The Ever Expanding Universe in Modern Cosmology,

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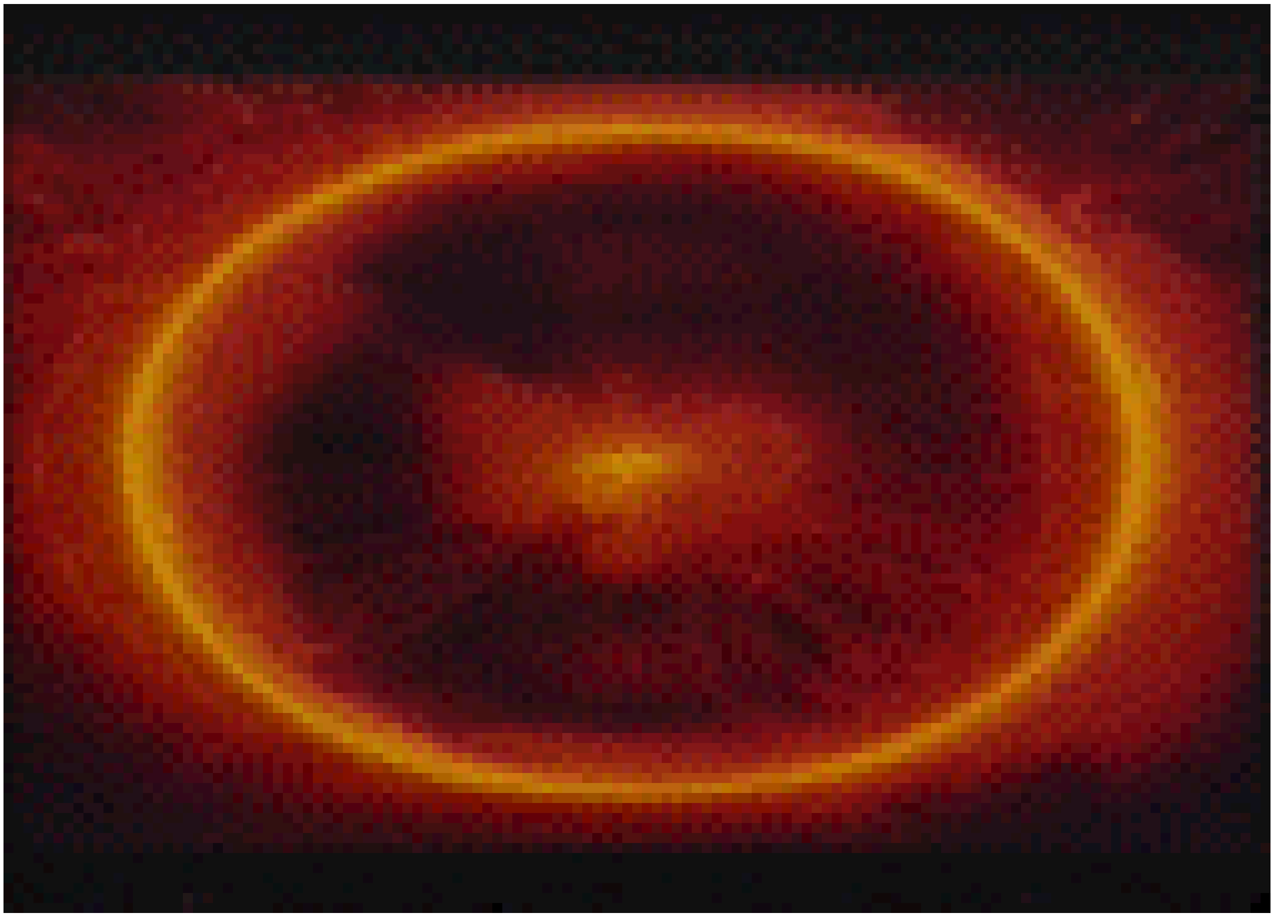


Abstract

An account of work done in modern times to determine the origin, behavior and fate of our universe from theory and observation. We begin at the beginning of modern cosmology, almost the beginning of this century with the publication of General Relativity. We swiftly work our through the corner stones of the century in modern cosmology up to current times with Alan Guth's theory of inflation and the miraculous observations made by Saul Perlmutter's group of many supernovae to infer universal expansion rates across the eons.

In the beginning…

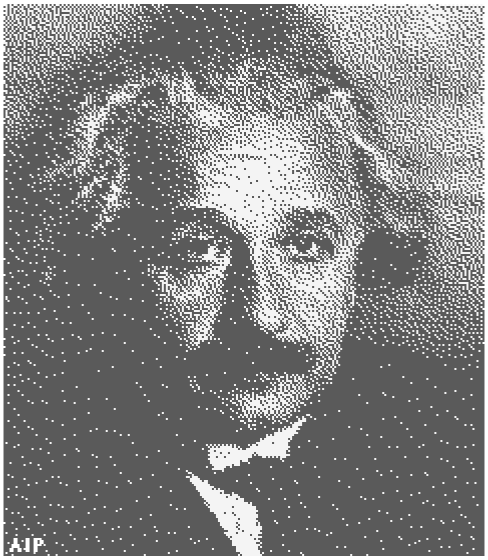


Figure One. Albert Einstein.

