Quantum theory and the early universe

1. Introduction

The equations of general relativity can be used to work back in time to calculate the temperature and density of the universe shortly after the Big Bang.1) Eventually we reach a point where the universe was the size of a quantum object with incredibly high density and temperature. At this point the theory of general relativity breaks down because it does not make provision for quantum effects. Quantum physics dominate and the smooth continuous spacetime described by general relativity no longer holds. Heisenberg's uncertainty principle dominated and the behaviour of matter and radiation were subject to the uncertainty principle. I will refer later in more detail to the fluctuations of space and time at the quantum level. It should be noted that the behaviour of matter and radiation in the extreme conditions of density and temperature in the early universe have been recreated and well researched in particle accelerators and the calculations referred to in this article can be confidently accepted as correct. Theories of what happened to the forces of nature in the early universe are somewhat speculative and here we have to rely heavily on the Grand Unification Theories.

2. Heisenberg's uncertainty principle

At this stage we should look at what Heisenberg's uncertainty principle is and its implications for spacetime in the early universe. Quantum theory tells us that space is not empty. At the quantum level it is teeming with fluctuations of energy which can also be seen as virtual particles flashing into existence and annihilate (virtual particle and its anti-particle annihilating) returning the borrowed energy within the time prescribed by quantum mechanics. A virtual particle cannot be observed using a particle detector but whose existence have measurable effects. The uncertainty principle tells us that two properties of a particle, such as velocity and position cannot be determined accurately at the same time. The more accurately you determine the velocity of an electron the less accurately you can determine its position. The measurement makes the position a delta (Δ) function. The measurement of the position would then be completely uncertain. Mathematically the uncertainty principle as described here can be stated as $\Delta p \, \Delta m \geq \frac{1}{2}\hbar$. A similar uncertainty relation exists between energy and time; $\Delta E \, \Delta t \geq \frac{1}{2}\hbar$.

Modern quantum theory incorporates the idea of a field and the early universe can be seen as consisting of *fields* and the force carrying particles of each of the fundamental forces; the photon of the electromagnetic force, the W^+, W^- and Z^0 particles of the weak force (responsible for radio-active decay) and the eight gluons of the strong force can be seen as fields. The force carrying particle of gravity is seen as the graviton. Similarly, particles such as the electron is not regarded as a point like particle, but rather as an electron field, the photon as a photon field, etc. But what is meant by a field? When you go through airport security the magnetic field created by the metal detector induces a magnetic field in the metal object you carry and the metal object is detected. A good example of a field is the iron filings on a piece of paper arranged in a magnetic field by a nearby bar magnet. The iron filings is evidence that the magnet creates a magnetic field exerting a force beyond the boundaries of the magnet. Michael Faraday in the 1800's carried out experiments proving that electricity and magnetism are two sides of the same coin because changes in an electric field cause changes in an adjacent magnetic field and vice versa and an electromagnetic field is created. The force carrying particle of the electromagnetic force is the photon. The photon is seen as a field and the photon quanta excited by the input of energy. At the temperature of 2.7 Kelvin in outer space and even at higher temperatures such as boiling water fluctuations of the field are very small, but at a temperature of 10^{32} K at 10^{-43} seconds after the Big Bang, all fields fluctuated wildly.2) As the universe expanded and cooled the extreme densities of matter and radiation dropped and the fluctuations of fields became more subdued. The ground state or lowest energy state of a field can never be zero, because that would mean a violation of the uncertainty principle since the energy and rate of change (time) of the field can be measured accurately at the same time.

3. The size of the early universe

In terms of quantum mechanics space and time can be quantized and it makes no sense to talk about a length shorter than the Planck length of 10^{-33} cm or a time interval smaller than 10^{-43} s (the time it takes a photon to cross the Planck length). This means that the early universe at birth could not have been smaller than a length of 10^{-33} cm across, with a density higher than 10^{94} grams per cubic centimetre and an age of 10^{-43} s at birth. Just as it makes no sense to ask: “Where is North?” when you stand at the North Pole, it makes no sense to talk about a length smaller than 10^{-33} cm or a time shorter than 10^{-43} s. According to quantum mechanics the universe could not have been born from a singularity of infinite density and temperature.

4. Phase transitions and the separation of the forces

What follows is still somewhat speculative and we draw heavily on the ideas of the Grand Unification Theories. We have seen that the electric and magnetic forces are one force. It is believed that the fundamental forces were one super force when the universe was born. The forces split apart releasing energy causing the universe to expand exponentially which flattened and smoothed the universe in what is known as inflation. The universe is not completely smooth. Tiny irregularities left by the uncertainty principle which can be detected in the Cosmic Microwave Background Radiation (CMBR), were the seeds from which stars and eventually galaxies were formed.

The splitting apart of the fundamental forces can be understood in terms of a well known process called *phase transition*. A phase transition can be described as a process during which energy is exchanged between the system that is changing and the rest of the world. When water freezes at 0^0 C, it releases energy (absorbed by the environment) while the temperature of the water stays at 0^0 C. Energy, known as latent heat, is released by the water. It is latent heat which is absorbed by the ice when it is melting. There are many examples of phase transitions such as when water vapour condenses condenses into liquid water, the formation of drops of rain in clouds. Although not exactly the same, processes similar to phase transitions occurred in the early universe. At the Planck time of 10^{-43} s gravity was the first of the forces to split apart followed by the strong nuclear force at about 10^{-35} s. Together these two phase transitions released the energy that triggered the exponential expansion of the universe.

The release of energy in the phase transitions can be explained by a metal ball hanging from a chain. In scientific terms the metal ball is said to occupy a local minimum in terms of energy associated with the gravitational field of the earth. The hanging ball represents represents a certain amount of minimum gravitational potential energy. This potential gravitational energy can, however, be said to be a false minimum. If the ball is released the true minimum amount of energy is released, at least until it lands on the surface of the earth, in equilibrium, but in a lower state of energy. Before inflation, the conditions in the early universe can be described as a false state of equilibrium, that is, in terms of the energy of the vacuum. During the phase transition this energy is released, causing the expansion of the universe. The universe settled down into the true minimum energy of the vacuum. The exponential expansion of the universe was very short, it lasted about 10^{-32} s, but it was enough to double the size of the universe every 10^{-34} s, This means that the universe expanded faster than the speed of light, but it was space expanding, nothing traveled through space.

5. Conclusion

Inflation explains why the universe appears to be almost flat as confirmed by NASA's WMAP satellite and later by ESA's Planck Explorer. The quantum theory explains why there are tiny irregularities observed in the CMBR. These irregularities grew to form stars and galaxies. Research done at the Large Hadron Collider at CERN will, hopefully confirm or reject the idea of a Higgs field which, if correct, gives mass to particles. The role, if any, of the Higgs field in the expansion of the universe may become clearer.

Frikkie de Bruyn

Note: The ideas used in this article came from John Gribbin's book “The Universe A Biography.

References:
1) 2)See Gribbin John, The Universe A Biography.Penguin Books, London 2006