Chapter 26 – Observational Evidence for the Big Bang

Under heaven and Earth there is more than one can imagine.

--Shakespeare

What is inconceivable about the universe is that it is at all conceivable.

--Einstein

Chapter Preview

Some of the most interesting and fundamental questions in astronomy deal with the Universe as a whole. How big is it? How old is it? How did it originate? How is it evolving? It is mind-boggling that by measuring distances and properties of faraway galaxies we can use this information to build theories of the origin of our Universe, the totality of all matter, radiation, and space that can be probed. What is even more incredible is that these theories are testable. In this chapter, we will examine the Big Bang theory of the Universe, the theory that explains the observed velocity-distance relationship for galaxies as the result of an expanding Universe that formed in a creation event. The Universe was infinitesimally small and infinitely hot immediately after this Big Bang. We can still see the cosmic fireball radiation from this creation event 13 billion years ago.

Key Physical Concepts to Understand: *General Relativity and cosmology, an expanding Universe, determination of the age of the Universe, the steady state cosmology, cosmic background radiation*

Web Videos (Youtube)

Why are we here?

http://www.youtube.com/watch?v=EUe_Vfi5IL0&feature=related

Birth of the Universe

1. **http://www.youtube.com/watch?v=NEZWtrvxyow&feature=related**
2. **http://www.youtube.com/watch?v=7WiBET8H3x0&feature=related**
3. **http://www.youtube.com/watch?v=uD8uFCQkpDE&feature=related**
4. **http://www.youtube.com/watch?v=gr8zLAxPs-A&feature=related**
5. **http://www.youtube.com/watch?v=_l0yxRRCrfk&feature=related**

I. Introduction

Never has so much been made from so little. From Slipher's red shift measurements of forty galaxies came the Hubble law describing the relationship between galaxy distance and velocity measurements. From this small amount of data, it was inferred that the Universe has expanded and continues to expand from the creation event. A model of this Big Bang has led for the first time to answers to some of the philosophical and previously unanswerable fundamental questions of the origin and evolution of the Universe: What is the global structure of the Universe? Is it evolving? Is it finite or infinite?

Newton believed the Universe to be infinite. He understandably looked at the Universe through the perspective of a scientist primarily concerned with gravity. If the Universe were finite, why wouldn't gravity cause it to collapse? He inferred that the matter in the Universe must be distributed throughout a volume of infinite extent, so that the gravitational pull on any one point is near zero, or equal in all directions. Gravity does indeed dominate the structure of the Universe, and his concern with the collapse of the Universe was prophetic.

We know now that the Universe is not only finite in size, but that the light from distant objects is red shifted. At great distances light from galaxies and the stars contained in them recede at velocities near the speed of light, reducing their energy, as received by us, considerably. We will examine the evidence supporting this modern view of the Universe.

II. General Relativity and Cosmology

Einstein's theory of General Relativity (Chapter 20) was developed at a time when most scientists considered the Universe as a whole static, or unchanging. In 1917, Einstein applied his General Theory of Relativity to the Universe in its entirety, and found that to maintain a static Universe he needed to add a "**cosmological constant**", or fudge factor (depending on one's point of view), to his equations. In 1919, the Dutch physicist W. de Sitter obtained a solution to Einstein's cosmological equations, without a cosmological constant, for the extreme case of a Universe with no matter. In this solution, any particles introduced into the Universe would move apart with velocities that would increase with time. In 1922, the Russian mathematician A. Friedmann obtained the solutions to Einstein's equations for matter-filled Universes, also without a cosmological constant. The results were three classes of solutions: open, marginally bound, and closed Universes. We will assume that in each case the Universe begins as an expansion from a singularity, which we can think of as a point. The open Universe is characterized by an unbounded expansion from a point that continues forever (Figures 1). A closed Universe expands from a singularity, reaches a maximum size, and then collapses into a singularity again. The marginally bound Universe is at the boundary between an open Universe and a closed one. In a marginally bound Universe, expansion proceeds from a singularity with the expansion rate slowing at a decreasing rate, as the Universe forever approaches a fixed size.

