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Universe: Thermal History

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HUBBLE's discovery of the expansion of the universe in 1929 revealed our beginning from a much smaller and much denser initial state (BIG BANG THEORY). Penzias and Wilson's discovery of the COSMIC MICROWAVE BACKGROUND radiation (CMBR) in 1964 implied further that just after creation the universe was a hot soup of the fundamental particles whose dynamics was controlled by the energy density of the CMBR.

The microwave radiation that A A PENZIAS and R W WILSON discovered is more precisely BLACK-BODY RADIATION characterized by a temperature of around 3 K. Because this black-body radiation fills space and its photons outnumber all other photons and known particles by a billion to one, it sets the average temperature of the universe. Of course, many hotter places exist in the cosmos—stars, planets and even the interstellar medium. As the universe expands its temperature decreases inversely as its linear size. While the temperature today seems unimportantly small, the fact that the universe still has a measurable temperature means that it was incredibly hot in the beginning.

The thermal history of the universe is thus the story of what happens when a tremendously hot and dense plasma expands and cools. Understanding the very earliest moments requires knowledge of the fundamental particles and their behavior under extreme conditions (high densities and temperatures). The connection between the inner space of elementary particle physics and the deep outer space of cosmology which plays such an important role in cosmology today was born with the discovery of the CMBR.

The known thermal history

The hot Big Bang cosmological model (see COSMOLOGY: STANDARD MODEL) provides an account of the universe from the hot soup of quarks, gluons, leptons and photons that existed before 10^{-5} s, when the transition from quarks and gluons to neutrons, protons and related particles occurred, until the present. During much of the time the universe was in a state of near thermal equilibrium; needless to say, the departures from thermal equilibrium are very important and make the universe an interesting place today! As the universe expanded, it cooled, $T \propto 1/R(t)$, where $R(t)$ is the cosmic scale factor which sets the size of the universe. As it cooled, layer upon layer of structure evolved, beginning with the neutrons and protons being produced from quarks culminating with the building of the largest structures seen today, the great walls of galaxies.

During its earliest moments, the temperature was the key to describing the state of the universe, because it sets the level of thermal particle energies. The thermal-energy scale $k_B T \sim 1$ MeV $(T/10^{10}$ K$)$ determines when it is energetically favorable for the next layer of structure to form, and which particle species are present in great number. When $k_B T$ was much greater than the rest mass of a particle, it and its antiparticle were easily produced in pairs and were present in the thermal soup in numbers comparable to photons. During the radiation era, the thermal-energy scale and age of the universe were related by: $k_B T \sim 1$ MeV $\sqrt{t \text{ (in s)}}$.

The soup of particles that existed at 10^{-5} s consisted of the up, down and strange quarks and their antiparticles; electrons, electron neutrinos, muons, muon neutrinos, tau neutrinos and their antiparticles; eight types of gluons and photons (the eight massless gluons are the carriers of the strong color force). The thermal-energy scale at this time was about 200 MeV ($T \sim 2 \times 10^{12}$ K), and the other quarks (charm, bottom and top) and the tau lepton were too heavy to be pair produced and were not present (any present would have annihilated). At even earlier times, when it was hotter, they (and possibly other particles) would have been present in great numbers too.

According to quantum chromodynamics (QCD), the theory of the strong color force, a phase transition from a quark–gluon plasma to hadronic matter occurred at a temperature of around 10^{12} K. Because of the increasing strength of the color force with distance, all particles with color (quarks and gluons) became confined in colorless quark triplets (neutrons, protons and other particles, known as baryons) and quark–antiquark pairs (pions, kaons and other particles, known as mesons). Collectively, the mesons and baryons are known as hadrons; the hadrons are the particles that experience the strong nuclear force.

At the end of the phase transition from quarks and gluons to hadronic matter, almost all the hadrons were too heavy to be pair produced. They could, of course, still annihilate, and as the temperature approached 10^{11} K annihilations had eliminated almost all of the hadrons. Were it not for the slight excess of baryons over antibaryons (whose origin is still a mystery, but see next section), nucleons (neutrons and protons) would have annihilated and disappeared too. The one additional nucleon for every billion or so antinucleons, left a few nucleons for every several billion photons without antinucleon partners to annihilate with. The primordial excess of baryons over antibaryons is responsible for all the ordinary matter that exists in the universe today.

