COSMOLOGY

The Creation and Fate of the Universe

Cosmology is the study of the Universe as a whole. In modern cosmology we try to understand the origin of the Universe, its organization, its evolution, and its ultimate fate.

Early cosmologies assumed that the Earth or Sun was at the center of the Universe. The Greek astronomer Ptolemy (140 A.D.) had the Earth at the center, which lasted until the time of Copernicus. Copernicus's less complicated cosmology (1515 A.D.) had the Sun at the center of the Universe.

However, with the discovery of the Sun's location in the Galaxy by Shapely (1920s), it became clear that in any cosmology, the Earth, Milky Way Galaxy, Local Group or Local Supercluster should **occupy no special position in the Universe.**

Modern cosmology relies on Einstein's Special and General Theories of Relativity which relate measurements of length, time, velocity and mass. In contrast to Newton's view, Einstein saw the gravity of mass not as a force, but as a manifestation of the curvature of spacetime.

Observational Constraints

1. Distribution of Galaxies

Very distant galaxies are uniformly distributed on the sky. This implies that the Universe is the same in all directions.

Cosmological Principal

The Universe is homogeneous and isotropic. The distribution of matter, **on large scales,** does not depend on the distance from the Sun or on the direction in which we look.

2. The Universe is Expanding.

The spectra of galaxies are redshifted implying that the galaxies are moving away from us. The speed of recession, v, is linearly related to the distance, d, of the galaxy by

$$v=Hd$$

(Hubble's Law)

3. Age of Universe

Universe must be older than the oldest stars. The age of the Sun implies that the Universe is at least 5 billion years old. Stars in globular clusters **suggest** that the Universe is at least 15 billion years old.

4. Composition of Universe

In the early Universe the principal elements were Hydrogen and Helium. Miniscule amounts of Deuterium (isotope of hydrogen) and the light elements Lithium and Beryllium were also created.

5. The Microwave Background Radiation

The isotropy (uniformity) of the Microwave Background Radiation provides the strongest evidence that the Universe is isotropic and homogeneous on large scales.

6. Why the Sky is Dark at night.

Olber's Paradox.

7. Formation of Stars, Galaxies, and Clusters of Galaxies.

Cosmic Horizon

Light requires time to travel from one point to another. Since the age of the Universe is 15 Billion years, we can see nothing farther than 15 billion light years away, even if matter exists there. Thus light defines a cosmic horizon. The region inside the cosmic horizon is called the Visible Universe.

Size of the Visible Universe

We can use the distance to the Cosmic Horizon as a measure of the Radius of the Universe. Thus the Radius of the Visible Universe is 15 billion light years. At present Astronomers can detect objects at distances up to about 10 billion years.

Olbers' Paradox

In 1823, Olber considered the question:

Why is the sky at night dark?

Olber was confused by the darkness of the night sky when observations showed that stars appeared to be evenly distributed throughout space.

Olber reasoned that if stars (or galaxies) were evenly distributed throughout space, then eventually an observer's line-of-sight should encounter the surface of a star. **Therefore, the whole sky should be glowing like the surface of a star.**

The resolution to Olber's paradox is that the Universe has only been in existence for 20 billion (or less) years. Since we look back in time when we look at distant objects, we eventually look back to a time before stars existed. Thus most random sight lines do not hit a star --- for them to do so the Universe would have to be very very much older.

(Another effect is that the expansion of the Universe also diminishes the brightness of the night sky, because as light from distant galaxies is redshifted it loses energy.)

The resolution to Olber's paradox tells us about the nature of the Universe.

Cosmological Theories

In the 1940's and 1950's two competing cosmological models were heavily debated. These were the Big Bang Model (now accepted) and the Steady State Model. The debate between proponents of the models considerably sharpened our views about the Universe, and about cosmology.

Steady State Theory of the Universe (A failed theory).

According to the Steady State Theory (1940s), the Universe never had a beginning and will never have an end. Furthermore, the Universe should have about the same amount of matter everywhere and look about the same in every direction. These conditions are called the **perfect cosmological principal**.