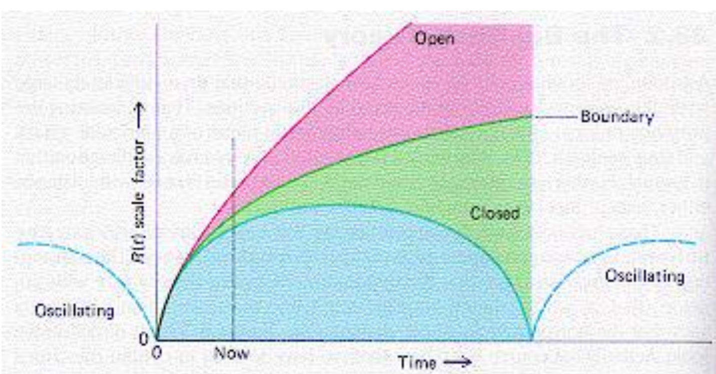
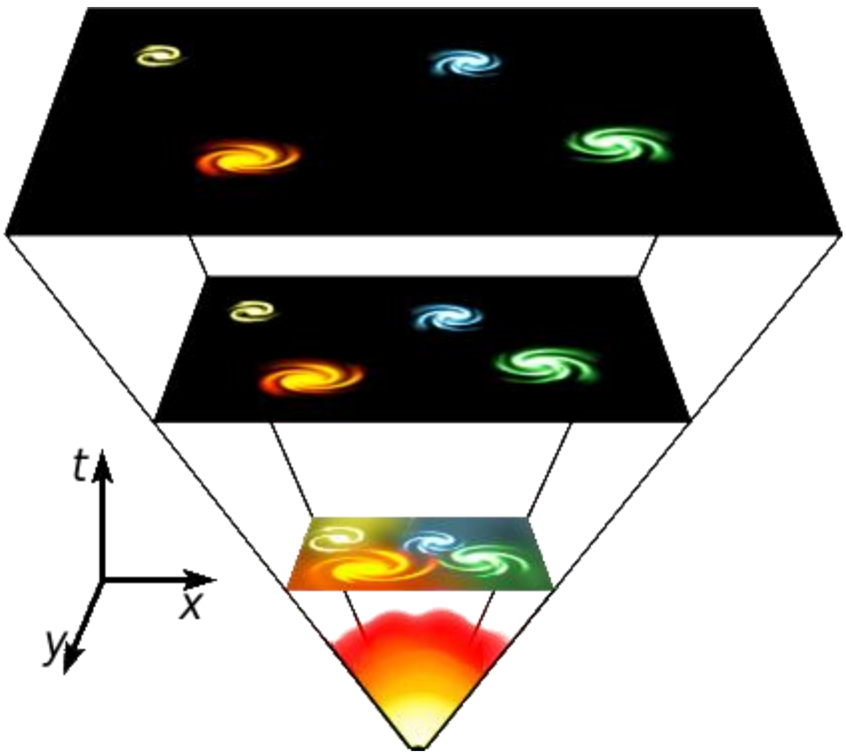
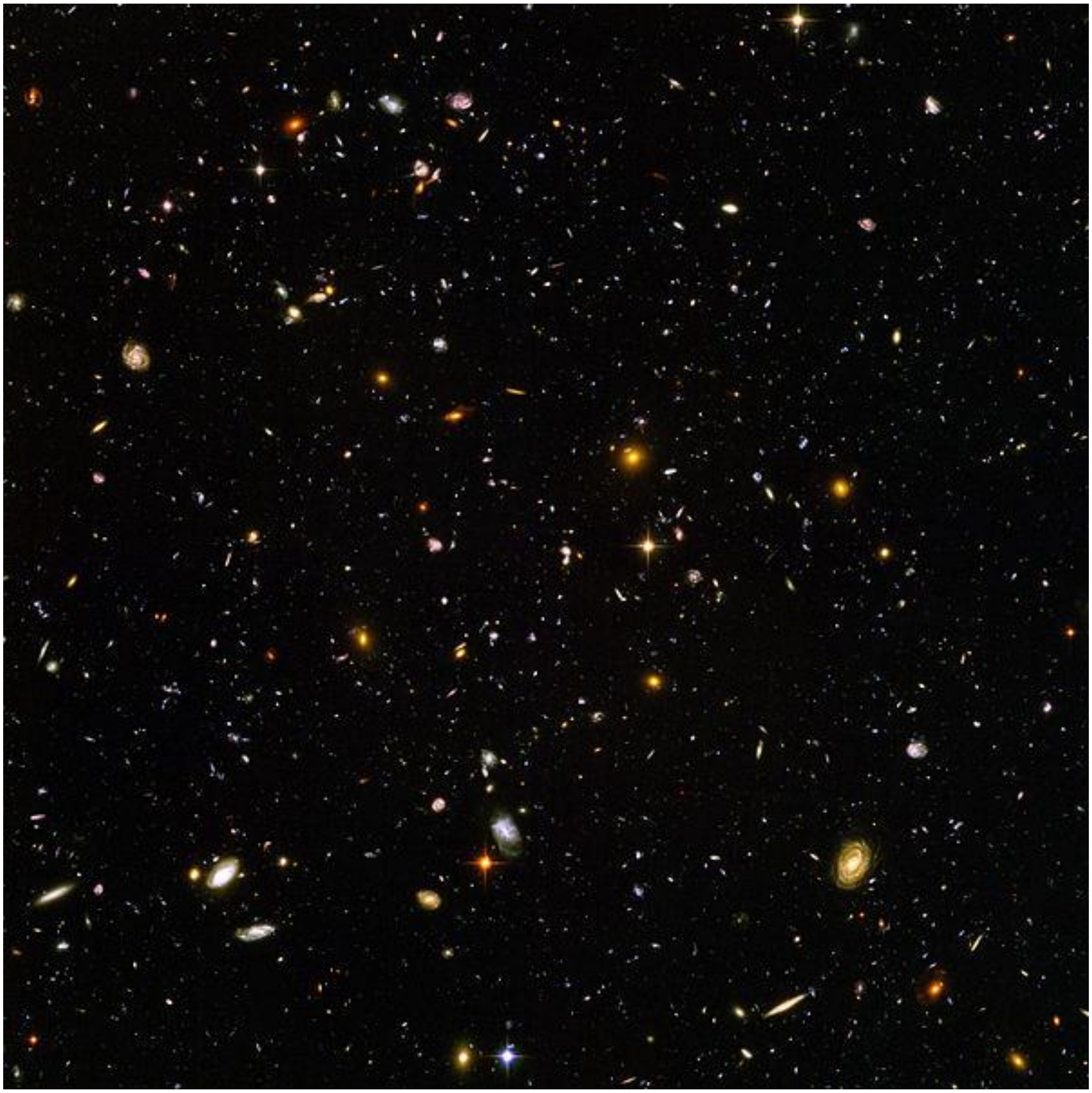
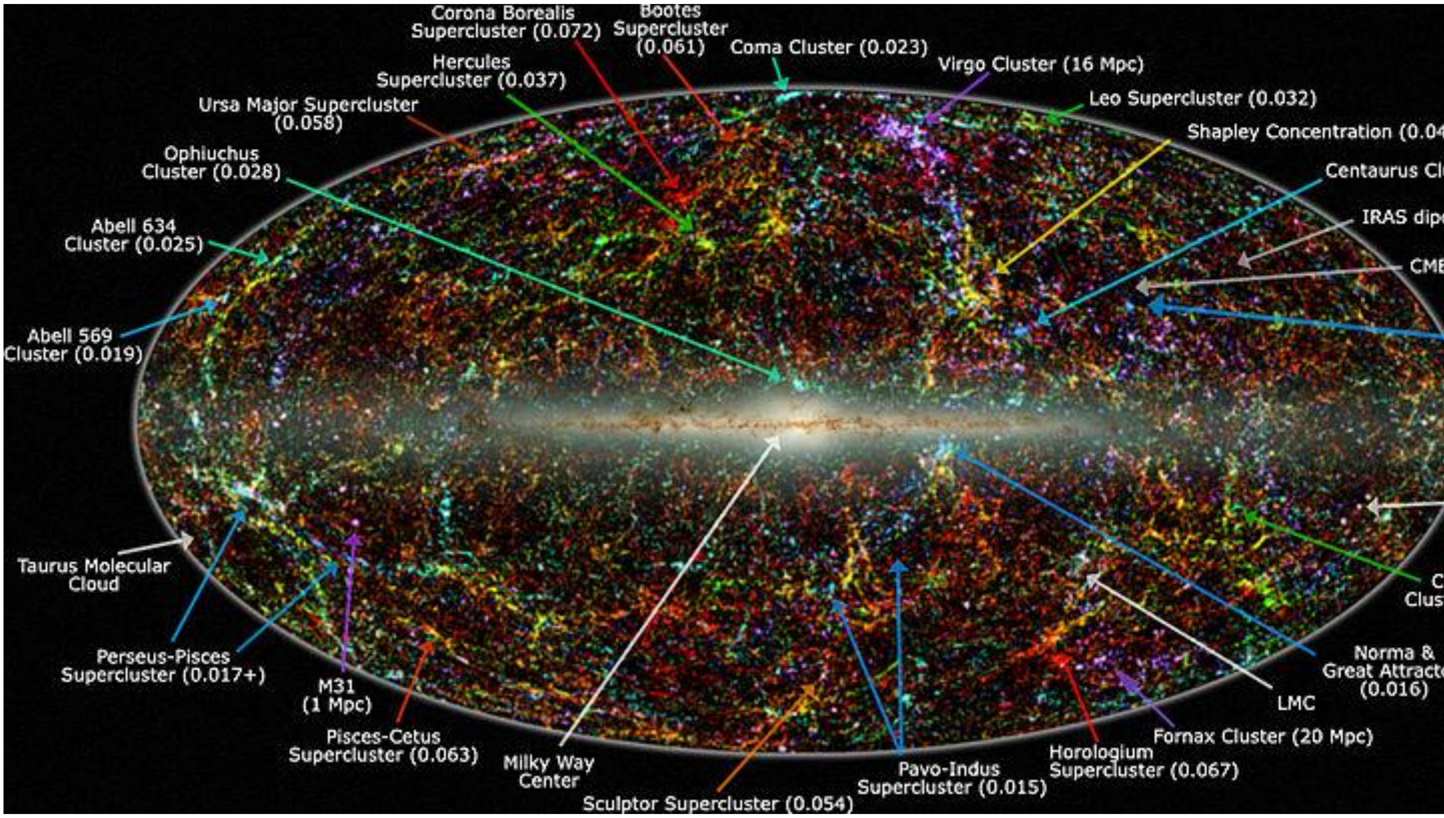


