Initially, there are both matter and antimatter particles. The matter particles are found today, whereas the antiparticles were annihilated by matter prior to the time of nucleosynthesis. At present just the excess of matter particles over antimatter particles remains in existence. One of the first questions that must be confronted in understanding the formation of the elements is as follows: "Why is there an excess of matter over antimatter?" There is no evidence that any regions of the universe contain pockets of antimatter, so some asymmetry in the conservation laws governing the early universe must favor that form of matter that prevails today. Either form of matter could have been favored by this asymmetry, and naturally one refers to the form one is not made of "antimatter." The study of this question is called barygenesis.

A successful barygenesis model must include forces that favor particles instead of antiparticles. This, however, is not enough and the forces must include other nonsymmetric aspects. All particles are described by sets of numbers that specify their properties. An example of such a property is the charge. Another property is called the parity, and it depends on the handedness of a particle. A normal corkscrew goes down into the cork when it is turned clockwise as viewed from above. An anticorkscrew would have to be turned counterclockwise to penetrate the cork. The forces between particles depend on their parities and charges. If the force depends on these properties in a nonsymmetric manner, the force is said to violate CP symmetry. Andrei Sakharov pointed out in 1967 that in order for a process favoring matter over antimatter to succeed in leaving our present universe with the observed matter excess, there must be an asymmetry between the forces on the particles and antiparticles and there must be a force that violates CP symmetry. Models that have both these features are not developed to the level where they can reproduce the observed baryon density in the universe, and Big Bang nucleosynthesis beyond barygenesis treats the baryon density as a free parameter from which the relative abundances of the light elements are deduced.

FIGURE 1



CREDIT: Combined from figures 13.4 and 13.8 in Hawley, John F. and Katherine A. Holcomb, *Foundations of Modern Cosmology*, NY: Oxford University Press, 1997, and the web site of E. L. Wright at UCLA.

The sequence of key events in the expansion of the universe.

As one follows the expansion of the universe past the time when the baryon density is established, there are two general principles that govern the unfolding of the universe's content: (1) The more matter and energy the universe contains per volume at a given time, the more rapidly it expands, and (2) many constituents of the universe are not in balance with other constituents. The first point is true because the universe is in the reverse of a free-fall collapse—a free expansion. Neither free fall nor free expansion involve frictional processes, and so these two processes are time-reversed versions of each other. It is easy to see that the more mass attracting an object in free fall, the more rapidly the object will accelerate. Because of this effect, if the energy content in one model of the universe is larger than that of a second model of the universe at a moment of time, its rate of expansion will also be larger. The second point says that the relative abundances of the elements need not be in thermodynamic equilibrium with each other. During the key period of the universe expansion, various isotopic species have abundances that differ from those characteristic of a steady thermodynamic equilibrium. When the temperature changes more rapidly than the forward and backward reaction rates can follow, the abundances become fixed near values appropriate to this last equilibrium temperature. Different isotopes are characterized by different last equilibrium temperatures. This process is described as the freeze-out of particle species.

In the time prior to element building, neutrinos are formed in equilibrium with their associated electrons, muons, and tau particles. The number of distinct leptons governs the number of neutrino families that can be created during the lepton era. This, in turn, governs the energy density of the universe since a larger number of distinct neutrino types increases the energy in the form of neutrinos. Because of the free expansion character of the early evolution of the universe, a larger number of neutrino types increases the rate at which the universe expands and reduces the time available for element building. Consequently, the abundances predicted by the Big Bang nucleosynthesis models constrain the number of independent neutrino families.

The temperature drops during the universe expansion until the neutrons and protons have frozen out. The era of element building is somewhat later than the neutron/proton freeze-out, but the time interval is short enough that the decay of the free neutrons has no major impact on nucleosynthesis. Although reactions involving leptons and the neutron-proton conversions are generally slow, their reaction rates are very temperature-dependent and initially the neutron/proton ratio is the thermodynamic equilibrium value. This ratio depends on temperature since the mass energy of the neutron at rest is larger that of the proton—a higher temperature gives a higher neutron/proton ratio. For a more rapid expansion the freeze-out temperature is higher so that a more rapidly expanding universe has a greater neutron abundance and ultimately a greater ^{4}He abundance.

