Origin(?) of the Universe

4. The First Three Minutes

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In this part of the series we discuss the standard cosmological model valid close to the big bang epoch. The origin of light nuclei is believed to have taken place within the first three minutes or so when the universe was very hot and dominated by radiation. Subsequently, it cooled down and today we should see radiation decoupled from matter but spread almost homogeneously all over the universe with a black body spectrum. This expectation has been realized by the discovery of the microwave background in 1965.

Probing the Past of the Universe

In the previous part of the series we described the simplest models of the expanding universe, first worked out by Alexander Friedmann. These models contain matter in the form of dust, i.e., pressureless fluid. In this idealized situation we may regard each dust point as a galaxy and the large scale motion of the galaxy population conforms to the Weyl Postulate (see Part 2 of the series). This motion is the one that follows the Hubble law.

In reality, of course, galaxies do have random motions in addition to that of the expansion. The random motions arise because they are members of a cluster wherein the gravitational field of all other members affects the motion of each member galaxy. Normally these motions are in the range of 200 - 300 km/s. Thus if we use the Hubble law, the Hubble motion of expansion of a typical cluster member at a distance of say, 100 Mpc[1] will be around 5,000-10,000 km/s, far larger than the random motions in that cluster. By the same token, for a nearby cluster the random motions may *dominate* the Hubble motion. Our nearest neighbour, the giant galaxy Andromeda is in fact moving

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This six-part series will cover: 1. Historical Background. 2. The Expanding Universe. 3. The Big Bang. 4. The First Three Minutes. 5. Observational Cosmology and 6. Present Challenges in Cosmology.

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[1] Mpc = Megaparsec; one parsec equals 3.26 light years $\cong 10^{18}$ cm.

towards us, because of the attraction between it and our galaxy.

In the expanding universe one can show that the random part of the momentum[2] of a free particle decreases in inverse proportion to the scale factor. Thus, at redshift unity[3], the random motions would have been typically double those in a nearby cluster. So, as the universe continues to expand, random motions become less and less significant and the approximation to the Weyl postulate becomes more and more accurate.

However, if we are interested in discussing the past history of the universe, the dust approximation may not hold all the way. Our rule of the momentum growth in the past tells us, for example, that a random motion of 300 km/s today would have been close to the speed of light at an epoch of redshift around a thousand. Clearly we must take into account the growth of pressure in the cosmic fluid as we go further back into the past.

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The Radiation Dominated Universe

Since we are interested in discussing the behaviour of the universe very close to the big bang, we will skip the more recent epochs and go to one where the random motions were so high that the typical constituents of the universe were moving relativistically, i.e., with near-light speed. At those epochs the galaxies did not (indeed could not) retain their large and bound structures of today. Indeed, we expect that all constituent particles moved freely across space. We thus have a cosmic brew with particles like neutrons, protons, electrons, neutrinos, etc. moving relativistically along with the particles of light, the photons, which of course move with the speed of light. All are moving at random, colliding and interacting in marked contrast to the situation described by the Weyl postulate. In such a state the universe is said to be radiation dominated. Let us look at this scenario more quantitatively.

[2] This momentum is to be measured by an observer at the particle with no random motion, i.e., one obeying the Hubble expansion.

[3] At redshift z the size of the universe was $1 + z$ times smaller than now.

We shall refer to this epoch as that of the *early universe*. We shall assume, to begin with, that the universe consists mainly of photons. The photons are in constant interaction with charged particles like electrons and positrons and these interactions maintain the photon population in thermodynamic equilibrium. That is, the photons are distributed in momentum space as in a *black body*. The temperature T and the energy density u of such a distribution are related by the Stefan-Boltzmann law:

$$u = aT^4$$

where the constant a is known as the radiation constant. The pressure of this distribution is given by $p = u/3$.

The next step is to substitute these quantities in the dynamical equations which drive the universe, viz. the Einstein equations. In the previous part of the series we had done the same for the dust distribution. The two independent relations that emerge are:

$$u S^4 = \text{constant},$$

$$[(\mathrm{d}S/\mathrm{d}t)^2 + kc^2]/S^2 = 8\pi G u/(3c^2).$$

Standard thermodynamics tells us that the first relation is simply the rule of attenuation of radiation energy density with the