Figure 1. The evolution of the size of the Universe for closed, open, and marginally bound Big Bang Universes**.** If the Universe is open, it will increase in size forever. If it is closed, its expansion velocity is decelerating causing it to eventually reverse its expansion and decrease in size. An oscillating Universe is a special type of closed Universe that repeats this cycle of expansion and contraction. In a marginally bound Universe the expansion continues forever but at an ever-decreasing rate. **P 632-33.3.**

Web Animation: The Big Bang







III. Galaxy Red Shifts and the Expansion of the Universe

The discovery by Hubble in 1929 that galaxies are moving away from each other with a velocity proportional to their distance (according to the Hubble law, velocity = H × distance, where H is the Hubble constant) was one of the major scientific discoveries of the 20th century. The Hubble law provided hard experimental verification to the Einstein model of the Universe, *without* the cosmological constant. Einstein later confessed that the addition of a cosmological constant to his equations was the biggest mistake of his career. The distance red shift relationship also confirmed the Friedmann models of the Universe.

Subsequent measurements have shown that *all* distant galaxies are moving away from us and that the Hubble law is the same in all directions. Does this mean that all galaxies in the Universe are expanding with the Milky Way at the center of the expansion? There has been a historical tendency for humans to regard the Earth as the center of the Universe, or the Sun as the center of the Milky Way, or now, the Milky Way as the center of the Universe. This assumption was found in error in the first two cases, and we will soon see it is not true in the third instance either.

A. Raisin Bread Model of the Universe - an Ant's Perspective

To see how an expanding Universe would look from any location therein, we'll model it in familiar terms. Imagine the Universe as a loaf of rising raisin bread with raisins dotting the loaf's interior a uniform spacing (Figure 2). We'll consider raisins to be galaxy analogs. But wait! On one raisin is sitting an unsuspecting ant, munching away with little concern. *We* are that ant. Assume that the bread is expanding at a uniform rate. Initially the raisins are spaced 1 centimeter apart. As the bread rises the spacing changes, to 2 cm in 15 minutes, 3 cm in 30 minutes and so on. If we look at the raisins along one line of sight, we can measure their distance and the rate at which they recede (Table 26.1). Using the data in Table 26.1, we can plot the velocity vs. distance for raisins along this same line of sight. The result, shown in Figure 2b, is a Hubble law for raisin bread (with apologies to Edwin Hubble). Notice that we have assumed nothing about the position of our raisin in the loaf or the direction of the line of sight. The Hubble law is valid for any direction in the raisin bread and from the viewpoint of any raisin. It is not correct to infer from the observations that one is sitting on some central or preferred raisin in the loaf. Our raisin has no philosophical significance.

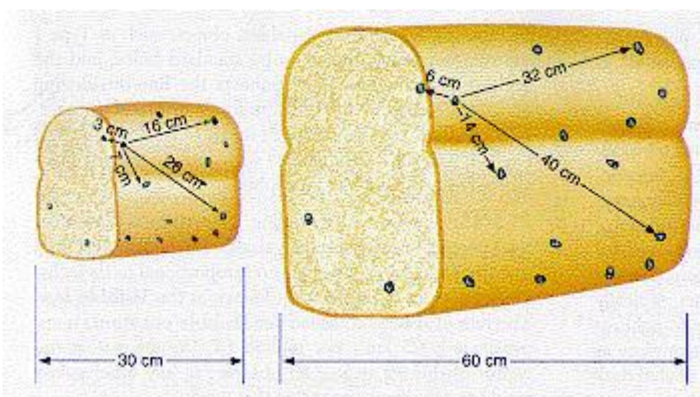


Figure 2. **Panel A:** A raisin bread model of the Universe. In a loaf of rising raisin bread as in a Big Bang Universe, an ant standing on any raisin would see all the other raisins moving away such that the farther the distant raisin, the faster the ant sees it move. **FMW 515-25.18 Modified. Panel B:** *Hubble law for raisins.* **Original.**