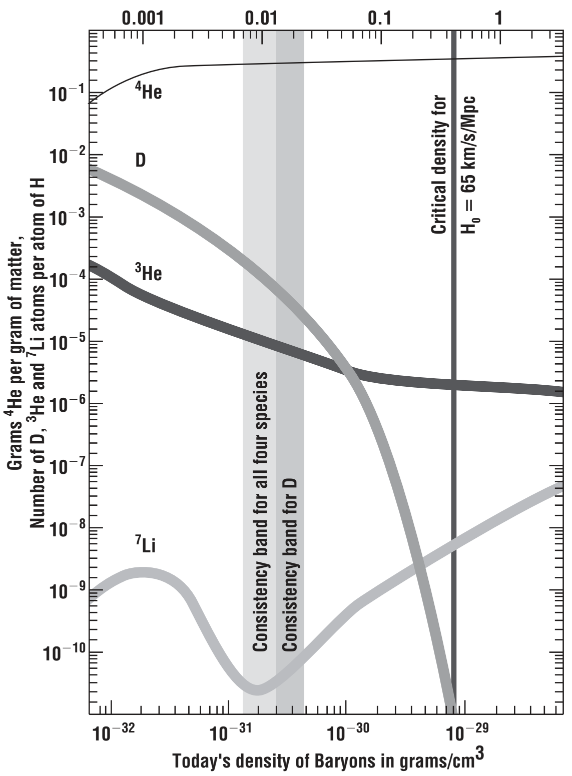
After the neutron/proton ratio has become frozen, the building of the light isotopic species ^{2}D, ^{3}He, ^{4}He, and ^{7}Li can take place. If one is able to determine the present abundances of these species and be sure that no other process has contributed to their production, these abundances may be used to learn about conditions during the early universe. As a complication, nucleosynthesis also occurs in stellar cores, and the production or destruction of species can alter their present abundance.

To distinguish between stellar and Big Bang nucleosynthesis one can use the fact that the early universe differs from stellar cores in two important respects: (1) The product of matter density and the time available for nucleosynthesis is very small compared to conditions in stellar cores, and (2) with few exceptions there are no free neutrons in stellar cores. These two differences have consequences that permit the identification of nuclei that have been produced exclusively by Big Bang nucleosynthesis and those that have been altered by star-based nucleosynthesis. In particular, ^{12}C, ^{13}C, ^{14}N, and ^{16}O as well as most other heavy isotopes require longer times and higher densities than are available during the Big Bang; they are considered to be the products of nucleosynthesis in star cores or supernovae. In contrast, the light isotopes except for ^{4}He are destroyed in stellar interiors, and ^{4}He is generally not ejected back into space from stars with a higher abundance than is found in the interstellar gas. Thus, the light isotope abundances are the best evidence about conditions during Big Bang nucleosynthesis.

Big Bang nucleosynthesis begins with the individual baryons—the protons and neutrons. The neutrons are unstable as free particles, but due to the shortness of time during the nucleosynthesis era of the Big Bang, their abundance is only slightly reduced by this decay. In order to build up multiple baryon isotopes, pairs of the individual baryons must combine. In the absence of the neutrons, the first step would have to combine two protons to form a product described as ^{2}He. This combination cannot exist even briefly unless one of the protons is converted into a neutron to produce deuterium. However, this conversion involves a weak interaction and is too slow to occur during the Big Bang. Consequently, the presence of the neutrons at the beginning of Big Bang nucleosynthesis is a critical requirement for the formation of the light isotopes. With neutrons starting the sequence, the nuclei with more than two nucleons are easily created by adding either protons or neutrons until ^{4}He is reached as the dominant product. Heavier nuclei are more difficult to build due to the absence of nuclei having five or eight nucleons. The combination of ^{4}He with one of the lighter intermediate species permits the mass 5 gap to be bridged but at the expense of a reduced abundance of the product. Big Bang nucleosynthesis is effective in the production of isotopes up to ^{11}B. Of the light isotopes useful observational constraints are available for ^{2}D, ^{4}He, and ^{7}Li. Observed abundances are also available for ^{3}He, but these are not as useful because of possible alterations by stellar processing.

