THE BIG BANG

February 1, 1999

I. Observational Basis

1) Universal Expansion (The Hubble Law)

a) History-By 1912 V. M. Slipher noted that the radial velocities of many "spiral nebulae" had Doppler shifts greater than 300 km/s, the maximum found for stars in the Milky Way. K. Lundmark had also found similar results. In 1929 Hubble and in 1931, Hubble and Humason published their classic papers on the redshifts of remote galaxies. It was shown that the farther away a galaxy is from us, the greater is its redshift. Interpreted in terms of velocity, the further away a galaxy is the faster it appears to be moving away from us. Stated mathematically,

$$V_r = H_o r$$

where H_o is Hubble's constant and has units of inverse time (usually in km/s/Mpc), r is the distance of the galaxy from us, and V_r is the radial velocity of the galaxy measured from the Doppler effect.

This discovery has far reaching consequences.

1) The entire universe is expanding in the sense that the separation of galaxies increases with time. This does not imply that matter is moving through space, but rather space itself is stretching or expanding. This does not mean that matter is moving through space, but rather that space-time itself is stretching.

2) It does not imply a center of the universe, only that all galaxies and clusters of galaxies are increasing their separation with time. A center would imply a preferred coordinate frame which would violate a key precept of relativity theory.

3) The Universe was earlier denser, hotter, and smaller than today.

4) Hubble's constant H_o, represents a maximum age of universe

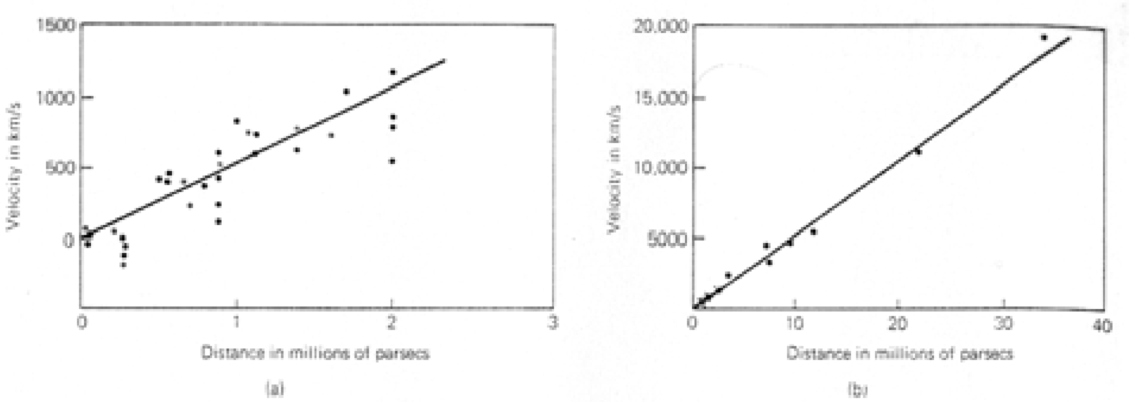


Figure 37.2 (a) Hubble's original velocity-distance relation, adapted from his 1929 paper in the *Proceedings of the National Academy of Sciences.* (b) Hubble and Humason's velocity-distance relation, adapted from their 1931 paper in the *Astrophysical Journal.* The small dots at the lower left are the points in the diagram in the 1929 paper (a).

2) The Abundances of the Light Elements

D, He, and Li imply the present mean density of baryons

(primarily protons, neutrons) in the universe. The idea here is that during the first few minutes after the cosmic fireball (Big Bang) was initiated, the universe was hot enough to initiate nuclear burning (build-up of subnuclear particles (protons and neutrons) to synthesize atomic nuclei of the lightest elements. The universe itself was literally a nuclear furnace. During this period the ratio of neutrons to protons was very sensitive to the temperature determined the relative abundance's of D, ^{3}He, ^{4}He, and Li. Determination of the cosmic relative abundance's of these elements tells us the early temperature history of the universe, it final neutron to proton ratio, and the confirms the fact that the universe went through a very hot phase at the beginning.