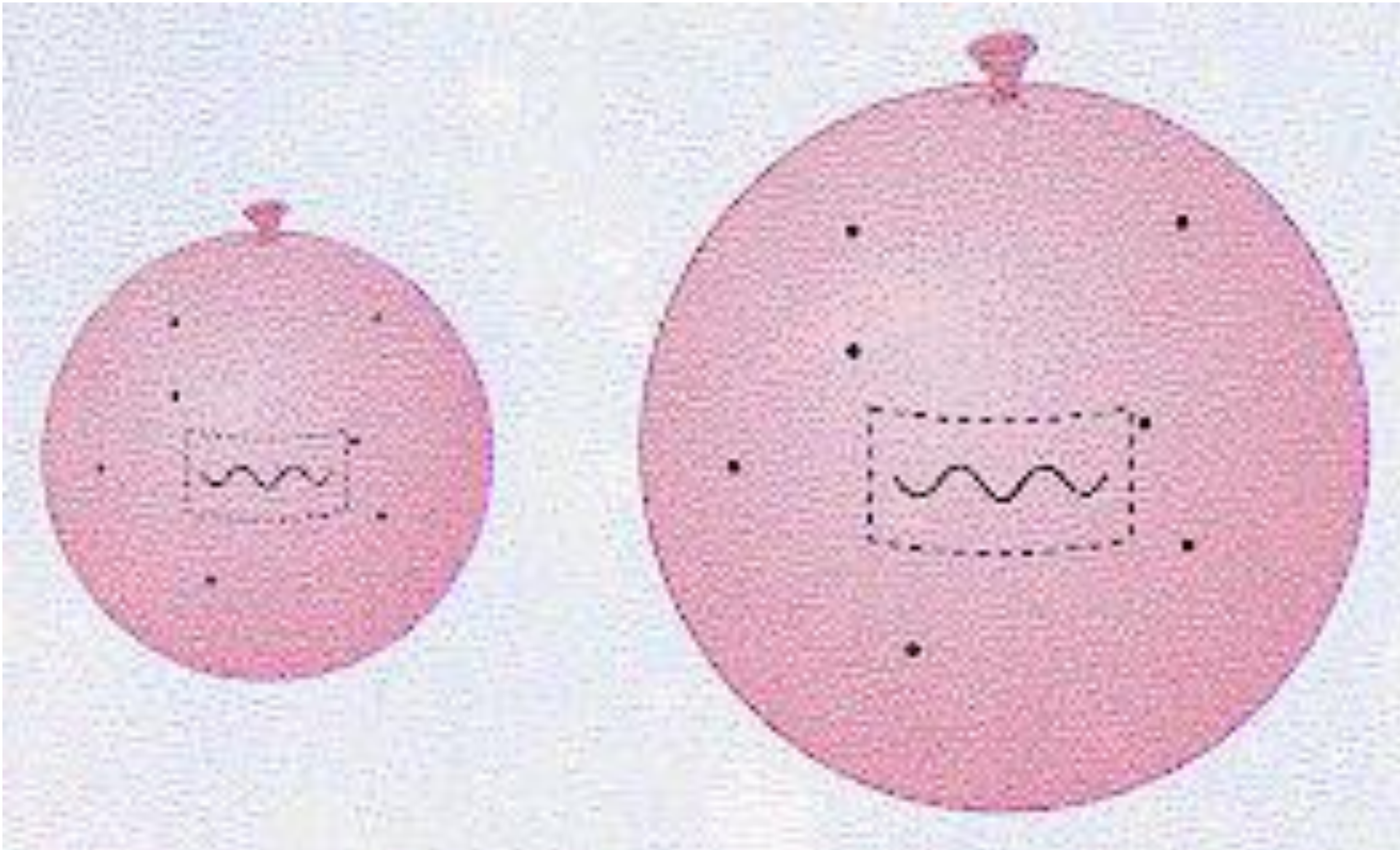
Table 26.1: *The Raisin Bread Recipe for an Expanding Universe*

Raisin	Time = 0	1 hour	2 hours	3 hours	4 hour
#1 position	1 cm	2 cm	3 cm	4 cm	5 cm
velocity	1 cm/hr				
#2 position	2 cm	4 cm	6 cm	8 cm	10 cm
velocity	2 cm/hr				
#3 position	3 cm	6 cm	9 cm	12 cm	15 cm
velocity	3 cm/hr				

B. The Improved Balloon Model of the Universe – a Finite but Unbounded Universe

The curvature of space-time may produce a finite but unbounded expanding Universe that cannot be adequately illustrated with the raisin bread analogy. We will upgrade our model to a more sophisticated balloon model of the Universe to take into account the curvature of space.

As three-dimensional creatures there is no adequate way to visualize the curvature of a three-dimensional space. It can be conceptually illustrated with the curvature of a two-dimensional space. Imagine that we live as paper-thin two-dimensional creatures that work and live in a two-dimensional surface, able to think in terms of North and South but unable to conceive of up or down. On a local scale our Universe seems flat and extends without limit in all directions. On a global scale the Universe is spherical and can be modeled as the surface of a balloon. Our Universe is also an expanding one, the sphere, or balloon surface, growing in diameter at a constant rate as it is blown up (Figure 3).