At an age of about 1 s and temperature of about 10^{10} K, the primary constituents of the universe were photons, electron–positron pairs, and neutrinos and antineutrinos of all three species. There were also a few nucleons for every ten billion or so photons, about equally divided between neutrons and protons. Over the next 200 s or so, a sequence of nuclear reactions occurred out of thermal equilibrium and synthesized about 25% of the nucleons into ^{4}He. Trace amounts of D (a few parts in 10^5) and ^{3}He (about one part in 10^5) escaped being incorporated into ^{4}He and a tiny amount of ^{7}Li (a few parts in 10^{10}) was produced. The other 75% of the nucleons remained as free protons. This series of events is known as Big Bang NUCLEOSYNTHESIS (BBN). The rest of the periodic table was produced billions of years later by nuclear reactions in stars.

Big Bang nucleosynthesis occurred rapidly and at low density (around 10^{-2} g cm^{-3}), while the rest of the elements were cooked more slowly and at higher density (around 10^2 g cm^{-3} or higher) in stars and stellar explosions. This explains the great differences in the nuclear yields of the Big Bang and stellar nucleosynthesis. In particular, Coulomb barriers and the lack of stable nuclides of mass 5 and 8 prevented BBN from producing elements beyond ^{7}Li.

Big Bang nucleosynthesis provides the earliest test of the standard cosmology as well as a probe of conditions in the early universe. The fact that the pattern of abundances seen in the most primitive samples of the cosmos is consistent with its predictions is one of the experimental cornerstones of the standard cosmology. Further, the exact yields of the light elements, most especially deuterium, depend upon the baryon mass density; from recent measurements of the primeval deuterium abundance in high-redshift clouds of largely unprocessed hydrogen, we can infer that ordinary matter (i.e. matter comprised of neutrons and protons) today contributes between about 4% and 6% of the critical density. (The average density of the universe determines its curvature: a critical-density universe is spatially flat; a subcritical-density universe is open or negatively curved and a supercritical-density universe is closed or positively curved.) Because BBN 'weighs' all the ordinary matter at a simpler time, it provides the most accurate determination of the amount of ordinary matter. Today, baryons exist in many forms—bright stars, faint stars including white dwarfs and black holes, clouds of cold gas and of hot gas, and dust—and are more difficult to inventory. Thus far, only about one-third of the BBN-determined baryon abundance has been directly accounted for.

Light-element production also depends upon the ambient conditions in the universe, and Big Bang nucleosynthesis can thus also be used as a probe of the particle soup that existed then. For example, the existence of an additional neutrino species beyond the tau neutrino would have led to additional ^{4}He production, in contradiction to the observations. This argument against the existence of another neutrino species was put forth in the 1980s by David SCHRAMM and his collaborators and was confirmed by experiments at particle accelerators in the 1990s.

Two other important thermodynamical events took place during Big Bang nucleosynthesis. At a temperature of around 10^{10} K neutrinos and antineutrinos (all three species) ceased interacting with electron–positron pairs and decoupled from the electromagnetic plasma. Thereafter, they evolved independently of the rest of the universe, interacting only through gravity. Neutrino decoupling occurred because the decreasing particle energies and densities made neutrino interactions with other particles increasingly infrequent. When the temperature was around 10^9 K, essentially all of the electrons and positrons disappeared as pairs destroyed by annihilations were no longer replenished by thermal pair creation. The slight excess of electrons over positrons preserved the few electrons per ten billion photons required to balance the charge of the protons. The electron–positron annihilations raised the number of photons in the universe by a factor of 11/4 and heated the photons slightly relative to the neutrinos; thereafter $T_\nu = (4/11)^{1/3}T$.