D can only be destroyed (by stellar nuclear burning) but is not created in significant abundance by any natural process, except in the big bang. He can be made in stars and in the first few minutes of the birth of the universe. The trick is to determine the primordial abundances of these two elements. This has been done using various clever obserrvations and it is found that $He/H \approx 0.10$ and $D/H \approx 1\text{-}2x10^{-5}$. These values imply that the baryonic density in the universe today is too low to close the universe. That is, the universe will continue to expand indefinitely It does not have enough self gravity to stop the expansion although the rate of expansion has been slowing down from the beginning. The universe appears to be unbound. This is true even if one adds in the "dark" matter which accounts for 90% of all the mass in the universe. One can also show that the observed abundance’s of the light elements cannot have been primarily produced in stars and therefore had to have been produced in the Big Bang which required that the early universe had to have been very hot and very dense.

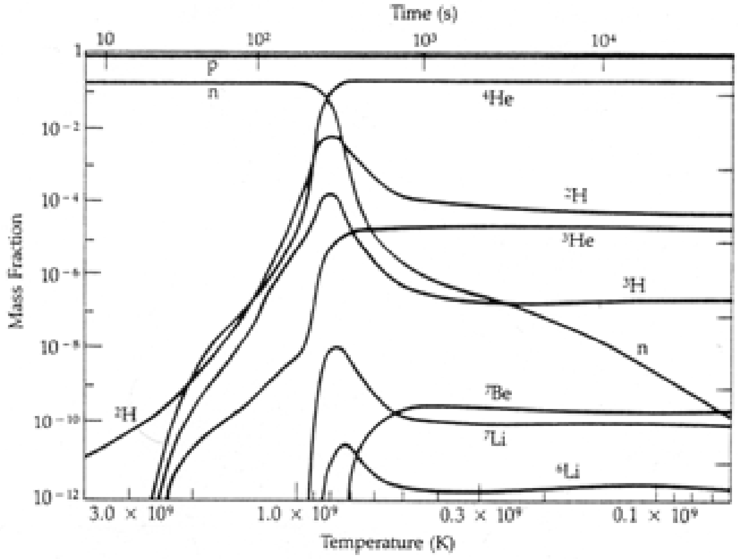
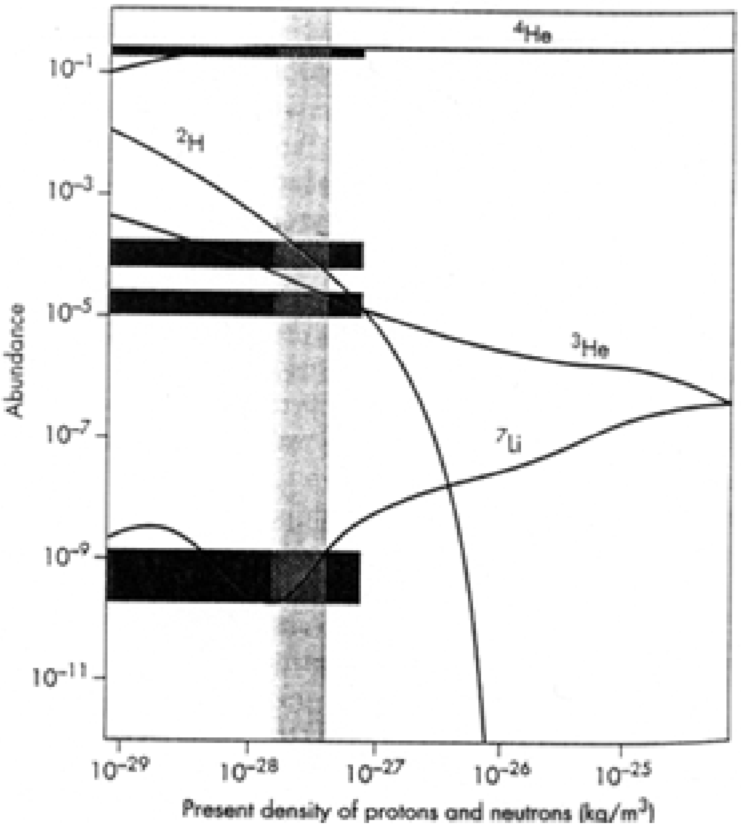