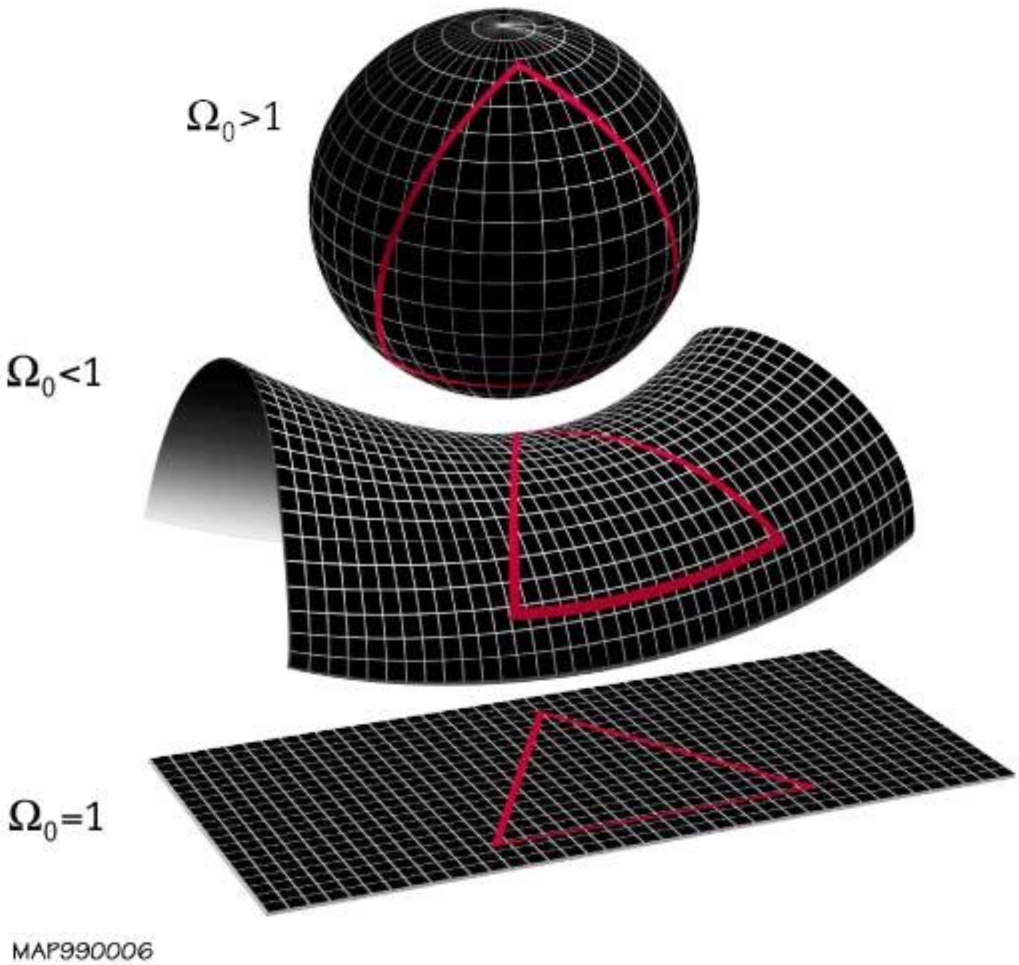


Figure 3. **Panel A:** A balloon model of the Universe. A two-dimensional creature living on the surface of a balloon lives in a finite but unbound expanding Universe, just as we live in a three-dimensional finite but unbound expanding Universe. The balloon creature could set out in one direction and eventually return to where it started, due to the curvature of the space in which the creature lives. **FMW 565-28.6 Modified.** Panel B: Hubble law for dots on a balloon. **Original.**

To us the inside and outside of our spherical surface have no significance. As we begin to explore our Universe we can leave our residences and walk in a straight line, eventually to return to the exact spot from which we started. This occurs because we live in a curved space, unbounded but of finite extent.

As the balloon expands, we can measure the distances and velocities between points on the surface of a balloon as we could in the rising raisin bread. The velocities correspond to the cosmological red shifts that we see in the real Universe. The results are the same as those in Table 26.1 and result in a Hubble law for an expanding two-dimensional space (Figure 3).

In the expanding balloon model, we can calculate the scale of the Universe in past epochs. By extrapolating back in time we find that there was a time when the balloon's radius was zero. We can say that the observable Universe was a singularity; it had no size.

The same train of reasoning used in the balloon model can be performed theoretically on our own Universe. We are three-dimensional creatures living in a curved three-dimensional space, which we can ill-conceive. Our space is finite but unbounded as in the balloon example. That means we can find no edge and no center to our Universe. Although we could theoretically travel in a straight line and return to the beginning of our journey, the Universe is far too big to attempt this experiment, even if we could travel at the speed of light. Extrapolating back in time there was an instant in the past when the size of the observable Universe was zero. Whatever happened before this time has no scientific meaning as space and time originated at this epoch in the past and has been expanding since. No measurement allows us to explore times before this event or outside our observable Universe. The event of the origin of space-time was the violently energetic event called the Big Bang, before which space and time have no meaning.

We say that the observable Universe had zero size at the time of the Big Bang. Does that imply that the size of the Universe is and was finite? No, it does not. The *physical* size of the Universe may have been infinite but we say that the *observed* size was zero. Even if the Universe was infinite in size at the moment of the Big Bang, space and light were created at that instant and light has only been able to travel distances of ct, where c is the speed of light and t the age of the Universe (Figure 3a). The radius of the observable Universe is then ct. If the Universe is 13 billion years old, the size of the observable Universe expanded from zero radius at the Big Bang to 13 billion light years at the present epoch.

Where did the Big Bang occur? Since space was created in the Big Bang, it didn't occur at a single location, it occurred everywhere simultaneously. Think of the Big Bang as the sudden creation of a balloon of finite size. To then ask "Where in space did the Big Bang occur?" is irrelevant.

If the Universe is infinite in size, how can we quantify its expansion? The Universe can be parameterized in terms of its scale, which we can think of as the mean distance between galaxies, R. As the Universe expands, the distance between galaxies becomes larger so R increases. This increase occurs whether the Universe began as finite or infinite. Although this behavior is counterintuitive (much about cosmology is impossible to comprehend), the Universe may have begun as an expanding infinite Universe that has continuously increased in scale factor from the Big Bang on.

It should be emphasized that the cosmological velocities of galaxies associated with the Universal expansion are not ordinary velocities. Galaxies are not moving apart through space, but are moving *with* the expansion of space. Each galaxy can be viewed as being at rest with the space around it, except for small random local velocities, like those resulting from the gravitational attraction of a galaxy to a nearby galaxy cluster.

If we look at distant galaxies, we view them as they were when the light that we see left those galaxies on its journey to Earth. A galaxy at a distance of 5 billion light years appears as it did 5 billion years ago. Nonetheless, observers in all galaxies in the Universe can agree on a universal time scale, e.g., the number of years after the Big Bang. Each observer in the Universe would see a similar local Universe at any given epoch of cosmic universal time, but would view earlier epochs when looking out at distant galaxies, as a result of the finite velocity of light. Aliens in other galaxies might now be viewing the Milky Way as a quasar because they are viewing it as it looked billions of years ago. We can only see distant stars and galaxies as far as the look-back time corresponding to the age of the Universe.

IV. Age of the Universe

In the 1940s, American Physicist George Gamow proposed that the Universe began in an explosion, which we now call the Big Bang. **When did the Big Bang occur?** A simple calculation gives us an estimate of the length of time that has passed since the creation event. If we reverse the cosmological expansion by traveling back in time, galaxies were closer in the past; at times near the time of the Big Bang all matter, all points in the observable Universe, were in the same infinitesimal neighborhood. The age of the Universe can be calculated by assuming that the distance between any two points in the expanding Universe is equal to the age of the expansion times the relative expansion velocity between the two points. We can use the distance between a distant galaxy and the Milky Way and the velocity that the distant galaxy has been receding to estimate the age of the Universe:

Equation 26.1: **Age of the Universe = galaxy distance/galaxy velocity.**

Rearranging the Hubble law gives us: H = galaxy velocity/galaxy distance.