In 1916 Albert Einstein published his famous theory of General Relativity (GR). This theory gave the world a brand new way of considering the universe. Einstein postulated that space and time were simply ordinates of the same co-ordinate system. Furthermore that this *space-time* was warped in the presence of matter.

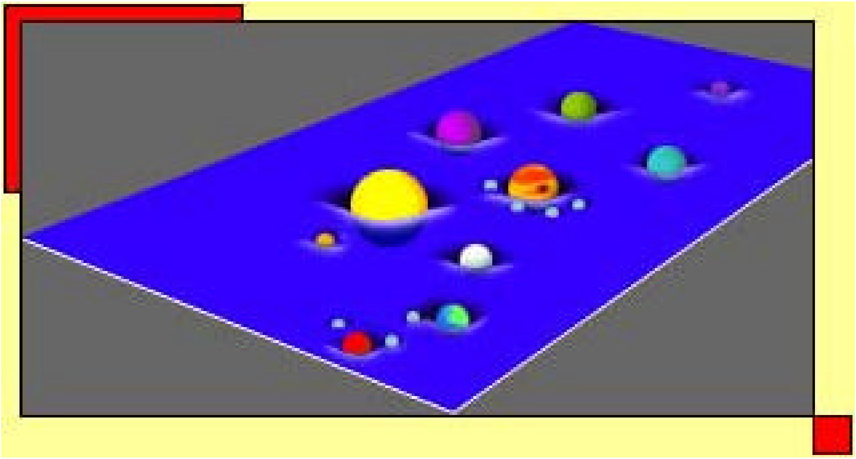


Figure Two. Einstein's model of space-time and matter.

Einstein based the geometry for his space-time on the geometrical structure of Riemannian space-time. Rienmann was the first person to publicly suggest that there exist a possibility of a finite and unbounded universe by treating space as a 3 manifold on the surface of a hypersphere (this was in 1857, the lecture was posthumously published in 1868). Einstein was keen to keep his theories consistent with the observations of the time. In 1917, the Milky Way galaxy (our galactic home!) was observed as the whole universe (given the range of the instruments of the time) which was not expanding or contracting.

Since Einstein's theory (and even Newtonian theories predicted the same thing, *with hindsight*) predicted a dynamic universe. So strong was the idea that we lived in a static universe, Einstein revised GR to include a **Cosmological Constant** (denoted by Λ) to obtain a relativistic yet static universe, and is well known he later called this the *biggest mistake of his career*. However newer theories have resurrected this constant to introduce a long-range *anti-gravity* force to explain long range expansion in the universe.

Come 1919 and GR was generally accepted as a framework for a model of our universe. Sir Arthur Eddington headed an expedition to the North Pole to observe the position of certain stars during a solar eclipse. GR predicted these stars would appear where should do because the gravity (or space-time curvature) around the sun would deflect the path of the light from these stars. Eddington's observations were in definite agreement with Einstein's predictions. Given this success and the prediction of the perihelion of the planet Mercury, GR was embraced by all and the path for modern cosmology was laid, despite the belief of a static universe.

Face Value…

At the time Russian physicist, mathematician and meteorologist, Alexander Aleksandrovich Freidmann seemed to be the only person that would accept GR at face value, such that it tells us that we do live in a dynamic and changing universe. Freidmann based his model on two simple assumptions. Firstly, that the universe looks the same in all directions. Secondly, that the first assumption would be true from any other point in the universe. This is clearly not true on the scale of planets or even solar systems and galaxies, but the justification comes from looking on very large scales, because the universe does have a large-scale homogeneity (as would later be found by two bell laboratory researchers!). Freidmann only found one model of the universe that worked for his assumptions. In this model the universe begins from zero volume and infinite density and expands from the beginning of time. During the expansion gravity would always be pulling at everything in the universe, eventually it would win. After the universe had expanded for a certain time it would begin to contract and fall back to it's original state of zero volume and infinite density. This is what is termed as a closed universe. In 1922 Freidmann published his work, which included a prediction that would be independently found by observation in 1929 by Edwin Hubble. Despite this and that future models of the universe would be based on *Freidmann models and assumptions* his worked remained largely unknown in the western world for another 13 years. We will come back to this later.

Observing the end of the static universe…

Edwin Hubble worked at the University of Chicago during the 1920's. Until 1924, it was thought that our galaxy spanned the observable universe and that it was a unique system (at the time, our galaxy did cover all we could observe!). However, Hubble showed that there were many other galaxies. At the time it was virtually impossible to measure the distances incurred between galaxies, but using the indirect method of measuring the luminosity of Quasars (pulsing stars that lie near the centre of galaxies, *'quasi-stellar* *objects'*) he showed that the distances involved were far greater than that of local stars. This already countered Einstein's justification of using the cosmological constant.