FIGURE 26–1 Nucleosynthesis in the Big Bang. The top axis gives the age of the Universe; the bottom gives temperature; the vertical axis is abundance in terms of the fraction of total mass. *(Adapted from a diagram by R. V. Wagoner)*



3) The Cosmic Background Radiation (CBR)

In 1965 Penzias & Wilson of Bell Labs reported detection of an approximately 3 K background radiation that seemed to be the same in all directions in the sky. In the meantime this has been refined and frequency coverage extended by many other observers, the most recent and spectacular is that of the COBE (<u>Co</u>smic <u>B</u>ackground <u>E</u>xplorer satellite) results which show that this radiation field which fills the entire universe has a present day temperature of 2.735±0.005 K. Its deviations from a Planck curve (i.e. black body) is less than about a milliKelvin. This radiation is now interpreted as the doppler shifted radiation from the Big Bang at the time when the universe became transparent to optical light (about a redshift of 1000). The significance of this discovery is that it tells us the photon/baryon ratio ($\approx 10^9$ which does not change with time) and it also confirms that the universe went through an enormously hot and dense phase during its early history.

4) Deep observations of galaxies and quasars have shown that visible matter is not distributed uniformly on fairly large scales (~100 million parsecs). There are superclusters of galaxies

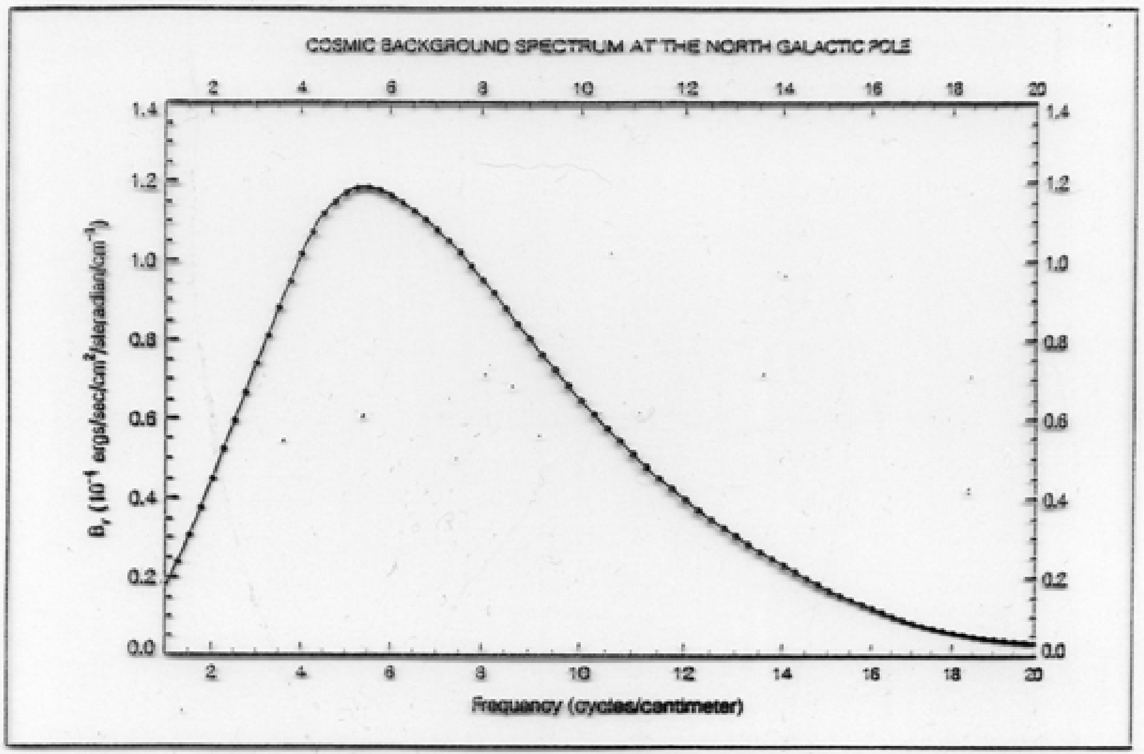


Figure 29.15 The revised cosmic background spectrum from *COBE*. The Cosmic Background Explorer (COBE) *has measured the background radiation at many wavelengths, as indicated by the points. The result is the most accurate measurement yet of the temperature of the radiation, which is found to be 2.735 K, derived by fitting a theoretical thermal radiation spectrum (solid line) through the points. (NASA, courtesy of the* COBE *Science Working Group)*