In the Steady State Theory, as the Universe expands matter must be created to fill the space left behind. Matter is created out of nothing. Thus, the properties of the matter in some large volume of the Universe should be constant with time.

The fact that matter is created, which violates the important conservation of energy law (remember energy and mass are equivalent), is not a real problem. After all, when the issue is the origin of the Universe, at some point matter must be created. [Only one atom would have to be created in a cubic cm of space every million billion years (10^{15} years)].

In its purest form, the Steady State Theory is not consistent with observations of the Universe. For example, we now know that the Universe has many more quasars and active galactic nuclei as we look out to larger and larger distances from the Milky Way. Since we are looking further and further into the past this implies that the Universe is not constant --- **it evolves with time.**

Attempts (sometimes very elaborate) to modify the Steady State Theory to account for the observed evolution do not provide a convincing explanation of the Universe. The Big Bang model is now preferred by most scientists since it provides a more "simple" explanation for some fundamental observations.

Big Bang Theories of the Universe.

Lemaitre proposed a specific Big Bang model for the Universe in the 1940s.

Since the Universe is expanding, it must now be evolving into a state where the matter in the Universe is becoming more and more spread out. **At some time in the past, however, the matter in the Universe must have been extremely compressed.**

In Big Bang theories, the Universe began some time ago (in the past) in a primeval fireball. From that moment on the Universe has been expanding, and as it does so, its properties change. For example, at some point in time (redshift) galaxies will begin to form.

Big Bang theories explain:

1. How the observed amounts of deuterium, helium and lithium are produced in the early Universe.
2. The existence of the 3 degree Kelvin cosmic background radiation which is the electromagnetic spectrum of a black body observed in every direction out into space.
3. Provide a natural explanation for the observed changes in the Universe as we look back in time.

Cosmic Nucleosynthesis of Light Elements in the Universe

When the Universe was only about 10 seconds old, its matter was extremely compressed and it had a temperature of about 3×10^9 degrees K. From this time, to a time when the Universe was about 15 minutes old and its matter had a temperature of about 0.4×10^9 degrees K, cosmic nucleosynthesis took place.

Cosmic nucleosynthesis refers to the fusion of protons and neutrons into **light** elements. [Note that stellar nucleosynthesis refers to fusion reactions inside stars which can also result in the production of heavy elements.]

Model calculations predict that **deuterium** (isotope of hydrogen with one proton and one neutron), **helium**, and small amounts of **lithium** were synthesized in the Big Bang. The models predict that **75%** of the mass should be hydrogen, while the remaining **25%** should be helium.

The observed amounts of light elements are in rough agreement with predictions of cosmic nucleosynthesis in Big Bang models. Complications make it difficult to test the models precisely. For example, clumping of matter during cosmic nucleosynthesis could alter the ratios of the elements produced. In addition stellar nucleosynthesis contaminates primordial matter.

The 3 Degree Kelvin Cosmic Background Radiation

In 1965, observations by Penzias and Wilson in the microwave (radio) region revealed a signal which did not depend on the region of the sky that was being observed, and which did not vary with time or the seasons. Subsequent observations showed this signal to have the spectrum of a black body at 3 degrees Kelvin (3 K). We interpret this radiation as a relic of the Big Bang.

After cosmic nucleosynthesis, the Universe continued to expand. As the Universe expanded, it cooled so that after about 1 million years it reached a temperature of about 3,000 K.

At this point in time the temperature of the free protons and electrons that made up the bulk of the matter in the Universe was low enough that the protons and electrons combined to form hydrogen atoms. This was a major event (called **RECOMBINATION**) because it meant that the Universe was now transparent to radiation.

Prior to becoming transparent to radiation, a photon could not travel very far in the Universe before being absorbed (like a photon in the interior of the Sun). However, once the Universe became transparent to radiation it could travel throughout the Universe without a high probability of ever being absorbed.

The radiation arising at this time had the spectrum of a **3000K** black body. However, when we observe this radiation today it is redshifted due to the expansion of the universe. The redshift is so high ($z = 1000$) that the spectrum of this cosmic background radiation peaks at a wavelength of a **3 degree black body**.