The radiation era ended when the universe was around 40 000 years old and the temperature was about 10 000 K. At this epoch, called matter-radiation equality, the energy density contributed by matter (both baryons and exotic dark matter, more below) and that by relativistic particles (photons and three neutrino species) were equal. Thereafter, the matter density would exceed that of relativistic particles, growing in proportion to the linear size of the universe. (The matter density decreases as $1/R(t)^3$ due to the volume dilution effect of the expansion; the energy density of the CMBR decreases as $1/R(t)^4$, with the extra factor of $1/R$ arising because photon energies are redshifted with the expansion.) Today, the energy density of matter is about a factor of 4000 times larger than that of the energy density of photons and neutrinos.

The dawning of the matter era marked the beginning of the formation of large-scale structure in the universe (see also UNIVERSE: SIMULATIONS OF STRUCTURE AND GALAXY FORMATION). The small inhomogeneities in the distribution of the exotic matter that existed (spatial variations in the mass density at the level of about one part in 10^5) began growing through the attractive force of gravity; prior to matter–radiation equality the universe was expanding too fast for this to occur. Their tight coupling to photons prevented baryons from participating in this growth.

Shortly after the radiation era ended, at a time of around 400 000 years and a temperature of around 3000 K, two related and very significant events involving the radiation took place. The first was the transition from ionized matter to neutral matter (called 'recombination', which is paradoxical since neutral matter had not previously existed). As the temperature dropped below 3000 K neutral matter became thermodynamical favored, and all but a few ions combined with the free electrons to form neutral atoms (a residual ionization fraction of around 10^{-4} persisted thereafter because ions and electrons became too rare to find one another to combine to form atoms). When the universe became neutral, its opacity dropped precipitously (free electrons efficiently scatter light, neutral atoms do not), and matter and radiation decoupled. Photons streamed freely and have not scattered since; this important event is referred to as last scattering. Once baryons decoupled, they were rapidly pulled into the cosmic structures being formed by the gravity of the exotic dark matter.

The black-body character of the radiation, established by the hot, dense conditions in the early universe, was preserved by the expansion of the universe (the deep mathematical reason involves the conformal invariance of Maxwell's equations and the conformal nature of the expansion), albeit with a decreasing temperature, $T \propto 1/R(t)$). Today, this black-body radiation, which at last scattering resembled the light emitted by the Sun today, has been redshifted to the microwave part of the spectrum. In 1996, the far infrared absolute spectrophotometer (FIRAS) instrument on the Cosmic Background Explorer (COBE) satellite made the most precise measurement of its temperature, $T = 2.7277 \pm 0.002$ K, and showed that any deviations from a perfect black-body spectrum are smaller than 0.005%. Because there is no other viable mechanism for producing such perfect black-body radiation, the spectrum of the CMBR is one of the experimental pillars of the hot Big Bang cosmology.

The radiation in the CMBR has not scattered since the universe was 400 000 years old, and so it provides a snapshot of the universe at a simpler time, when matter was still nearly uniformly distributed and stars, galaxies and clusters of galaxies did not exist. The variations in the intensity (or temperature) of the CMBR across the sky today map the two-dimensional distribution of matter at this time because variations in the mass density produce temperature variations of the same size. Thus, the temperature variations of a few parts in 10^5 measured by the differential microwave radiometer (DMR) on the COBE satellite and other balloon and ground-based experiments imply the existence of variations in the matter density of approximately the same size. This level of inhomogeneity is just what is needed to produce the large-scale structure seen today—provided that the bulk of the matter is exotic dark matter and not baryons (more below). The variations (or anisotropy) of the CMBR also encode a wealth of information about the early universe and how large-scale structure formed. Higher precision and higher angular-resolution measurements will be made by future experiments including NASA's MAP satellite (scheduled for launch in late 2000) and ESA's PLANCK SURVEYOR satellite (scheduled for launch in 2007).