Combining Equation 26.1 with the Hubble law produces the following:

Equation 26.2: Age of the Universe = 1/H.

With the currently accepted Hubble constant of 75 km/s/megaparsec, we compute an age of 13 billion years. The actual age of the Universe may be a few billion years younger or older. It is comforting that this age is longer than the accepted age of the Solar System and the modeled ages of the oldest stars in the Milky Way. If it were otherwise there would be a contradiction. This satisfactory state of affairs was not always so. In 1997, estimates of the age of the Universe were actually less than estimates of the ages of globular clusters, 16-18 billion years. New stellar measurements caused astronomers to revise the ages of globular clusters to anywhere from 9 to 15 billion years old.

Math box: Let's estimate the age of the Universe from H.

If the age of the Universe is 1/H and H = 75 km/s/megaparsec, then we can determine the age by the following:

$$1 \text{ megaparsec} = 3 \times 10^{19} \text{ km, so}$$

$$\text{age of the Universe} = 1/H = 1 / 75 \text{ km/s}/ 3 \times 10^{19} \text{ km} = 4 \times 10^{17} \text{ seconds}$$

There are 3×10^{7} seconds in one year, so the age of the Universe is:

$$4 \times 10^{17} \text{ seconds} / 3 \times 10^{7} \text{ seconds/year} = 13 \text{ billion years.}$$

The calculation above is only an estimate. It assumes a Universe containing no matter. The gravitational pull among all matter in the Universe gradually slows the universal expansion. Therefore we should expect that the Universe was expanding more rapidly in the past; galaxies have separated to greater distances than their current cosmological red shifts would indicate. The actual age of the Universe may be somewhat less than 13 billion years, depending on the mean density of matter in the Universe.

As we look further and further out in the Universe, we are looking back in time. If the Universe is 13 billion years old, we shouldn't be able to see any objects more than 13 billion light years distant. At a distance of a little less than 13 billion light years, we might actually be able to see galaxies being formed.

V. A Rival Model: the Steady State Cosmology

Hubble's original measurements gave an H of 550 km/s/megaparsec, ten times the current estimate, giving an age of the Universe of 2 billion years, compared to the estimated 4.6 billion year age of the Earth. This was a result of errors in distance calibration, which have improved since. This enormous discrepancy between the age of the Earth and the age of the Universe spurred a flurry of theoretical activity. In 1948, Fred Hoyle, Herman Bondi, and Thomas Gold proposed a model of the Universe called the **Steady State Theory** in which the Universe was assumed homogeneous, isotropic (appearing the same in all directions), and infinite and *unchanging in space and time*. The latter is unique to the Steady State Theory. Galaxies would recede from each other with apparent velocities in proportion to their distance, obeying Hubble's law. Essentially, the Steady State Universe is an infinite Universe that expands. Ordinarily this expansion would cause a decreasing mean density of matter. In order to maintain an unchanging Universe, the density of matter should be constant. Hoyle, Bondi, and Gold proposed that matter must be created continuously throughout the Universe to maintain a constant density (Figure 4). Although this theory seems unsettling, it can be argued that it is no more difficult to accept than the sudden creation of the Universe in the Big Bang. The direct creation of matter in the Steady State Theory only amounted to about 1 atom per cubic meter every billion years or so, so that it would be undetectable**.** The heated debate between the Big Bang and Steady State theories lasted until 1964 and the discovery of the cosmic background radiation, light from the Big Bang.

VI. Independent Confirmation of the Big Bang: Cosmic Background Radiation

After World War II, physicist George Gamow, of George Washington University, proposed that the Universe immediately after the Big Bang was incredibly hot, filled with high intensity high-energy photons called the cosmic background radiation. Physicists Ralph Alpher and Robert Herman of Johns Hopkins proposed shortly thereafter that as the universe expanded the cosmic background radiation cooled and was red shifted (Figure 5).

Figure 4. *Drawing of look-back time and galaxy evolution.* **Original.**

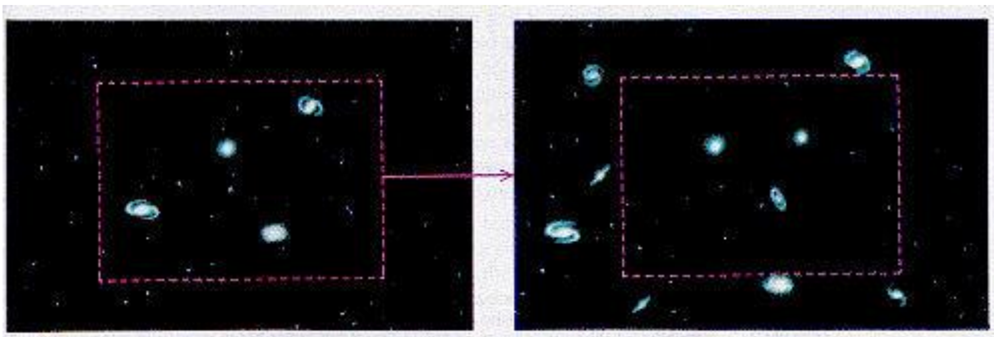


Figure 5. The Steady State cosmology and the creation of matter. This highly exaggerated schematic shows that as the Universe expands, some galaxies leave the dashed box representing a fixed volume, but new matter (galaxies) is created to maintain a constant mass density within the box. **P 607-33.10 Modified.**

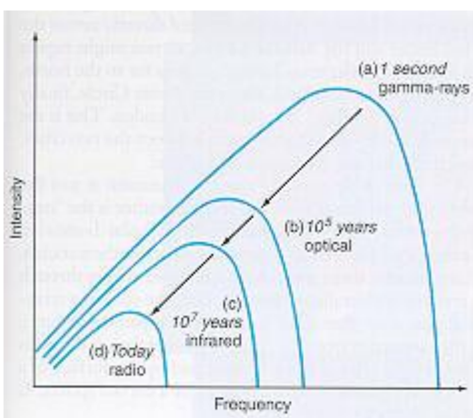


Figure 6. Blackbodies at various red shifts corresponding to cosmic background radiation at different times after the Big Bang. **Modify. Chaisson.**

In 1964, Arno Penzias and Robert Wilson, Bell Telephone Laboratory physicists, built a microwave antenna to relay phone calls from Earth-orbiting satellites. With it, they detected a signal emanating from the sky in all directions. They initially believed this to be a problem with their instrument. In 1965, after laboriously trying to eliminate this apparently spurious signal from their antenna, they concluded that it was a nearly uniform emission from the sky. This microwave radiation was the cosmic background radiation predicted by Gamow, Alpher, and Herman. Penzias and Wilson are credited with the first detection of the cosmic background radiation and for this discovery, they won the 1978 Nobel Prize in physics. **This detection of cosmic fireball radiation was the first experimental verification of the Big Bang independent of the velocity red shift relation.**

More recent and precise measurements of the cosmic background show that it has a blackbody spectrum with a temperature of 2.73 degrees (Figure 6). It is commonly referred to as the **3-degree background radiation**.