COBE

In 1989 NASA launched the Cosmic Background Explorer (COBE) satellite. Observations from this mission showed that

(1) the microwave background **spectrum matches that of a black body at 2.74 K.**

(2) the microwave background is extremely smooth (to a few parts in 10^5).

(3) **The small residual fluctuations that are seen may represent inhomogeneities that are the seeds of galaxy formation.**

Note:

The motion of the Sun through the Universe produces a dipole anisotropy which can be corrected out of the raw data. The microwave background provides a very accurate way of determining the Sun's (or Milky Way's) peculiar velocity (ie the velocity of the Milky Way with respect to the uniform expansion of the Universe).

The Structure of the Universe

The large scale structure (shape) of the Universe and its ultimate fate are determined by the Universe's (current) density. The different fates of the Universe are determined by a quantity known as the **CRITICAL DENSITY.**

1. Closed Universe.

The Universe will someday cease expanding because its density is sufficiently large (i.e. it is above the critical density) that gravity will eventually stop the expansion. The large scale structure of a closed universe is **spherical.**

After the expansion ceases, the Universe will collapse back in on itself in a `**big crunch.**' Some speculate that after the big crunch another big bang would occur and that the Universe oscillates (i.e., ..., big bang, then expansion, then collapse, big bang etc ...).

The **2 dimensional analogy of space in this model is the surface of a sphere.**

2. Flat Universe.

If the density of the Universe equals the critical density, its large scale structure is **flat** and its expansion will need an infinite amount of time to stop.

The **2 dimensional analogy of space in this model is the surface of a plane.**

Theoretical work suggests that the Universe is flat. This model cannot be ruled out by present observations.

3. Open Universe.

The Universe will expand forever because its density is too low (i.e. below the critical density) for gravity to stop the expansion. The large scale structure is **saddle-like**. Even after an infinite amount of time the Universe will still be expanding. The **2 dimensional analogy of space is the surface of a saddle.**

Observations currently indicate that the Universe is open, but this assumes that we have correctly estimated the amount of non-luminous dark matter present in the Universe.

Remember that the large scale structure of the Universe refers to its overall shape as determined by its density. According to General Relativity, within the Universe itself space will have many small scale curves caused by individual masses.

With all 3 large scale structures, every observer in the Universe statistically sees about the same thing in every direction. There is no center to the expansion which exists within the Universe itself. (This is a modified form of the perfect cosmological principle in the Big Bang model.)

NB. We can determine the shape of the Earth from Observations. For example, If we walk in a straight line we return to our starting point, Hence the Earth must posses positive curvature.

Similarly the structure and shape of the Universe can be determined by many techniques such as counting galaxies and quasers, or by performing a direct measure of the density of the Universe. Unfortunately, many other effects (eg galaxy evolution) also influence the quantities being measured, so that no technique has been implemented successfully.

Size of the Universe

Because distances to objects are measured in terms of look back time or billions of light years, **the observable size of the Universe is related to the age of the Universe.** We clearly cannot look back further in time than the age of the Universe.

The 3 degree Kelvin cosmic background radiation **creates an opaque wall** in the Universe which we cannot see beyond. We cannot see further back in time than when the Universe was about 1 million years old.

The age of the Universe depends on its density and its true expansion rate. Observations suggest that the **Universe is between 11 and 20 billion years old.**

The Missing Mass

It is estimated that about **95% of the mass of the Universe is non-luminous dark matter of an unknown nature.** Determining the exact amount of dark matter is necessary if *we are to know the ultimate fate of the Universe*.

We would also like to know what the dark matter is, since this gives us fundamental information about the bulk of matter in our universe, and hence tells us about the nature of our Universe. Astronomers hope they can determine the fate of the Universe by studying clustering and motions out to greater and greater distances.

The nature of dark matter remains a mystery. Many different types of dark matter have been proposed. At the present time the best approach is to **reject** those suggestions that are **inconsistent** with observations.

Possible forms for the Dark Matter

1. Brown Dwarfs

Stars with very low mass such that the fusion of hydrogen into helium never occurs.