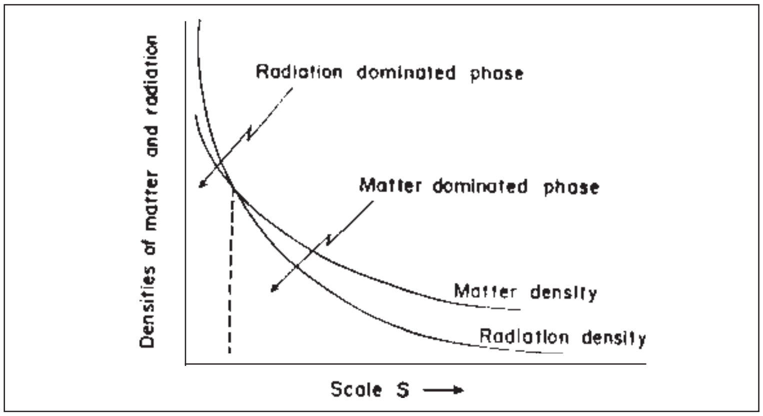

Figure 1 This graph shows how radiation density and matter density fall off as the universe expands, i.e., as the scale factor increases. In the early universe, radiation dominated whereas the present universe is matter dominated. The matter and radiation were of comparable strength when the scale of the universe was approximately a thousandth of its present value.

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adiabatic expansion of gas. If we compare the expressions of how matter and radiation density fall off in the expanding universe we find that the former falls off as S^{-3} and the latter as S^{-4}. Today the universe is matter dominated while in the early era it was radiation dominated. As the importance of radiation vis-à-vis matter declines with expansion, the two may have been comparable at an intermediate epoch. As we shall see later, the present radiation density is about 10^{-3} of the matter density. Thus the epoch of equality would be around redshift 1000. We can therefore say that around that epoch, the universe switches over from the solution described in this part to that described in the previous part. The second relation describes the gravitational force of the radiation on the expanding gas. We will assume that the curvature term is not important for the solution that we are interested in. This assumption is non-trivial but we will postpone its discussion to Part 6 of the series.

If we ignore the curvature term in the second of the above equations, they can be solved easily. We find, after a little manipulation, that

$$S \; \alpha \; t^{1/2}$$

and,

$$T^4 = [3\,c^2 / (32\,\pi\, Ga)]\, t^{-2}.$$

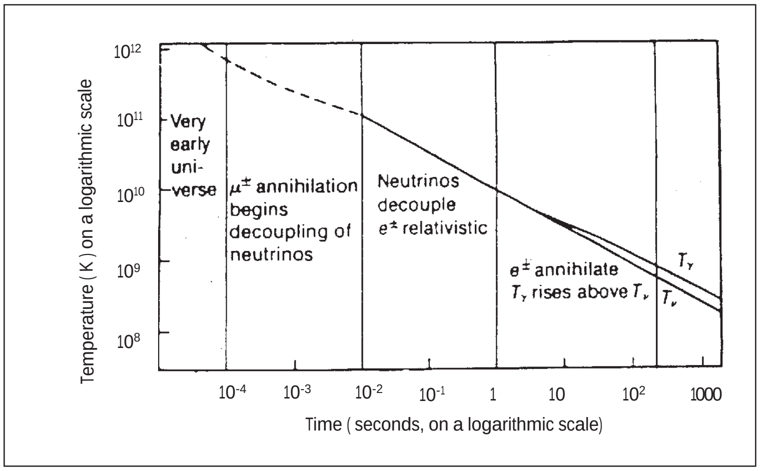

Figure 2 The time temperature relationship shows how the radiation temperature in the universe falls off with expansion. The smooth curve has discontinuous tangents at epochs when the composition of the universe underwent a phase transition, e.g., when the electrons and positrons annihilated to produce more radiation.

In the latter result we have used the earlier relation between u and T. Note also that t denotes the time elapsed since the epoch when we had $S = 0$, i.e., since the big bang epoch. We thus get from the last relation, the profound result that the temperature of the universe is determinable in terms of its age through constants a, c, G all of which belong to fundamental physics. If we put in the numerical values of these constants then the time-temperature relationship is simply

$$T(\text{Kelvin}) = 1.52.\ [t(\text{second})^{-1/2}].10^{10}.$$

Thus we conclude that in a universe filled almost purely with radiation, the temperature one second after the big bang was about 15 billion degrees Kelvin.

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Primordial Nucleosynthesis

A result of this kind convinced George Gamow in the mid-1940s that the early universe could hold the key to the origin of chemical elements. If the universe started with a relatively simple set of particles like electrons, positrons, neutrinos, muons, pions, neutrons and protons along with photons, then during the first 200 seconds its temperature was in the range $10^{10} - 10^{8}$ K, high enough to bring about synthesis of neutrons and protons to form chemical nuclei in ascending order of their mass numbers.