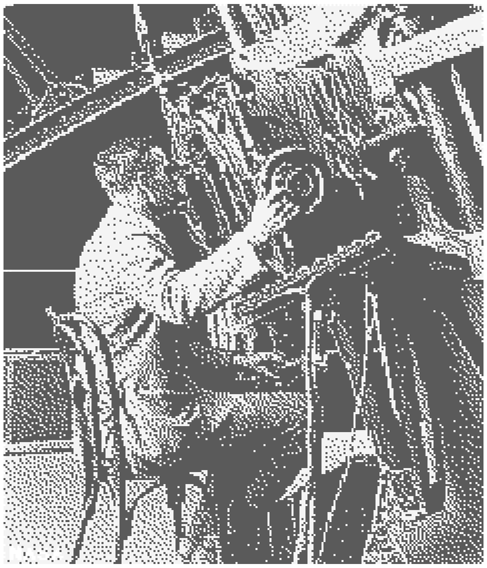
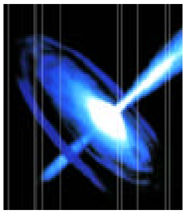


Figure Three. Edwin Hubble.

A Quasar



Hubble was one of the last privileged few that access to a telescope for him alone, unlike in the 1980's and 90's when astronomers can only have limited periods of time to use the best telescopes. After Hubble's discovery of other galaxies, he painstakingly measured and cataloged galaxies for five years, the results of his findings would have ramifications for all of cosmology (and even beyond science!). Hubble discovered that every galaxy he observed was red shifted which inferred everything was moving away from us. Hubble measured the red shift for all of the galaxies that he observed as well as their distance from us. What Hubble found was that there was a strong correlation between the red shift and the corresponding distance. Hubble then made **Hubble's law** from his observations,

$$\mathbf{v=H_od}$$

Where v is the recessional velocity and d is the distance from us. H_o is **Hubble's constant**. The value of H_o is very important and is largely sought after right up to present day. Consider this argument. If everything started from a big bang and since everything has been moving away with a constant velocity v, then at any time the distance between two points is d. Thus the age of the universe is simply, $\mathbf{t=d/v}$, the time taken to travel out to a distance d. That is, the age of the universe is just the inverse of the Hubble constant. A more accurate calculation must take account of the fact that the gravity arising from all forms of matter and energy in the universe slows down the expansion. The Belgian priest Lamaitre, who obtained, first performed this calculation: $t = (2/3) \times (1/H_o)$ as the age of the universe. General relativity predicts that a denser universe expands faster than a less dense one. Therefore, a denser universe will expand to a given size sooner than one that is less dense. One of the first people to determine the age of the universe was Bishop Ussher, who defined the age of the universe as the time since its creation by God. He determined that the universe was created on Sunday, 23 October, 4004 BC. Modern estimates are somewhat earlier than this!

We should also note that in addition to the velocity and distance relationship Hubble's law also includes another formula, for the critical density of the universe. This is density such that the universe would eventually stop expanding but never quite stop, so that it would not contract (this is called a flat universe but more on that later).
$\rho_{critical}$ =(3H2)/(8pG). It should be noted because it leads us to the third cosmological constant value that modern theories rely on, the omega (Ω) constant, which is the ratio of the real density of the universe to the critical density.

Appendix One goes onto to discuss further Freidmann models and their implications for models of the universe.

Time Warp…

We now pick up the trail in 1965. Two American physicists at Princeton University, Bob Dicke and Jim Peebles were working on suggestion made by George Gamow (who was actually a former student of Freidmann). They argued that if the universe had begun with a big bang and that the initial state of the universe was some sort of intensely hot primordial soup then we should still be able to see the radiation from that era of the universe. However, given the size and expansion rate of the universe, by the time this radiation would hit us it would be so red shifted that it would appear to us as microwaves.

At about the same time two physicists at nearby Bell Laboratories, Arno Penzias and Robert Wilson were working on a "radio horn" to detect microwaves. While testing their equipment they found that they were detecting a lot more noise than was expected. The noise did not seem to be coming from any particular direction either. At first they discovered bird droppings in the detector. Once the detector had been cleaned and the rest of the electronic systems checked, they knew that there was no malfunction occurring. The detector still detected the same amount of noise night and day, and day to day. This inferred that the radiation must have been coming from beyond our galaxy. Atmospheric noise would change as the detector was tilted because the depth of the atmosphere would be different at different angles. Radiation from the solar system or our galaxy would vary as the earth rotated on it's axis and orbited the sun.

Figure Four. Penzias and Wilson in 1965.

Penzias and Wilson heard about Dicke and Peebles pending search for background cosmic radiation, and informed them that they had found it! Penzias and Wilson won the Nobel prize for physics in 1978 for their discovery.