After the Big Bang, the matter and radiation in the Universe cooled as the Universe expanded. Gamow, Alpher and Herman predicted that about 700,000 years after the Big Bang the Universe would cool to about 3,000 K, cool enough for electrons to combine with individual protons, forming hydrogen atoms. Individual charged electrons and protons are relatively opaque to electromagnetic radiation. When electrons and protons combine to form uncharged hydrogen atoms, they become quite transparent to most electromagnetic radiation. When the Universe was opaque, in the first 700,000 years after the Big Bang, frequent interactions between light and matter, in which photons scattered off of electrons and protons, bound matter and radiation to the same volume of space. As matter cooled and formed, uncharged hydrogen atoms, light, and matter were free to go their own ways; matter, no longer pushed around by light as in some cosmic blender, was free to collapse into mass condensations, including protogalaxies. When light and matter decoupled, theory predicts that radiation would have had a blackbody spectrum of 3,000 – 4,000 K.

The cosmic background radiation filled all of space. When we observe the cosmic background radiation today, we are looking at radiation coming from a distance corresponding to the look-back time of the age of the Universe minus 700,000 years, just as when we look at a galaxy at a distance of 5 billion light years we are looking back 5 billion years in time. The main difference is that a galaxy is seen only in one direction in space, while the cosmic background radiation comes from all directions because it fills space. The 3,000 K background radiation should experience the same kind of cosmological red shift that galaxies do. The radiation we observe 700,000 years after Big Bang would be red shifted by a factor of roughly 1,000, from the visible to a wavelength of about a millimeter (corresponding to temperatures of 3,000 K to nearly 3 K). This is the same millimeter-wavelength radiation detected by Penzias and Wilson.

The Cosmic Background Explorer satellite, COBE, was launched in 1989 to map the cosmic background radiation (Figure 7). COBE has shown that the cosmic background is isotropic on a large scale to one part in 1000, with the exception of an additional red shift in one direction due to the combined velocity of the Earth about the Sun, the Sun about the center of the Milky Way, and the Milky Way through the Universe. The entire Milky Way appears to be moving 600 km/s relative to the neighboring Universe as the Milky Way and Local Group appear to be pulled toward four nearby galaxy clusters and a massive supercluster. COBE measured slight differences in the intensity of the cosmic background radiation that may indicate clumps of matter 500 million light years across from which galaxies and galaxy clusters formed (Figure 8).

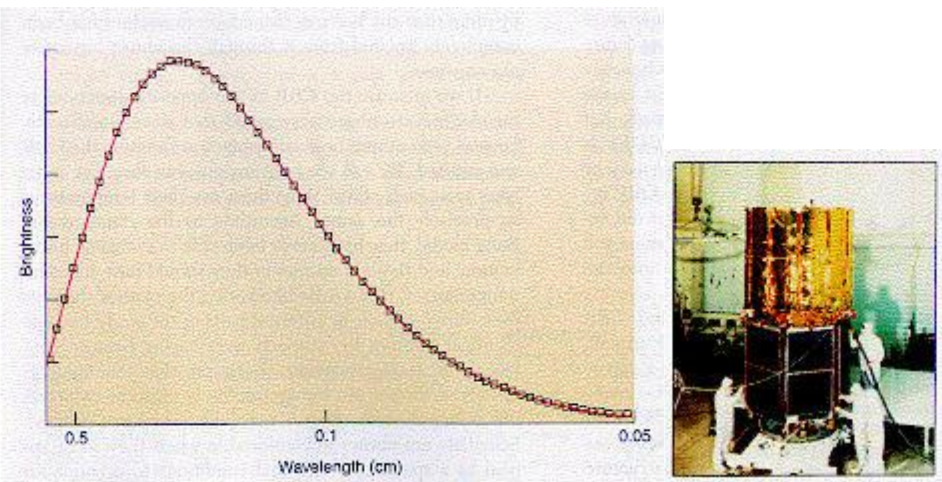


Figure 7. Panel A: A COBE (Cosmic Background Explorer) cosmic background spectrum compared to a 2.73 K blackbody. **FMW 575-28.15 or P 612-33.16. Panel B:** The COBE satellite. **P 612-33.15.**

