The Final Frontier

In cosmology we are at the final point, a point so final that it can be called the final frontier. This frontier is the Planck length, about 10^{-35} cm, and the Planck time (the time it takes a photon to cross the Planck length), about 10^{-43} seconds. Theory tells us that any length smaller than the Planck length cannot exists since the enormous energy in such a small area will result in a black hole. One interpretation of the Big Bang Theory is that this was the point at which time was born in the very, very early universe. In terms of the quantum theory spacetime at this point can best be described as being “quantum foam”. The expansion of space from this point onwards could only have occurred because time was born and the universe entered the inflationary phase.

It makes no sense to ask what happened before this. Since time was born at this point, it makes no sense to think of time or space beyond this point. There was “nothing” beyond this point. According to this view the universe was literally born from nothing. The physicist, Frank Wilczyk once said: The reason that there is something instead of nothing is that nothing is unstable”. To ask what is beyond the Planck length is like standing at the North Pole and ask: “What is North?”. It can be argued that the laws of physics are not redundant or inadequate beyond this point since space and time do not exist at scales smaller than the Planck length.

We do not know what the nature of the singularity beyond the inner event horizon inside a black hole is. Presumably at time 10^{-43}seconds, the final point at which matter enters a black hole, time and space get separated, time is destroyed and space becomes a probabilistic foam. In other words, it is the process that created space and time in the very, very early universe in reverse. It is important to point out that here are no infinities in the very, very early universe or in a black hole. The singularity theorems of Roger Penrose and Stephen Hawking merely indicate that the curvature of spacetime became so severe that quatum effects could no longer be ignored.

I have dealt with this matter at length because it is important in the understanding of the very, very early universe and to remove popular misconceptions of the Planck era. It is difficult, but we simply have to get rid of incorrect preconceived ideas of the very, very early universe.

At the Planck length in the very early universe, the temperature was an incredible 10,000 trillion, trillion degrees Kelvin and the densities were so enormous that the entire Milky Way Galaxy could fit into a volume no larger than a single hydrogen atom. Particles were created from the enormous energies. Electrons and quarks with their antiparticles, were the major constituents of matter and, very massive particles called Leptoquark Bosons caused the quarks to decay into electrons and vice versa. When we look back to earlier and earlier times we encounter temperatures and densities so high tha particles like muons, pi-mesons protons neutrons and so on would have been present in copious numbers in thermal equilibrium, and all in a state of continual mutual interaction.

At temperatures above 100,000 million degrees Kelvin a problem occurs due to the interactions of the strong nuclear force in elementary particles. The strong nuclear force is the strongest of the four fundamental forces, but its range ia the shortest, about 10^{-13} cm. When two protons are pushed close enough together, the strong nuclear interaction between them becomes about 100 times greater than the electric repulsion; this is why the strong nuclear force is able to hold together atomic nuclei against the electric repulsion of almost 100 protons. I do not want to elaborate on this problem beyond saying that the strong interactions make them difficult to deal with mathematically because of the difficulty of calculating rates for processes involving strong interactions.

However, strong interactions only affect a class of particles known as “hadrons”, which include nuclear particles and pi-mesons and other unstable particles known as K-mesons, eta mesons, lambda hyperons, and so on. Hadrons feel the effects of strong interactions but the lighter particles known as leptons, do not. Leptons include neutrinos, electrons and muons. Together with the small mass of the electron, this fact that the cloud of electrons in an atom is 100,000 times larger than the atomic nuclei, and also that the chemical forces which hold atoms together in molecules are millions of times weaker than the forces which hold protons and neutrons together in nuclei.

How do we deal with hadrons and antihadrons at temperatures above their threshold? There are two schools of thought in this regard known as “nuclear democracy” and the other that the hadrons are composites made up of quarks. The hadrons can therefore be regarded as really elementary particles. I must say that I prefer the latter because it is more conventional and, I think, closer to the truth. We are all aware of the different types of flavours of quarks like “up,” “down,” “strange,” and “charmed” with colours like red, white and blue.