The big bang model of the universe (whatever variant, open, flat or closed) was now generally accepted. The big bang model could account for universal expansion, microwave background radiation and the abundance of light elements (namely, H,He,C,N and O). However it was not without it's problems the big band model could not account for factors including;

Why the microwave background so uniform (Horizon Problem).
Why the galaxies are distributed in vast sheets (Structure Formation Problem).
Why space-time is so flat (Flatness Problem).

New horizons…

In 1980 Alan Guth proposed the theory of **inflation.** This is basically a modification to the big bang theory. The universe now expands with a scale factor **a(t)**. The main postulate of this theory is that when the universe has existed for only around a trillion trillion trillionth of a second there is still a vacuum, i.e. there is no matter present, but turning to quantum field theory we can say that there are *virtual particles* present. **Paul A M Dirac** first proposed virtual particles in 1930.

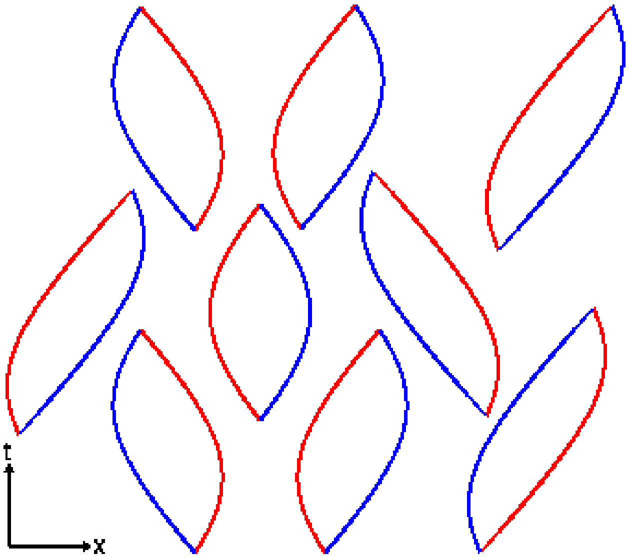


Figure Five. A space-time diagram of particle - anti-particle pairs appearing and then annihilating each other.

For inflationary models we assume that this energy density is huge. The expansion that occurs during the inflationary period is so called because within 10^{-32} seconds the universe expands (or inflates!) by a factor of 10^{50}. This huge expansion rate solves the flatness problem of the big bang theory, the expansion is so great that the curvature of space-time appears to be locally zero. Consider that the area of the world that you are stood on seems flat, but the earth is really spherical (approximately!).

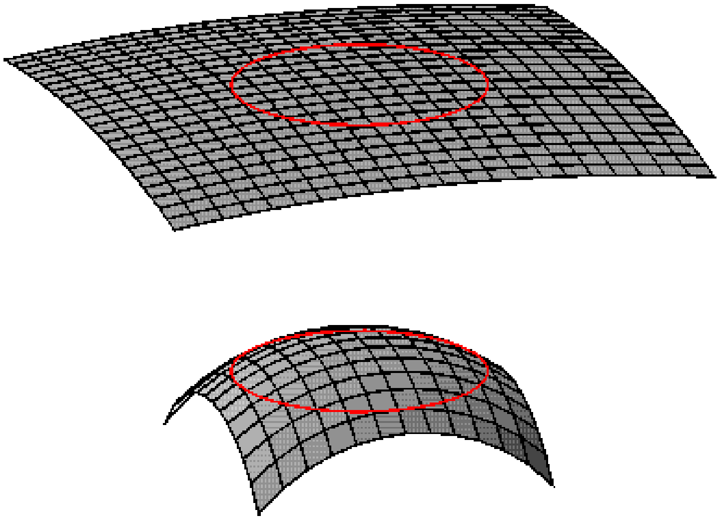


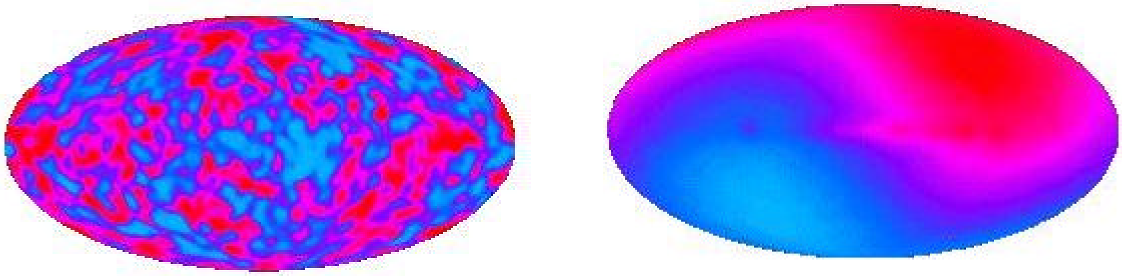
Figure Six. Our event horizon (in red) superimposed on a large and small curved surface.

Figure six shows our horizon superimposed on a very large radius sphere on top, or a smaller sphere on the bottom. Since we can only see as far as our horizon, for the inflationary case on top the large radius sphere looks almost flat to us.