⇒ Photon/baryon $\approx 10^9$

and voids where almost no matter is found. These pose some very interesting problems for cosmology.

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II. Assumptions

Finally, it is generally assumed that if one includes a large enough volume, that the universe would look the same to all observers no matter where they are in the universe. This is called the **cosmological principle** and is an assumption not a proven fact.

III. The Standard Model

Using the above observational constraints, and solving Einstein's field equations (equivalent to the equation of motion) with the assumption of the cosmological principle plus the application of basic physics, a model of the evolution of the universe, which has become known as a the standard model, has been constructed. This model seems to be consistent with present observational constraints. I want now to describe the predictions of this model.

First, we have to understand a little bit about the physics of annihilation and creation of matter. Einstein has shown in his theory of relativity that matter and energy are different forms of the same thing. That is, matter and energy are equivalent through his now famous equation, $E=mc^2$ where E is energy, m is mass, and c is the speed of light. However, there are strict rules on how matter and energy can be interchanged. Conversion from matter to energy occurs through the annihilation of a particle of matter and its antiparticle. For example,

$$e^- + e^+ = \text{two photons each of energy 0.511 Mev}$$

and

$$p^- + p^+ = \text{two photons each of energy 938.2 Mev}$$

and

$$n + \bar{n} = \text{two photons each of energy 939.5 Mev}$$

Annihilation of matter to form energy can occur at any temperature as long as there are matching pairs of matter and antimatter particles present. The other direction, in which photons are converted to matter-antimatter pairs of particles cannot occur in empty space and can only occur if the photons have energies at least equal to the rest energy of the individual particles. This is called pair production. Here the energy of each photon has to have at least the rest energy of the particle and antiparticle formed,

$$h\nu \geq m_o c^2$$

where $h\nu$ is the photon energy. The important point here is that there is a threshold energy below which pair production cannot occur. Cosmologists usually denote this in terms of the equivalent temperature of the radiation field.

$\bar{E}_{rad} = \bar{E}_{th} \geq E_{rest}$ **but** $\bar{E}_{rad} = h\nu, \bar{E}_{th} = kT$ **, so that** $T \geq m_o c^2 / k$

The threshold temperature for pair production of neutrons is 1.090E13 K and for protons it is 1.088E13 K, and for electrons it is 5.930E9 K. Once the temperature of the universe drops below any of these thresholds, it becomes impossible for more of that particular particle to be produced by photons in the universe. As the cosmologists say, they "freeze out" of the universe. Then the matter and antimatter particles will annihilate each other until there are no more of one or the other particle. That remaining represents the initial imbalance in the number of matter and particles. In this case, we know from the CBR that the net imbalance was about 1 more matter than antimatter particle for every billion pairs. Now let's look at the conditions in the universe as a function of time according to the currently accepted best model of the Big Bang.

IV. Evolution of the Universe

Reference: "The First Three Minutes" by Steven Weinberg
Basic Books, NY This is a little dated, but accurate
as far as it goes.

"Introductory Astronomy & Astrophysics" Zeilik,
Gregory, and Smith, 3rd Edition, 1992
Saunders College Pub.

Problem: At the very beginning of the universe, temperatures and densities were so high that we are not sure how particles interacted with each other, also the four forces (electromagnetic, strong, weak, and gravity) were probably a single unified force rather than the 4 separate forces that we know today. Gravity is believed to have separated out as a separate force at about 10^{-45} s. Before this, there was only one force that controlled the interactions of particles. We will begin the story at 10^{-35} secs after the initial fireball.