2. Stellar remnants

White Dwarfs, Neutron stars, Black holes

3. Neutrinos

If neutrinos have mass they may contribute significantly to the mass of the Universe, since large numbers were created as the Universe formed

4. Exotic particles

e.g. WIMPS --- Weakly interacting massive particles. Predicted by theory, but not yet o

The Early Universe and Beyond

When considering processes in the Universe which occurred when the Universe was less than a few seconds old, we say we are studying the `early Universe.' Our current understanding of the laws of physics suggests that we can understand what physical processes happened in the Universe back to a time when it was only 10^{-43} seconds old.

Prior to 10^{-43} seconds, there is no agreement on what the correct laws of physics are.

As we go back in time, and approach the “beginning” of the Universe the density and temperature increases rapidly. As a consequence the nature of the Universe continually changes.

For example:

At times less than 10 seconds, positrons and electrons were continually being created out of gamma rays. The positrons and electrons would immediately annihilate each other, establishing an equilibrium with the radiation field.

At times earlier than 10^{-6} seconds, the temperatures (greater than 10^{13} K) and densities were sufficiently high (Visible Universe in a volume the size of Earth) that neutrons and protons broke into their constituent components called quarks.

Very early in the evolution of the Universe it was filled with both matter and anti-matter. As the Universe cooled, all the anti-matter was annihilated by the matter. Fortunately, there was a slight excess of matter which is what we see today.

Some other major events in the Universe's history:

1. When the Universe was 10 seconds old cosmic nucleosynthesis began, but radiation dominated until the Universe was about 1 million years old (radiation era).
2. When the Universe was 1 million years old, electrons and protons combined to form hydrogen and the Universe became transparent to radiation (beginning of matter era).
3. Depending on the properties of the dark matter, galaxies and clusters of galaxies may have started to form when the Universe was about a billion years old.

Three major problems in cosmology are:

Why is the Universe uniform on large scales?

Why is the Universe nearly flat?

Why is there a preponderance of matter?

At present it is suggested that the Universe suffered a phase transition when it was between 10^{-35} and 10^{-32} seconds old. (An example of a phase transition is when matter changes from a solid to a liquid). This is called the inflationary period in the Universe's history. At this time the Universe underwent a rapid expansion. Inflation helps to explain why the microwave background radiation is so smooth.

NB

Astronomical observations cannot verify the evolution of the Universe before it was 1 million years old. Our understanding of the evolution of the Universe is based on our current understanding of the physical laws of nature. (Observations, such as the deuterium abundance do provide some constraints).

The closer we approach the "beginning" of the Universe the more likely it is that some of our ideas regarding the Universe's evolution are incorrect.

Unification of the Fundamental Forces of Nature

Modern physics is struggling to reconcile the various laws of physics with each other. For example General Relativity, the modern theory of gravity, is not consistent with Quantum Mechanics.

Quantum Mechanics is a theory which provides a description of behavior on small (microscopic) scales.

e.g.

It provides a theory for atomic structure.

General Relativity also predicts singularities (infinitely small points of infinite density), which suggests the theory is incomplete.

There are 4 fundamental forces in nature. Physicists hope to develop a **SINGLE** theory which can explain all 4 forces of nature. Attempts to do this are called Grand Unification Theories (GUTs).

The 4 fundamental forces are

1. Nuclear (or Strong) Force

The force that holds the nucleus of atoms together.

The force only operates over distances the size of a nucleus.

2. Electromagnetic Force

Leads to electromagnetic radiation.

Magnets etc

Force involved in chemical reactions.

Electricity and magnetism were once considered as separate forces, but were unified into a single theory 100 years ago.

3. Weak Force

Important in some types of radioactive decay

4. The Gravitational Force

By far the weakest force (The force on 2 protons is about 10^{36} times weaker than the electromagnetic force)

Gravity dominates over large scales, since the gravitational force from individual particles combine together.

Physicists already understand how to unify the weak nuclear force and the electromagnetic force into the electroweak force.

GUTs suggest that in the hot, compressed environment of the very early Universe the four fundamental forces of nature were symmetric (similar), but when the Universe underwent phase transitions the symmetry was broken and the properties of the forces became very dissimilar.