Three cosmic seas of thermal neutrinos should be with us today. Just as with the CMBR, the expansion of the universe maintained their thermal (Fermi–Dirac) distributions with a temperature that has decreased inversely with the cosmic scale factor since they decoupled. Because neutrinos did not share in the energy release from the electron–positron annihilations, the temperature of the neutrino seas is predicted to be smaller than that of the photons, $T_\nu = 1.947$ K. If they can be detected, these neutrinos will reveal the universe as it was about 1 s after the beginning. However, because low-energy neutrinos interact extremely weakly with ordinary matter their detection presents one of the greatest challenges in all of science.

Beyond the standard cosmology: the very early universe

The earliest history of the universe (before 10^{-5} s) is still a mystery, but is under intense study. The motivation is twofold: the hope that events which took place may explain some of the most pressing cosmological puzzles. For example, the reason for the small excess of matter over antimatter, the explanation for the regularity seen in the universe, and the origin of the primeval density inhomogeneities. The second motivation is the possibility that the early universe can be used to probe fundamental physics more deeply than particle accelerators and other Earth-based experiments. At the moment, the discussion of the universe at times earlier than 10^{-5} s is speculative, both because of uncertainties about the microphysics needed to describe these early times and the absence of cosmological tests like Big Bang nucleosynthesis. In any case, the physics and the cosmology are of sufficient interest to merit the discussion of the possibilities.

On fairly firm ground, the discussion of the thermal history of the universe can be extended back to around 10^{-11} s when the temperature was about 10^{15} K. This was sufficiently hot that the thermal-energy scale exceeded the rest masses of all known particles. At this time the thermal soup should have included all the quark and lepton species, gluons, photons and the $W^\pm$ and Z^0 bosons, all in roughly equal abundance.

The state of the universe earlier than this is much less certain. The prevailing belief is that a phase transition occurred and restored the full symmetry of the $SU(2)\otimes U(1)$ gauge theory of the electroweak interactions. ($SU(2)\otimes U(1)$ is the mathematical symmetry that underlies the unified theory of the electromagnetic and weak interactions.) At low temperatures the symmetry between the weak and the electromagnetic interactions is not manifest: the electromagnetic interaction has long range, while the weak interaction has very short range because the mediators of the weak force, the $W^\pm$ and Z^0 bosons, are very massive. The symmetry is said to be spontaneously broken, by the Higgs mechanism. When the symmetry is restored, all of the force mediators become massless. If the Higgs mechanism is correct, then there is at least one more spin-zero particle species, the Higgs boson, whose rest mass is greater than about 100 GeV and probably less than 300 GeV. Its discovery would be a striking confirmation of spontaneous symmetry breaking, and thus the Higgs is at the top of the 'most wanted' list at all accelerator laboratories.

As successful as the electroweak theory is, it provides only a partial unification of the forces, leaving out the strong color force and gravity. One possibility is there are other levels of symmetry breaking and symmetry breaking phase transitions. The simplest idea, grand unification, unifies the color force with the electroweak force. Estimates for the temperature at which the grand unification phase transition might take place are even more uncertain, but are around 10^{29} K, corresponding to a time of about 10^{-39} s.

Another interesting feature of symmetry breaking is the possibility that the phase transition did not occur smoothly and that 'defects' are created. (Such defects are known to be produced in phase transitions in condensed matter systems: vortices and magnetic flux tubes.) These so-called topological defects are concentrations of energy: point-like magnetic monopoles, one-dimensional cosmic string and two-dimensional domain walls. The kinds of defects that can be produced depend upon the symmetry breaking pattern. Thus far, the cosmology of topological defects has not been promising: monopoles should have been grossly overproduced, domain walls have disastrous cosmological consequences, and cosmic string, once thought to be a possible seed for the formation of structure in the universe, predicts a pattern of CMBR anisotropy that is inconsistent with the measurements.

A much more promising idea arising from the consideration of cosmological phase transitions is INFLATION. Inflation refers to an enormous burst of expansion which might have taken place very early on (probably earlier than about 10^{-32} s). Because of its potential to explain a number of the most fundamental and most puzzling features of the universe, inflation has been the dominant theoretical idea in cosmology over the past 15 years. It can account for the smoothness of the universe, the origin of the primeval matter inhomogeneity, the heat of the Big Bang, and the nature of the Big Bang itself. Originally inflation was thought to be driven by the latent heat (or false-vacuum energy) associated with a first-order phase transition. Most models of inflation no longer involve a phase transition, but instead rely upon the potential energy of a fundamental scalar field.