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Time=10^{-35} s

$T \approx 10^{27}\ K$

The universe is a soup of matter, antimatter and radiation which interact freely and rapidly with each other. It is in a state of ~perfect thermal equilibrium (i.e. all particles including radiation are at the same temp). Total charge, baryon number, and lepton number are all very very small or zero. All particles freely interact with each other. The rate between pair production and annihilation are equal.

Contents: photons, electrons, positrons, quarks, antiquarks, neutrinos, and antineutrinos

At this time the quarks and antiquarks begin to annihilate, leaving behind a small residual of quarks but no antiquarks. These will later combine to form neutrons and protons. The imbalance between matter quarks and antiquarks is believed to have occurred due to several processes that violated charge-parity conservation.

Inflation begins

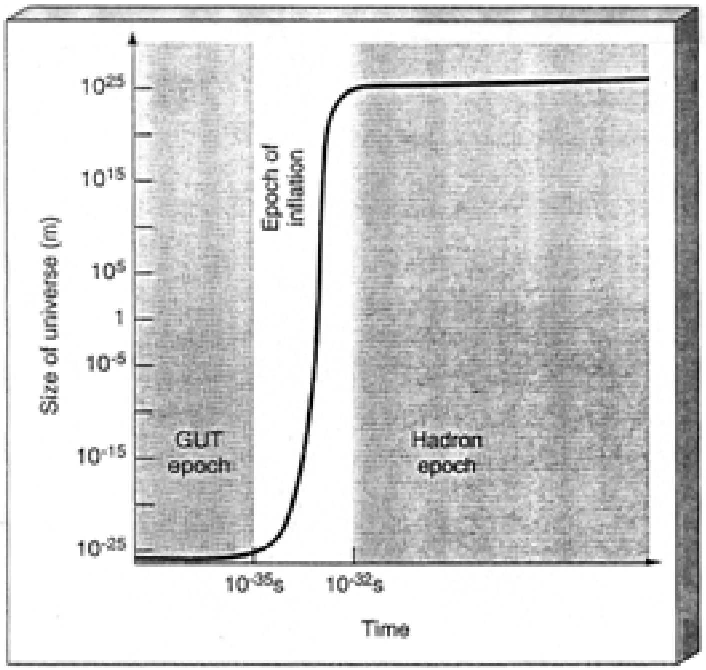

Figure 27.11 During the period of inflation at the end of the GUT epoch, the universe expanded enormously in a very short time. Afterward, it resumed its earlier "normal" expansion, except that the size of the cosmos was about 10^{50} times bigger than it was before.

Time=10^{-32} s

$T \approx 10^{21}\ K$

The temp is still too high for protons and neutrons to be stable. Period of inflation ends. The universe has increased in size by a factor of order 10^{50}.

Time=10^{-12} s

$T \approx 10^{15}\ K$

The weak nuclear and electromagnetic forces separate. Neutrons and protons are stable and freely interact with radiation.

Time=0.01s

The universe has cooled to a temp of 10^{11} K (100,000 million K). The temp is already below the threshold temps of neutron, and proton pair production and they and their antiparticles are rapidly disappearing from the universe (freezing out).

$\rho \approx 3.8 \times 10^{9}$gm/cm^3 (energy plus matter)-if Mt Everest were made of matter this dense, it would destroy the Earth by tidal forces.

The doubling time for the universe is about 0.02 secs.

At this time there are about 10^9 photons, electrons, and neutrinos for every proton and every neutron.

$N(n) \sim N(p)$

Size of universe? Don't really know, but if use the present value of H and assume the present density is about 2 times critical, then present circumference is about 1.25x10^{11} ly and the size at 0.01 s would be $3K/10^{11}K$ times smaller than now (~4 ly)

Time=0.11s

$T=3x10^{10}\ K$

Contents of the universe = electrons, positrons, neutrinos, antineutrinos, and photons

All particles are in thermal equilibrium and all above their threshold temps (except for the small number of neutrons & protons).

Energy density $\propto T^4 \Rightarrow \rho \approx 3\times10^7$ gm/cm3 (30 million times denser than water)

Doubling time of universe is about 0.2 secs.