The rationale for this conjecture is based on the following. At a temperature T the typical thermal energy per particle is kT, where k is the Boltzmann constant. A typical particle of mass m has rest-mass energy mc^2. If kT exceeds this value we say that the particle is moving relativistically. By this token, the neutrons and protons ceased to be relativistic when the temperature of the universe dropped below 10^{13} K, whereas for electron-positron pairs the temperature was around 5.10^{9} K. Statistical physics formulae tell us that as a species ceases to be relativistic, its number density drops very rapidly with decreasing temperature and it begins to be less and less important in contributing to the expansion of the universe.

The simple calculation of estimating the temperature that we carried out in the previous section was based on the assumption that of all particles only photons were contributing to the expansion of the universe. A more realistic calculation would take into account the other particles that were relativistic and the extent to which they contributed to the right hand side of Einstein's equations. This calculation modifies the coefficient in the temperature-time relationship from 1.52 to 1.04. Thus our simple derivation captures the physical situation reasonably well and we may use it for approximate estimates of the temperature of the universe.

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At the temperatures $10^{10} - 10^{8}$ K, particle energy is in the range comparable to the binding energy of nuclei like deuterium and helium. Thus, it is possible to argue that although initially the constituent particles were moving relativistically, as the universe continued to expand, its radiation temperature dropped and therefore the motions of these particles slowed down to values small enough for nuclear forces to be able to trap them to form composite nuclei. Since the universe provided a rapidly changing environment, it was necessary to include this in the calculations along with the details of nuclear reaction rates in order to determine the actual abundances of various nuclei.

Gamow and his younger co-workers Ralph Alpher and Robert Herman carried out calculations of this kind in the late 1940s. These calculations were redone by others as improved nuclear reaction data became available. The most comprehensive such attempt was in 1967 by Robert Wagoner, William Fowler and Fred Hoyle. Today high speed computers are needed to refine these results, but the essential conclusions have not changed since 1967. What are these conclusions ?

The entire process of primordial nucleosynthesis is completed in a very limited period, say in about the first three minutes. After this the universe has cooled down so much that the nuclear furnace is switched off. However, contrary to what Gamow had expected, the process of primordial nucleosynthesis is not able to deliver nuclei with mass numbers of 5 or more. The process thus produces mainly He^4 and very tiny quantities of deuterium, tritium, He^3 and also extremely small quantities of nuclei like Li^6, Li^7 and B^{11}. For the commonly found elements like carbon, oxygen, etc including metals like iron, one must turn to another scenario altogether. In 1957, in a pioneering paper in *Reviews of Modern Physics*, Geoffrey and Margaret Burbidge along with Fowler and Hoyle showed how stars in various stages of their evolution produced all these elements. As it happens, stars are not so effective in producing the light nuclei that the early universe is able to generate. Thus there seems to be some complementarity in the two scenarios.

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Relics of the Early Universe

Physicists by now will be inclined to argue that all this is fine so far as speculations go; but can these ideas on the early universe be verified through experiments or observations ? In short, they will be looking for relics of the high energy activity that went on during the first three minutes, in the history of the universe much as archaeologists look for relics of a bygone era. Fortunately the early universe model does provide two important relics. We will describe them here although we will discuss them in the light of observations in Part 5.

One relic is the light nuclei that we just discussed. For example, the primordial abundance of helium is expected to be in the range 23-24 per cent by mass while that of deuterium may be in the range $10^{-6} - 10^{-5}$. Stellar nucleosynthesis provides additional helium to the extent of only about ten percent of the primordial value whereas no stellar process is as yet known for producing deuterium. These and other light nuclear abundances are thus the relics of the early era.

The second important relic, first predicted by Alpher and Herman in 1948 in a paper in *Nature*, concerns radiation. Recall that we started with radiation as the main component of the primordial universe. What has happened to it today? In our discussion we had assumed that the radiation was in thermodynamic equilibrium in the early universe because it was in continuous interaction with charged particles through electromagnetic interactions. Charged particles are largely electrons which continue to remain free a long time after the light nuclei are formed. Thomson scattering by the electrons is sufficiently powerful to block the radiation from travelling coherently over cosmological distances. The early universe was, in technical jargon, optically thick and the radiation had the spectrum of a black body.