Besides inflation, the most compelling ideas of early-universe cosmology are particle dark matter and BARYOGENESIS. It has been known for more than 50 years that most of the matter that holds galaxies and clusters of galaxies together is not in the form of visible stars but is 'dark' (i.e. does not emit or absorb detectable radiation of any form; see DARK MATTER: ITS NATURE). For at least a decade it has also been known that the total amount of dark matter exceeds by more than a factor of three the amount of matter in the form of baryons as determined from Big Bang nucleosynthesis. Further, with the level of inhomogeneity measured by COBE, the observed large-scale structure can only form if there is exotic dark matter. These facts are strong circumstantial evidence for a new form of matter in the universe.

The most promising candidates for the dark matter are elementary particles that were present in copious numbers in the thermal soup early on and which failed to annihilate away because of the weakness of their interactions. Of all the possibilities considered, the three most attractive are neutrinos (if they have a small mass) and axions or neutralinos (if they exist). (The axion and neutralino are as yet hypothetical particles predicted to exist by theories that unify the particles and forces of nature.)

Baryogenesis is a higher-level analog of Big Bang nucleosynthesis: BBN explains how baryons come together to make nuclei and baryogenesis hopes to explain the origin of the excess of quarks over antiquarks that leads to the existence of ordinary matter. The idea is that particle interactions that violate matter–antimatter symmetry and the conservation of baryon number and which occurred out of thermal equilibrium produced a slight excess of quarks over antiquarks. When the quarks formed into neutrons and protons, this led to the excess of baryons over antibaryons needed to ensure the existence of the ordinary matter.

The weak interactions violate matter–antimatter symmetry at a small level and are also predicted to violate baryon-number conservation through subtle quantum effects. Moreover, baryon-number non-conservation is a generic prediction of grand unified theories. While the details are not currently understood, nor is there any experimental evidence for the non-conservation of baryon number, nonetheless baryogenesis is a promising framework for understanding how the crucial excess of matter over antimatter arose.

To date, superstring theory has been the most successful approach to the unification of gravity with the other forces. Superstring theory makes two generic predictions relevant for cosmology. First, the existence of a new symmetry of nature that relates fermions and bosons (supersymmetry), and second, the likely existence of additional spatial dimensions. Because the known particles of nature cannot be paired off as fermion–boson partners, supersymmetry requires the doubling of the number of fundamental particles. The superpartners, as they are called, are predicted to have rest energies of the order of 100 GeV. If correct, this implies a doubling of the number of particles in the primordial soup only occurs at temperatures greater than around 10^{15} K. The lightest superpartner, usually the neutralino, is stable or very long-lived and has a rest energy of order 100 GeV. As mentioned above, it is a prime candidate for particle dark matter.

If there are extra spatial dimensions they must be 'small' enough to have escaped detection or be otherwise hidden from us. Small here refers to their being curled up like the circular dimension of a straw. While many versions of superstring theory predict that the extra dimensions are exceedingly tiny—10^{-34} cm or smaller—some versions suggest that they might be as large as a millimeter in extent! The cosmological implications of extra dimensions are not well understood and raise a host of additional cosmological questions, for example the explanation for the size discrepancy between the familiar three spatial dimensions and the extra spatial dimensions.

Even if superstring theory does not prove successful in unifying gravity with the other forces and in providing a quantum description of gravity, 'interesting physics' should have occurred at times earlier than 10^{-44} s and temperatures greater than 10^{32} K. This is the Planck era, the epoch when quantum gravitational effects should have been extremely important and the classical description of gravity given by general relativity should have been inapplicable. It could be that the universe achieved a limiting temperature due to the exponentially growing number of particle species (also a prediction of string theory), or that space-time dissolves into a foam. Even by the standards of early universe cosmology, speculations about the Planck era are extraordinarily speculative.

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