The concept of horizons brings us to being able to explain why the universe is so uniform (homogeneous). What we call the visible universe was once confined to a single bubble no more than 3 x 10^{-26} cm across; the distance light can travel in the 10^{-36} seconds since the beginning. Therefore, every part of the visible universe was once in contact. This solves the Horizon Problem. So we then get a uniform distribution of background radiation, because the light was able to symmetrically distribute itself across a small volume which then *inflated*.

The final inadequacy of the big bang theory to mention here is the Structure Formation Problem. The density fluctuations (lumpiness) in the matter distribution, caused by the original quantum fluctuations in the vacuum energy, form the seeds of galaxies, which form in huge web-like sheets spanning the universe. It is these initial density fluctuations that the COBE satellite detected in 1992. It is thought that these *seeds* took affect because of the slight difference in gravitational fields due to *density perturbations*. Appendix Four shows a time line of the universe as predicted by inflation theory.

The Cosmic Background Explorer (COBE) was launched in 1992 in order to map the entire background cosmic radiation field. Cosmologists wanted to see the minute fluctuations in the radiation to support theories that small quantum fluctuations in the primordial universe gave rise to the super formations of galactic clusters seen in deep space. Below are some of the maps that COBE made.



COBE Data

Equal Power on All Scales Model

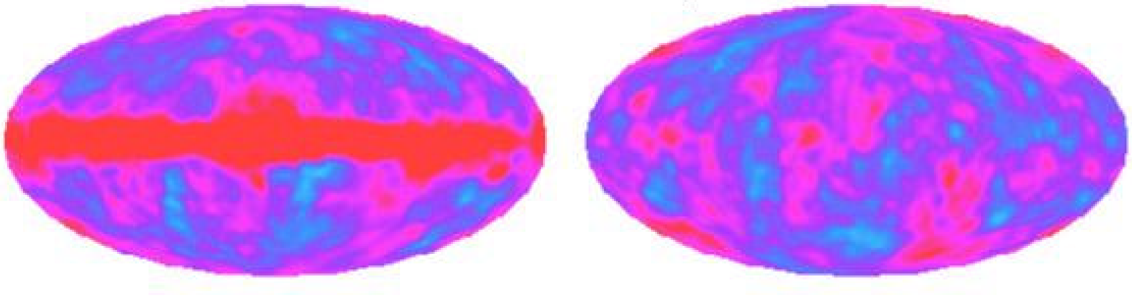


Figure Seven. Some COBE cosmic radiation maps.

COBE also reopened an avenue of cosmology made by a possibility realized in Einstein's GR. Einstein's theory explains gravity in terms of curved space-time. If space-time can curve it can surely ripple too, and gravitational waves are often described as ripples in space-time. They travel like waves on a pond, spreading outwards from sources of extreme gravitational disturbance, such as the collision of a star with a black hole. They cause a temporary distortion in space-time and then travel onwards, usually leaving no trace at all. These gravity waves are often called **Gravitons**. It was suggested that the temperature fluctuations (anisotropies, in the background cosmic radiation field) could be caused by at least in part by gravitational waves. This possibility was first advanced in the mid-1980s, through work by Roberto Fabbri and Martin Pollock in Italy, by Larry Abbott and Mark Wise in the US, and by Alexei Starobinsky at the Landau Institute of Theoretical Physics in Moscow. But at the time, their work was treated as a curiosity, and remained largely unknown. COBE changed all that. Within months, a flood of papers appeared 'reminding' scientists of the earlier work and reassessing it in the light of present thinking. The conclusion: what COBE was seeing could be caused by gravitational waves. In the early universe when the universe was very hot as the matter in the universe was in the plasma phase because the temperature was too high for electrons to combine with positive nuclei/ions. During this period photons *coupled* very well with plasma constituents. It was not until the universe cooled down and electrons combined positive ions (the *recombination period*) that photons would decouple with the surrounding matter and such interactions would cease. Gravitons interact with space-time as they make their way through the universe, and as they interact with space-time as well as the matter embedded on it. If gravitational waves were passing through the Universe just as the microwave background decoupled from matter, they would have permanently influenced the pattern of the microwave background. The radiation would have been moved in and out along with the matter. Where matter and radiation were pulled towards our part of the ancient Universe, their velocity and energy would have increased, and therefore the temperature of the microwaves would have increased. Where gravitational wave motions pushed matter away from our part of the ancient Universe, their temperature would have been reduced. Because the cooling of the microwave radiation has continued uniformly with the expansion of the Universe, these differences in the microwave background will have been preserved.

It turned out that COBE did not have a high enough resolution to determine whether graviton interactions had been observed. However the search still continues with more traditional techniques. Examples are Graviton/Photon interferometry with laser beams in high vacuum chambers which are under construction or actually working in the US and Europe. Smaller-scale experiments with lasers, and attempts to spot the effects of passing gravitational waves on large metal bars, have yet to meet with success.