Rate of expansion continues to slow down.

As T decreases, it becomes easier for heavier neutrons to turn into protons than vice versa ⇒ the number of neutrons decrease relative to the number of protons. N(n)~38% of nuclear particles and N(p)~62%.

Time=1.09 s

$T=10^{10}\ K$ This is about twice the threshold temp of electrons and positrons and they are beginning to annihilate more rapidly than they can be created out of radiation. It is still too hot for neutrons and protons to bind into atomic nuclei.

$\rho \approx 3.8\times10^5$gm/cm3. At this density and temp. the mean free path of neutrinos and antineutrinos have become large enough that they are beginning to decouple from the rest of the matter and radiation in the universe and they therefore are no longer in thermal equil with the electrons, positrons, and photons.

Doubling time ~2 secs

Decreasing temp has allowed the proton-neutron balance to become ~24% neutrons and ~76% protons.

Time=13.82 secs

$T=3x10^9\ K$

This is below the threshold for electron-positron pair production and they are rapidly disappearing from the universe (via annihilation). This adds 0.511 Mev of energy per annihilation and slows the rate of cooling of the universe until the process is completed.

Since the neutrinos have decoupled from the rest of the particles in the universe, they do not share in the heating by elec-pos annihilation and are therefore about 8% cooler than the rest of the particles in the universe. From this point on when we refer to the temp of the universe, we will mean the temp. of the photons only.

Temp is still too high for D nuclei to be stable ⇒ no atomic nuclei yet.

Neutrons are still being converted to protons and the present values are N(n)~17% and N(p)~83%

Time=3 min and 2 secs

$T=10^9\ K$ (about 70 times hotter than the center of the Sun). The temp is now low enough that stable nuclei such tritium, ^{3}He, and ^{4}He can exist but deuterium is still too short-lived to allow significant amount of heavier atomic nuclei to be built up. Thus, no atomic nuclei exist yet.

$\rho \approx 38$ gm/cm^3, about 38 times that of water.

By this time the electrons and positrons have mostly disappeared and the main constituents of the universe are neutrinos, antineutrinos, and photons. A tiny trace (one for every 10^9 photons) of neutrons, protons, and electrons are also present but they are insignificant relative to the photons and neutrinos.

The energy released by electron-positron annihilation has given the photons a temperature 35% higher than that of the neutrinos.

Free neutrons are beginning to decay to protons, electrons, and antielectron neutrinos, further reducing the neutron/proton ratio which has been decreasing all along via the reactions

$$\bar{v} + p \leftrightarrow e^- + n \quad \text{and} \quad v + n \leftrightarrow e^- + p$$

both of which favor formation of the neutron at lower temperatures because it takes more energy to form the neutron which is slightly more massive than the proton.

The n/p balance is now 14% neutrons and 86% protons

Time=3 min and 46 secs

$T=9\times10^{8}\ K$ The temperature has now declined to a low enough value that deuterium is stable. Once this occurs, it is possible for heavier atomic nuclei such as Li, helium, Be, and B to be formed. Because of the formation deuterium and synthesis of heavier nuclei, the free neutrons are rapidly incorporated into atomic nuclei where they are safe from further decay and so the n/p ratio is fixed. The n/p ratio at this point will determine how much He and D can be made in the Big Bang. If n/p is about 0.15 and most neutrons -> He, then $He/H \approx 2x(n/p) \approx 26-28\%$ by mass.

Time=34 min 40 secs

$T=3\times10^{8}\ K$ The density is now too low to support nuclear processing, even though the temperature is high enough. All elements capable of being produced in the Big Bang have been made.

$e^{-}-e^{+}$are completely annihilated leaving only the small residual of e- (1 in 10^{9} of the original number). The same is also true of neutrons and protons, all that is left is the small matter-antimatter imbalance.

The main constituents of the universe are photons, neutrinos, and antineutrinos. The number of electrons=number of protons. No stable, neutral atoms exist yet because it is too hot.