However, as its temperature dropped below the 3000-4000 K mark, the randomly moving electrons became too slow to escape being trapped by protons via the Coulomb force of electrical attraction. Thus the electrons get into orbitals around protons and form neutral atoms of hydrogen. The trapping stage is governed by the *Saha ionization equation* discovered by Meghnad Saha in the 1920s in the particular case of stellar atmospheres. So at the temperature mentioned above, the radiation finds itself free from the charged scatterers![4] This is the epoch of last scattering of

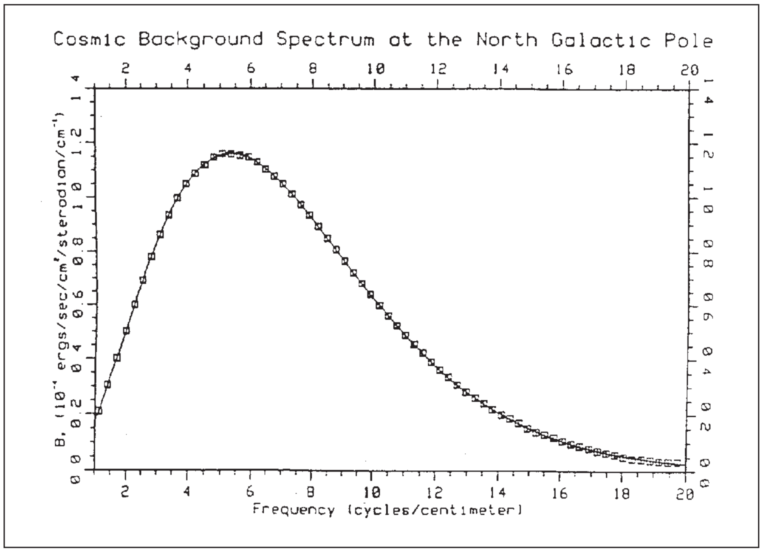

Figure 3 The spectrum of the microwave background as measured by the COBE satellite. The smooth curve is the blackbody curve that best fits the data.

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[4] As temperature is raised, a physical system can be found with increasing probability in states of higher energy. Since it takes energy to remove electrons from an atom, this process (called *ionisation*) becomes more and more important at high temperatures. Saha's noteworthy contribution in deriving his formula was to correctly account for the *number of states* available to the electron once it is freed. This depends on the temperature but also the volume of space available in between the atoms. This effect is very important. Neglecting it would give a completely wrong answer (100,000 K) for the temperature of recombination mentioned in the text!

the cosmic radiation which thereafter remains decoupled from matter. Since the electrons combine with protons at this epoch it is sometimes (erroneously) called the recombination epoch.

The physics of such radiation tells us that it would adiabatically cool down as the universe expands, while retaining its primordial stamp of a black body radiation. The temperature itself would drop as S^{-1}. Its magnitude at the present epoch, however, cannot be determined by the early universe models but has to be taken as a given observational input.

The discovery in 1965 by Arno Penzias and Robert Wilson of the uniform and isotropic microwave background at a wavelength of about 7 cm was thus regarded as a vindication of the above early universe scenario. Subsequent studies at many other wavelengths culminating in comprehensive measurements by the Cosmic Background Explorer satellite in 1989 established the blackbody nature of its spectrum with a temperature of 2.735 ± 0.06 degrees Kelvin. In total energy content this microwave radiation background far exceeds any other radiation arising from other causes of astrophysical origin at various wavelengths.

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If the present value of the radiation temperature is denoted by T_0, the temperature of the radiation at epoch of redshift z would be given by $T_0(1+z)$. Hence the last scattering epoch had redshift around 1000-1500.

Thus if we use this value of temperature for the radiation energy density we find that its magnitude is about 4.10^{-13} erg / cm^3 compared to the present energy density of visible matter estimated around $3\text{-}4.10^{-10}$ erg/cm^3 (a more complete discussion will be given in Part 5). That is, *matter dominates over radiation by some three orders of magnitude*. This result was used earlier by us to decide the epoch when the universe switched over from being radiation dominated to matter dominated. Note that this epoch is roughly the same as the epoch of last scattering.

Concluding Remarks

This part essentially summarizes the theoretical basis of big bang cosmology. To proceed further it is necessary to take stock of the observational constraints to see whether our picture developed here meets the basic observational checks. This we will do in Part 5 of this series.

The work on the early universe has prompted further speculations about what the universe was like even closer to the big bang epoch. As we shall see in Part 6 these speculations take us close to fundamental particle physics where physicists are interested in speculating about the ultimate structure of matter and its origin.

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Suggested Reading

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