The impossible dream…

In 1987 physicist Saul Perlmutter joined the ranks of astronomers and observational cosmologists in trying to determine the fate of the universe. Perlmutter had worked in particle physics, but decided that he had to go after the question that had inspired him, *what is the fate of our universe?* In doing so, he assembled an international team of scientists. To determine how the expansion rate of the universe was changing he needed to compare how fast stars/galaxies were moving apart in the early universe to how fast they were moving apart in the present day. Observing objects from the early universe meant observing things from immensely huge distances. The only way making such a comparison would be possible would be to compare something that always shone in the cosmos with the same luminosity. In such a dynamic universe such a thing was highly improbable. However there is one stellar object that does just this, **Supernovae**. Supernovae are the explosions of giant stars dying, only stars that reach a critical density will produce a supernova, therefore supernovae will always have the same brightness. They are also one of the few things that still be visible over the great distances that Perlmutter and his team would have to probe. Supernovae easily outshine the galaxy in which they are situated. They usually only last for around three weeks but shine with the power of 10 billion stars! There is only one draw back with this plan, supernovae only occur in a given galaxy twice a century, so without waiting 500 years for something that could happen anywhere a new strategy was called for.

The plan devised was to observe hundreds of galaxies at the same time using high powered telescopes coupled with very wide angle cameras and an array of high resolution Charge Couple Device (CCD) detectors. Finding all the necessary apparatus took Perlmutter's team several yeas. Come 1992 the team had the apparatus and had managed to negotiate time at an Hawaiian telescope all they had to do was go and get the data and analyze it, no mean feat! The next hurdle for the team was one of image processing, every time they went to the telescope they generated hundreds of images of distance galaxies. The general process was to take pictures of the same galaxies twice, with a three-week gap between, then the images would be compared in the team's computers. The software they developed presented them with a short list of potential supernovae, leaving the final decision up to the naked eye. After five years of observations, in 1997 the team had found 42 supernovae on demand. They had proved that what was considered impossible could be done. They decided it was time to calculate what the fate of the universe would be. The expected and sought results was that they would be calculating how quickly the expansion of the universe was slowing down, however they found something quite different!

All the supernovae the group had found were 20% dimmer than expected. This meant that they were much further away in the universe than they should have been according to the known laws of gravity. This inferred that the rate of change of the expansion rate of the universe was actually positive, the universe seemed to be accelerating apart. Once this was announced theoreticians joined the mass of observers who had joined in the search for supernovae. They tried explaining this observation through virtual particles and vacuum energies, there must be some mysterious energy pushing against the pull of gravity in the universe. After looking at old papers it was realized that such an energy had already been proposed 81 years earlier by none-other than Albert Einstein himself. Although, this is what he had called the biggest mistake of his life, it was his infamous Cosmological Constant (Λ).

Up to present day the scientific community is still debating and calculating on whether Einstein was right or not about a type of Λ energy. Saul Perlmutter and his team are still working on their findings.

The final frontier…

So up to the time of writing (May 1999) the search still continues for the fate of this universe. If the current ideas are to be believed, whatever the fate of our universe it is going to be something that we never imagined possible. Some things are certain though, the fate of our universe still remains one of the few voyages of discovery that humanity has yet to complete, one of the few fundamental philosophical questions to be answered. Another question should be asked however, once we do know the answer to the best of our ability, will our world ever seem the same again?

Appendix One.

Model making…

In 1935 similar models to that made by Freidmann 13 years ago were made discovered by American physicist Howard Robertson and British mathematician Arthur Walker, in response to Hubble's discovery of the uniform expansion of the universe. Although Freidmann only found one model that fit his assumptions there are actually three *Freidmann models*. It is basically the goal of modern cosmology to determine which of these models our universe fits into. The first model is like the one that Freidmann discovered, the universe starts from an infinitely small volume and expands. The density of the universe is below the critical value so that gravity eventually wins and the universe begins to contract. In the end the universe goes from a big bang to a *big crunch*.

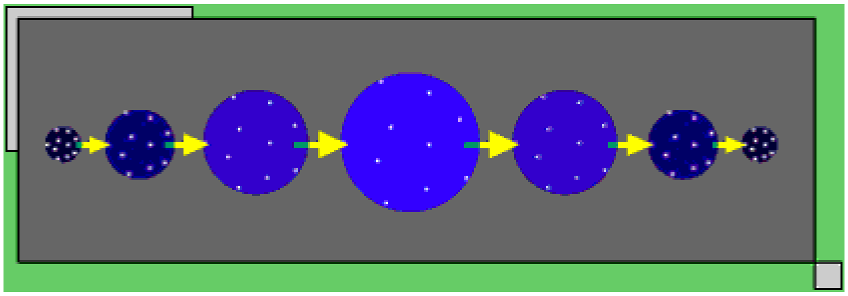


Figure Eight. Schematic of the Freidmann closed universe model.