$T_{photon} \cong 1.40T_{V}$

$\rho \approx 9.9$gm/cm3 About 31% of the energy density is in neutrinos and antineutrinos and about 69% is in photons (if neutrinos have no rest mass).

The doubling time of the universe at this time is about 1.5 hours

Time= 7×10^{5} years

T~3000 K

At this temperature the universe is cool enough for electrons to combine with atomic nuclei to form stable atoms. At this time the universe becomes transparent to photons and matter decouples from the radiation. This marks the change from a radiation to a matter dominated universe. This is the “surface of last scattering” which occurred at a redshift of 1000 and is the universe sampled by the CBR. $\rho \approx 9.9\times10^{-20}$gm/cm3

Time= 10^{8}-10^{10} years

Galaxies formed including stars and planets.

The universe becomes very cold and the average density is at least 19 orders of magnitude less than the air we breath.

378 THE BIG BANG

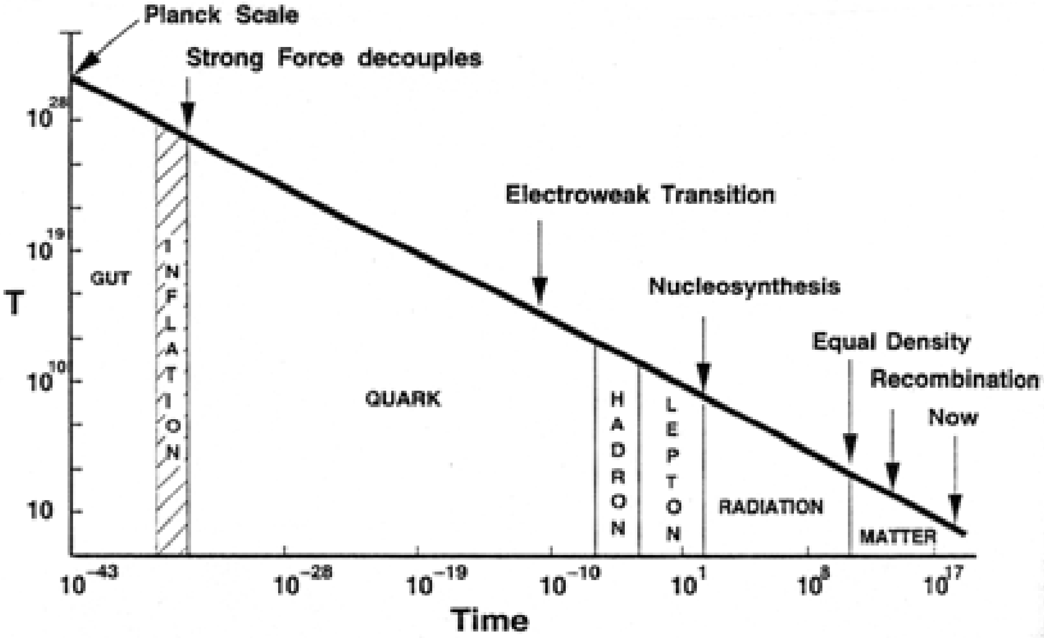

Figure 13.8 Great moments in the history of the universe. Important events and epochs are shown along a line indicating radiation temperature as a function of time.