If the quark idea is right, then the physics of the very early universe may be easier than we thought. It was found in experiments that the force between quarks seem to disappear when they are very close to each other at very high temperatures. This suggests that at temperatures of around several million degrees Kelvin, hadrons would simply break up into their constituent quarks, similar to atoms that break up into protons and neutrons at a few thousand million degrees. This process is known as quark deconfinement and it is hoped that this procees could be arrived at the LHC at CERN. The very early universe could therefore be considered as consisting of photons, leptons, antileptons, quarks and antiquarks, all moving as free particle species effectively furnishing just another kind of black-body radiation. It is known, in non-Abelian gauge theories, that quarks exhibit a property known as “asymptotic freedom”: at asymptotically short distances or high energies, quarks behave as free particles. Basically, the asymptotic freedom of non-Abelian gauge theories provides a solid mathematical justification for a simple picture, that the very early universe was made up of free elementary particles.

In the creation of matter, if the strength of interaction between two quarks decreases as they are pushed closer together, it also increases as they are pulled further apart. The energy to pull the quarks apart increases with distance and seems eventually to become great enough to create new quark-antiquark pairs. Eventually, one ends up not with several free quarks, but with several ordinary hadrons. In the very early universe quarks were close enough together, so that they were not far apart enough to feel the forces, and could behave like free particles. However, every free quark in the very early universe must, as the universe expanded and cooled, have annihilated with an antiquark or else find a place inside a proton or neutron.

An interesting part of modern theories of elementary particles is that the universe probably have undergone a *phase transition*, like the freezing of water below 0ºC (273º K). The phase transition is associated, not with the strong nuclear force, but with the weak force and the electromagnetic force. It should be noted that the weak force and the electromagnetic force were in fact unified by Stephen Weinberg and independently by Abdus Salaam. This theory predicted a new class of weak interactions, called neutral currents, confirmed experimentally in 1973. It was further supported by the discovery of a family of new hadrons. The key is a high degree of symmetry relating to the various particles and fundamental forces. In terms of this, all the forces of nature were one super force in the very early universe, including gravity. It is the ideal to include gravity but so far attempts to include gravity in the unification of forces in the very early universe have been met with no success. The critical temperature for this phase transition is about 3,000 million, million degrees ($3 x 10^{15}$ K).

So far I have dealt with the weak and electromagnetic forces at 3,000 million, million degrees, but can gravity be included? It can be imagined that at some stage in the evolution of the very early universe gravity would have been the same strength as the strong nuclear force. At the extremely high temperatures and densities of particles in thermal equilibrium it could have become so large that the gravitational interactions between them became as strong as any of the other forces. It should be born in mind that all forms of energy create gravitational fields. It is estimated that the equal strength of gravity and the other forces happened at a temperature of about 10^{32} K.

At such incredibly high temperatures the production of particles and antiparticles out of energy would have been copious. The time and energy at which such particles were produced cannot be determined with any certainty since this would be a violation of the uncertainty principle. At this stage in the evolution of the very early universe the word “particle” did not have the meaning we attached to it today. Particles were in thermal equilibrium and distances between them had no meaning. Each particle would have been as big (or as small) as the observable universe. It can be estimated that the temperature of 10^{32} K was reached some 10^{-43} s (the Planck time) after the big bang.

Quantum fluctuations in the very early universe were, like quantum fluctuations anywhere else, controlled by the uncertainty principle. It is thought that these quantum fluctuations provide the greater densities from which stars and galaxies were later formed.

It should be pointed out that the appearance of the universe before 10^{-43} s can only be adequately described by modifying the Big Bang Theory because this theory is, in turn, based on the General Theory of Relativity. General Relativity very successfully describes the large scale structures of the universe. However, at the Planck scale, General Relativity needs to be xtended to include the microscopic aspects of gravity. Scientists are currently trying to develop such a theory of quantum gravity. Today, quantum gravitational effects are detectable at the atomic and nuclear scale, but, during the Planck era the macroscopic and microscopic worlds merged and the quantum gravity of the microcosm became the quantum cosmology of the macrocosm.