The second Freidmann model is one in which the density of the universe above the critical value. The universe is expanding so fast that is *flies away from gravity* and simply carries on expanding forever.

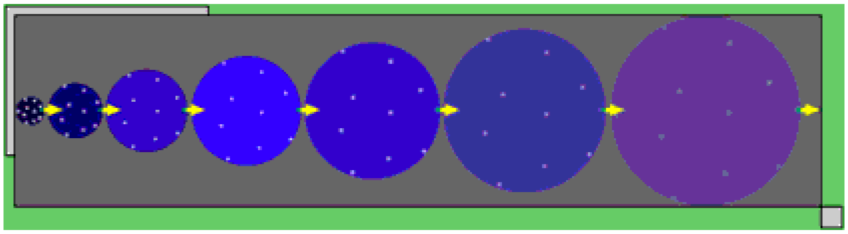


Figure Nine. Schematic of the Freidmann open universe model.

The third Freidmann model is one where the density of the universe is at the critical value. In this case the universe expands from the big bang, but is slowed down so much that the expansion rate tends to zero as we approach the infinite future, this is called a flat universe.

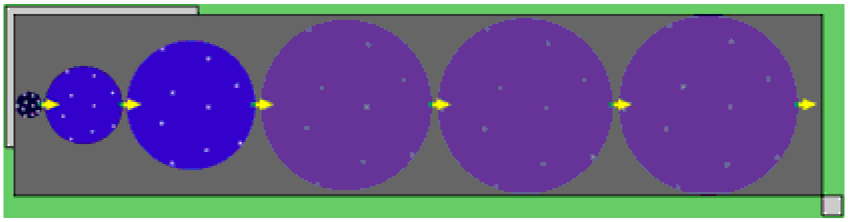


Figure Ten. Schematic of the Freidmann flat universe model.

The different types of expansion can be compared below.

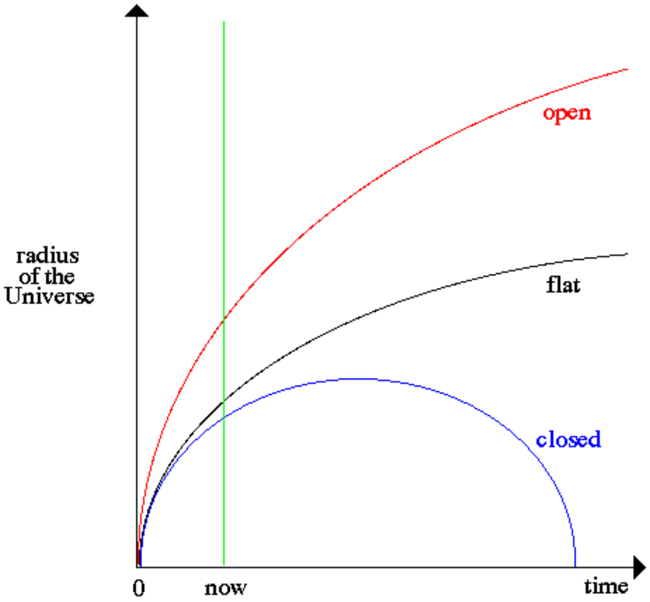


Figure Eleven. Plots of the three Freidmann models.

The geometry of each model is also shown, they are only representations since the real models are in four dimensions, which we are incapable of visualizing.

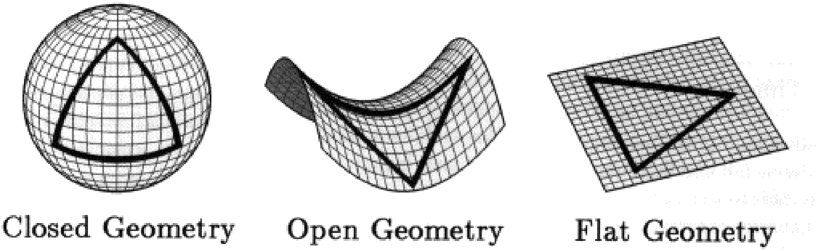


Figure Twelve. The geometry of each Freidmann universe.

Appendix Two.

The Steady-State theory

Figure Thirteen. Sir Fred Hoyle.

Despite the supporting evidence many people did not like the idea that the universe had actually had a beginning, so there were some groups that tried to build theories that avoided this. The theory that gained the most support was proposed in 1948 by two refugees from Nazi-occupied Austria, Hermann Bondi and Thomas Gold, together with Briton Fred Hoyle. Quite simply their theory stated that as galaxies drifted apart new matter was created in the spaces between, at the modest rate of one particle per cubic kilometer per year. Observations made by a college Martin Ryle during the late 1950's and the early 1960's using a radio telescope contradicted the predictions of the steady-state theory. Furthermore the discovery made by Penzias and Wilson meant that the steady-state theory had to be completely abandoned. Hoyle was still defending variations of the steady-state theory up to at least the 1970's.