The comparison between models of Big Bang nucleosynthesis and observations requires both good observations and good model calculations. The input parameters to the model calculation include the density of baryons relative to the cosmic background radiation, the number of neutrino families, and a set of nuclear reaction rates derived from laboratory observations. Figure 2 shows the output abundances provided by one of these model calculations as reported by M. S. Turner in 1999. Compared to the models and shown as the cross-hatched bands are recent estimates of the abundances and their uncertainties reported by K. A. Olive, G. Steigman, and T. P. Walker in 2000 (OSW[2000] in Figure 2) and S. Burles, K. M. Nollett, and M. S. Turner in 2001 (BNT[2001] in Figure 2). The vertical grey band indicates the density range where there is good agreement between the model and the observations of ^{2}D. The observations of ^{2}D in the interstellar gas along lines of sight to distant quasars provide the most precise constraint on the baryon density. The abundance of ^{4}He restricts the number of independent lepton families to three or possibly four. The final species shown in Figure 2 is ^{7}Li. Although there are stellar processes that form and destroy ^{7}Li, there is a large set of measurements for stars believed to be members of an older population, and the distribution of the abundances shows a plateau that is interpreted as the primordial abundance. This interpretation is subject to systematic uncertainty, for which an estimate is included in the plotted abundance range.

FIGURE 2



CREDIT: Turner, M.S. "Cosmology: The Nature of the Universe Debate, Cosmology Solved? Quite Possibly!" *Publications of the Astronomical Society of the Pacific* **111,** 264 (1999).

Ratio of the baryon density to the critical density for a Hubble expansion rate of 100 km/s/Mpc.

The application of Big Bang nucleosynthesis provides three important results:

(1) The widely distributed isotopic species of ^{2}D, ^{4}He, and ^{7}Li can be produced from a fully self-consistent model.

(2) There are no more than three or possibly four independent families of leptons and their associated neutrinos.

(3) The baryons can only account for about 8 percent of the mass needed to achieve a closed universe. Other methods of determining the amount of matter in the universe show that the baryons represent only a small fraction of the mass density.

See also: BIG BANG; CP SYMMETRY VIOLATION; SYMMETRY PRINCIPLES

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BOSON, GAUGE

The gauge principle is used to understand the interactions between fundamental particles. According to this principle, the weak, electromagnetic, and strong forces are all described by the interactions of spin-1 gauge bosons with the quarks and leptons. Each of the gauge bosons is associated with an underlying symmetry. The electromagnetic force is mediated by the photon, the strong force by the gluons, and the weak forces by the charged W^+ and W^- and the neutral Z bosons.

Basics

A quantum mechanical state is described by a wave function $\psi(x)$ where x is the space and time coordinate. Then all physical observables are described by the interactions of operators O with the wave function of the system:

$$\langle O \rangle = \int \psi^*(x)\, O \psi(x)\, dx.$$

The only physical observable is the expectation value $\langle O \rangle$ which is unchanged by changes in the phase of $\psi(x)$:

$$\psi(x) \rightarrow e^{i\vartheta}\psi(x)$$
$$\psi^*(x) \rightarrow e^{-i\theta}\psi(x)$$

where ϑ is a constant at every space and time point x. The wave function itself cannot be measured; the only measurable quantity is the expectation value. The invariance of the expectation value under phase changes implies that the phase of the wave function has no physical significance and so also can never be measured in an experiment.

The set of all such global phase transformations (change of the wave function by a constant phase) forms a U(1) (Abelian) symmetry group.

Since ϑ has no physical importance, one would like to be able to choose ϑ to be different for different space and time locations x. If this were the case, the system would be invariant under phase changes that were different in different places:

$$\psi(x) \rightarrow e^{i\vartheta(x)}\psi(x).$$

This is known as a local gauge transformation.

The interactions of particles in quantum mechanics (using the Dirac or Schrödinger equation, for example) always involve derivatives acting on the fields. Under a local phase change, the derivative operating on the wave function changes the wave function by a factor ($\partial_\mu = \partial/\partial x^\mu$):

$$\partial_\mu \psi(x) \rightarrow e^{i\theta(x)}\ (\partial_\mu \psi(x) + i\partial_\mu \theta(x)\psi(x))$$

In this equation, $\mu = 0, 1, 2, 3$, with x^0 being the time coordinate and x^1, x^2, x^3 representing the spatial dimensions. The second term, proportional to $\partial_\mu \theta(x)$, destroys the invariance under the local gauge transformation. The local gauge invariance can be restored, however, if the derivative is replaced by

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + igA_\mu(x).$$

D_μ is called the gauge covariant derivative, whereas the field $A_\mu(x)$ is called a gauge field and must change under local phase transformations as