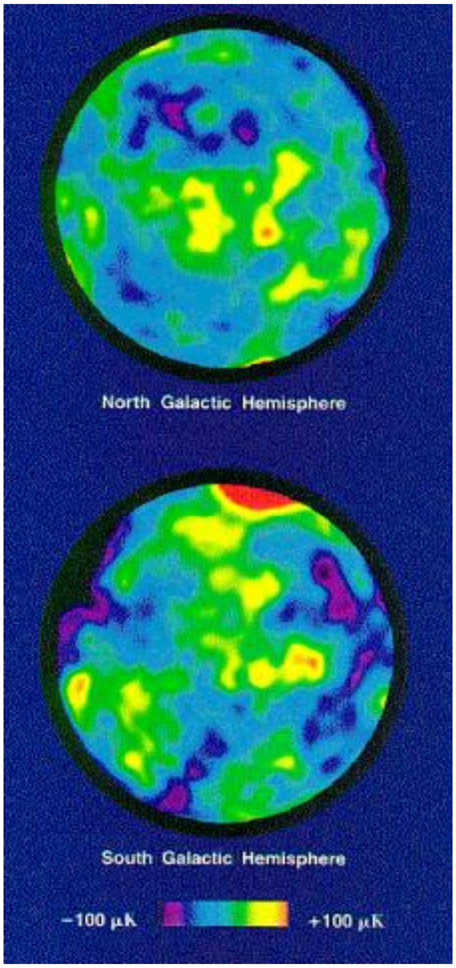
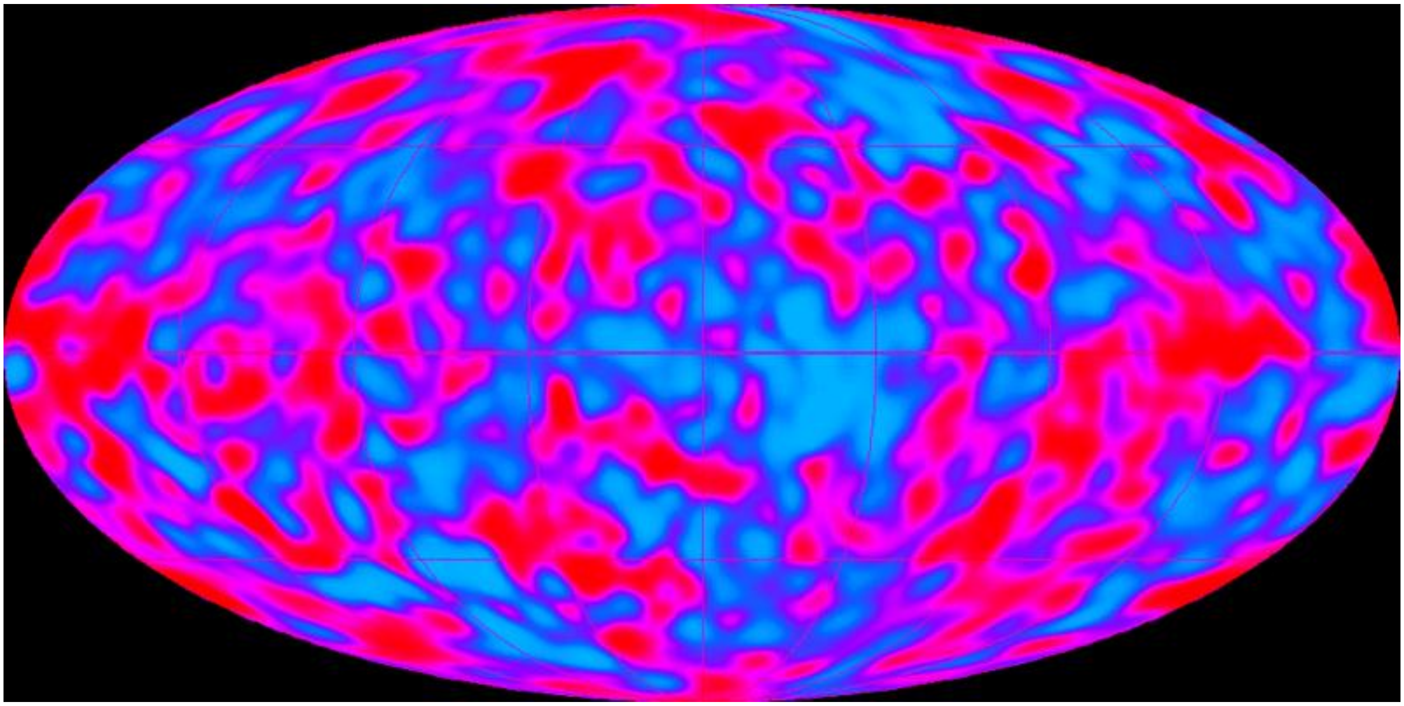


Figure 8. A COBE map of the Universe showing the anisotropy of the cosmic background temperature. Black represents the coolest temperatures, red the hottest. **FMW chapter cover or APOD, NASA.**



In the next chapter, we will see additional support of the Big Bang; the abundances of lithium and helium in the oldest stars in the Universe agree with the predictions of the Big Bang theory for elemental abundances in the early Universe.

Summary

The Theory of General Relativity was developed by Einstein in 1917 and used by de Sitter in 1919 and Friedmann in 1922 to show that the natural state of the Universe is one of the expansion of space. Hubble confirmed this in 1929 with his discovery that galaxies are moving away from each other with a velocity proporational to their distance. The age of the Universe can be calculated by assuming that the distance between any two points in the expanding Universe is equal to the age of the expansion times the relative expansion velocity between the two points. The current estimated age of the Universe is roughly13 billion years.

In 1948, Hoyle, Bondi, and Gold proposed the Steady State Cosmology in which the Universe was assumed infinite and expanding, obeying the Hubble law. To maintain a constant mean density of the Universe the continuous creation of matter was required.

Supporting proof of the Big Bang Cosmology came with the discovery of the cosmic background radiation, radiation with a 2.73 K blackbody spectrum that fills all of space. This fossil radiation from the Big Bang was predicted by the model of Gamow, Alpher, and Herman, which assumed an initial Universe that was infinitely hot and infinitesimally small at the moment of creation.

Key Words & Phrases

1. **cosmological constant –** the constant added to Einstein's General Theory of Relativity to keep the Universe from expanding.
2. **Steady State Theory** - a model of the Universe in which the Universe is assumed to be homogeneous, isotropic, infinite, and unchanging. To account for the cosmological expansion matter must be created continuously.
3. **three-degree background radiation –** cosmic fireball radiation from the Big Bang that has been red shifted so that it is observed with an intensity distribution vs. wavelength like a 2.73-degree blackbody.

Review for Understanding

1. Why do astronomers believe that the Universe is expanding?
2. What is the difference between 1/H and the actual age of the Universe (from the moment of the Big Bang)? Which is greater?
3. List observational evidence in favor of and against each of the following: (a) the Big Bang Theory, and (b) the Steady State Theory.
4. What is the Steady State Cosmology?

5. How can the Universe not have a center?
6. What is the cosmic background radiation and how did it originate?
7. Why is a low temperature, 2.7 K, measured for the cosmic background radiation when it had an extremely high temperature immediately after the Big Bang?
8. Why do astronomers believe that the Universe was extremely hot and dense immediately after the Big Bang?

Essay Questions

1. If you were located in a galaxy near the boundary of our observable Universe, would the galaxies in the direction of the Milky Way appear to be approaching or receding from you? Explain.
2. What was the scientific importance of the discovery of the cosmic background radiation?
3. Why should we as a society be interested in funding cosmological research with tax dollars?