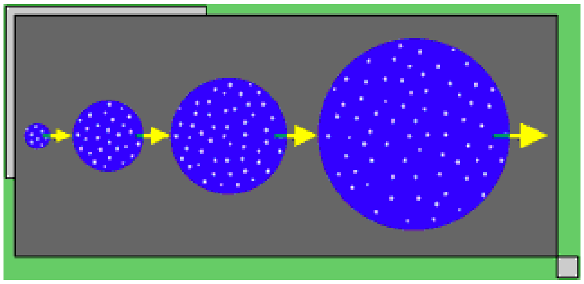


Figure Fourteen. Schematic of the steady-state theory.

Appendix Three.

The Oscillating Universe

One of the implications of the big-bang theory is that the universe will one day end, or at least any life in the universe will come to an end. If the universe is either open or flat, meaning that it expands forever, it will survive for an infinite period of time. But eventually all the material in all the generations of stars will be exhausted, and the universe will grow cold and dark. In a closed universe, in which the expansion eventually stops and a contraction follows, the end is far from cold and dark—as the Big Crunch approaches, the universe grows hotter and brighter until it implodes into a singularity and gets crushed out of existence.

But is that what would really happen? Some scientists speculate that the Big Crunch would not signal the end. Perhaps another Big Bang would follow the Big Crunch, giving rise to a new universe of possibilities. The idea that Bangs follow Crunches in a never-ending cycle is known as an oscillating universe. Though no theory has been developed to explain how this could ever happen, it has a certain philosophical appeal to people who like the idea of a universe without end

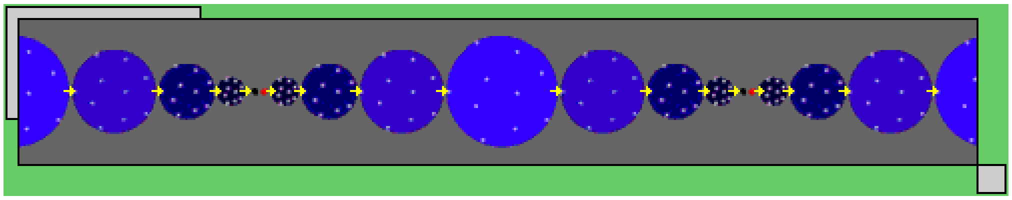


Figure Fifteen. The Oscillating universe.

Appendix Four.

A time line of the universe as predicted by inflationary theory.

•10^{-43} seconds--This is called the Planck Time.

•For shorter times all our current theories break down. Even the very notions of space and time cease to make sense.

•10^{-36} seconds--Temperature about 1028 K.

•This is the era of hyper-expansion called inflation. The maximum distance that light could have traveled since the beginning is a mere

3×10^{-26} centimeters!

This defines the size of the "visible universe" at that time. The universe expands from this micro-bubble by a factor of 10 trillion trillion (10^{25}) in about one 1 billion trillion trillionths of a second (10^{-33} seconds). This is surely expansion with a vengeance! The universe is now about 3 mm across.

The tiny quantum vacuum energy density fluctuations that existed in the original micro-bubble have also been expanded by this huge factor. They will form the seeds of galaxies.

The remaining vacuum energy is transformed explosively into ordinary matter and energy causing the universe to become extremely hot and to expand at a leisurely pace.

•10^{-6} seconds--Temperature about 10 trillion K.

•Quark and anti-quarks form out of pure energy and immediately annihilate back to energy. But, owing to an asymmetry between the behavior of matter and antimatter, an excess of quarks over anti-quarks of one part per billion builds up. Thus, most of the antimatter disappears from our universe.

•The quarks stick together to form neutrons and protons. The conversion of protons into neutrons and vice versa maintains equilibrium with equal numbers of each.

•1 second

•Because neutrons are slightly heavier than protons it is easier to convert neutrons into protons than to convert protons into neutrons and so the number of protons increases relative to neutrons, giving a final proton to neutron ratio of about 7 to 1.

- 5 seconds--Temperature about one billion K.
    - Electron and positron pairs are created. Matter creation ceases.

- 3 minutes--Temperature about 100 million K.
    - Nuclear reactions occur at a furious rate. Protons now move slowly enough to fuse into helium nuclei. Helium, deuterium, lithium created.

- 300,000 years--Temperature about 10,000 K.
    - The radiation density is now low enough that the universe becomes transparent. It is cool enough now for electrons and nuclei to stick together to form atoms of hydrogen and helium. This is called the recombination era.

- 1 to 5 billion years--Temperature a few Kelvin.
    - The density fluctuations (lumpiness) in the matter distribution, caused by the original quantum fluctuations in the vacuum energy, form the seeds of galaxies, which form in huge web-like sheets spanning the universe. It is these initial density fluctuations that the COBE satellite detected.

- 12 billion years--Temperature a few Kelvin.
    - Dawn of life on at least one tiny blue planet.

- 15 billion years--Temperature 2.7 K.
    - More-or-less intelligent life exists on this blue planet!

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