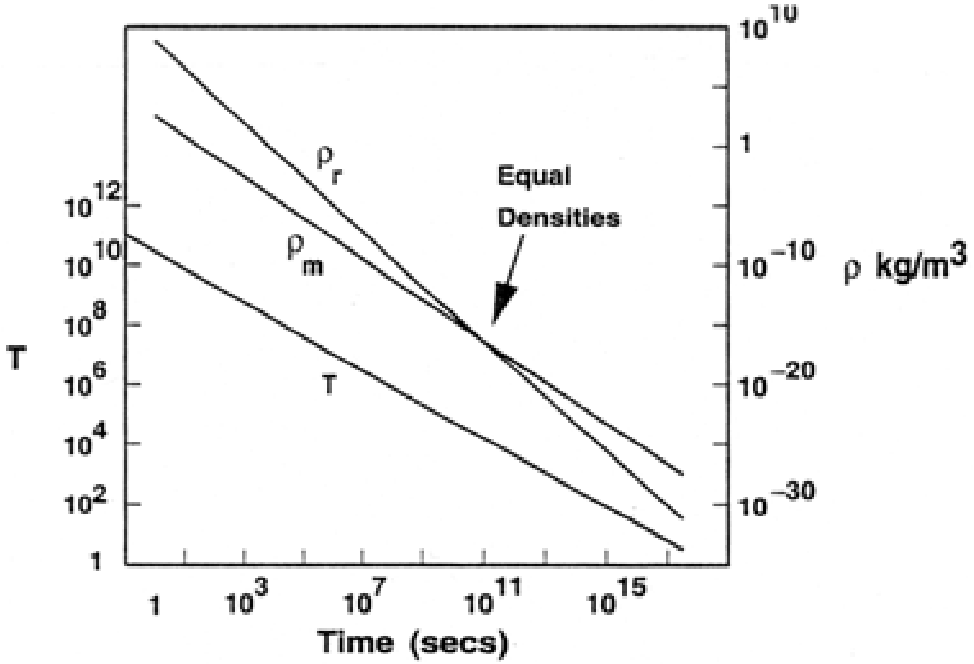

Figure 13.7 Time evolution of the temperature and densities over the history of the universe. The scale on the left is the temperature of the universe; the scale on the right is for density. The point at which the matter and radiation energy densities (ρ_m and ρ_r, respectively) are equal occurs around 10^{11} s after the big bang.

V. Problems with the Standard Model

1) Why the imbalance between matter and antimatter in the early universe? That is why are we here? This is believed to have occurred at about 10^{-36} sec after the Big Bang in the period when quarks were annihilating (which initiated inflation). It is believed that a number of processes that violated charge-parity conservation rules resulted in the annihilation of most of the quarks. Only about 1 in 10^{9} quarks survived and no antiquarks survived. This, however, still requires more experimental confirmation.

2) The horizon problem: This has to do with the incredible constancy of the CBR. It is the same temperature in every direction in the sky to a very high accuracy. If one looks back at the universe at earlier times, one realizes that two patches separated by large angular distances could never have been in "causal contact". That is, there is no way that one patch could have communicated its temperature to that of the other patch and there is absolutely no reason why they should be precisely the same temperature. One way around this is the suggestion that the early universe went through a period of rapid expansion called the **inflation period**. During this period from about 10^{-35}-10^{-33} secs the universe expanded by a factor of about 10^{50}! Prior to this period all parts of the universe were in causal contact.

3) The flatness problem: This has to do with the question of why the universe appears to be so near the critical density for closure. The name comes from the fact that at the critical density, the curvature of the universe (which specifies its geometry) would be zero, hence a “flat” universe. Any departure from flatness in the early universe would be magnified by many orders of magnitude due to expansion. In fact, the density found today must have been within 1 part in 10^{49} of the critical density. If an inflationary epoch did occur, it requires flatness and it would therefore solve the flatness problem as well as the horizon problem, but inflation is not yet confirmed by observations at the moment.

4) Where did galaxies come from? The CBR is so smooth, it is very difficult to understand how galaxies began to form. To form a galaxy it is necessary to have matter coagulate or clump into clouds of density greater than the ambient average density. One would expect to see some evidence of this in the CBR distribution on the sky. Until recently this was not detected. Now it appears that there are some "ripples" in the brightness distribution of the CBR. The question now is: are the fluctuations in the CBR large enough to possibly understand galaxy formation.

5) Grand Unified Theories (GUTs)
Prior to about 10^{-35} secs, it is postulated that the four forces of nature that we know today were combined or unified into a single force. That is the forces today are different aspects of a single unified force which under extreme density and temperature operates as a single force. These were decoupled into separate forces as the universe expanded. What is the nature of this force and is there any way we can establish the validity of this hypothesis?

6) What is the role and nature of dark matter in the evolution of the universe?

7) Age of the universe? This is tied up with evaluating the Hubble constant. It has to be larger than the ages of the oldest stars but less than that implied by the minimum experimental value of H.