The Birth of the Universe: The Current State of Cosmology by Eric Laurenson

- Introduction
- Overview
- Rationale
- School Demographics
- Background Cosmological Information
- Advanced Background Information
- Objectives
- Strategies
- Glossary
- Annotated Bibliography / Resources
- Appendix-Content Standards

Introduction

How did the Universe begin? What was the early Universe like? What is the Universe made of? How old is the Universe? What is the fate of our Universe? These compelling questions have stimulated thought throughout human history, but it is only within the last half a century that these questions have resided within the respectable pursuits of scientific inquiry. It is a remarkable endeavor that humans have the capacity to attempt to comprehend the Universe that they inhabit. The study of cosmology attempts to determine the origin and fate of our Universe and the very nature of time and space. Teaching cosmology to high school students offers the perfect opportunity to introduce students to the explorative nature of the scientific approach and the evolution of scientific knowledge. This unit is designed for high school physics courses at varying degrees of mathematical and conceptual sophistication but it can also be simplified conceptually so that it serves as an introduction to cosmology for a freshman general science course.

Overview

The current advances in cosmology instill the very nature of the scientific approach and the promise of scientific discovery. It is essential to introduce our students to the wonders of the cosmos as they are currently being discovered and to generate enthusiasm about the remarkable scientific advances. This course will attempt to impart to the students the most contemporary understanding of the state of the Universe. An additional purpose is to discuss and develop the subtle scientific reasoning that allows scientists to make the claims they do about what we currently know. My goal is to create a unit which, as accurately as possible, presents the current state of our knowledge of the Universe so that my students will be able to comprehend the current developments in cosmology and potentially will be interested in contributing to the scientific pursuit of these sciences. I will incorporate this cosmology unit into the high school physics courses I teach as part of the modern physics curriculum. The unit is written for first year physics courses, comprised of 11 th and 12 th graders, and can be adapted to different levels by increasing or decreasing the sophistication of the mathematical and conceptual ideas that are presented so that it is appropriate for gifted, honors or general first year physics courses. This unit will be presented at the end of the year once we have covered the basic concepts of Newtonian physics and improved the students' mathematical skills in algebra and geometry. There are supplemental materials and topics for discussion that are particularly intellectually challenging that are meant for an Advanced Placement or second year physics course. In my general science course of 9 th grade students, I will introduce the unit as part of the Universe curriculum. I will simplify the unit conceptually and mathematically to make it appropriate for ninth grade mainstream students.

The unit focuses on preparing students to evaluate how we know what cosmology claims to know about the Universe. This will be achieved by focusing on five essential issues in cosmology and developing a critical and discerning comprehension of the nature of these concepts. The goal is to create a skeptical and exploratory approach to the pursuit of knowledge that exemplifies the scientific approach. In effect, the vision of this curriculum unit is to learn science by doing science. However, in this context, doing science is not only performing labs to obtain experimental data, but more significantly, in the study of cosmology, it is to apply known data to figure out how we know what we claim to know and to determine if in fact our conclusions can be validated.

I intend to do this by exploring five major questions. First, what is the evidence for the Big Bang Theory? Second, how old is the Universe? Third, are we at the center of the Universe? Fourth, what is the evidence for the existence of dark matter? And lastly, what is the evidence for the existence of dark energy?

It is my hope to delve into these five questions with the intention of developing a deep enough understanding that my students will be able to explain their conclusions in their own words and thereby internalize the scientific knowledge. In addition, I hope that this process will give them the discerning skills to apply the scientific method of questioning, finding evidence, evaluating the evidence and creating conclusions based on their evaluation that will encourage them to utilize this critical process more broadly in their decision making.

This unit is intended to cover ten lessons in two weeks but can be implemented in part if it is so desired. Perhaps this unit could also be implemented by teachers, outside of science, who are interested in introducing the concepts of cosmology which are so broadly applicable to our human condition. The scientific background in this unit could certainly be applied to the creation of myths about the origin of the Universe within any discipline. In addition, this unit on cosmology could be utilized by other disciplines to compare the scientific approach to knowledge to the nature of the pursuit in other disciplines. Is all of our "knowledge" equal? Are there commonalities among our approaches or is it beneficial to be aware of the differences within our approaches? Does asking why we are here, how did we get here or where are we going, make us more human?

Rationale

I believe that asking the question why is an essential aspect of education, and trying to develop the discerning capacity to pursue that inquiry is the obligation of the educator.

Cosmology is a fundamental science and is experiencing an unprecedented expansion of available knowledge. A myriad of telescopes are reaching billions of years back in time to determine the origin, scale and future of our Universe. The knowledge obtained has led to the surprising discovery that the Universe is made up of 23% dark matter and 73% dark energy in addition to the very small percentage of ordinary baryonic matter of which we are made. So 96% of the Universe has been discovered within the past decade and very little is known about it! Although physicists have only determined the presence of dark matter from its gravitational effects and still do not know what dark energy is other than that it provides a repulsive force, the essence of the scientific pursuit is to search into the unknown for greater comprehension.

Cosmology is establishing the very parameters of the unknown and guiding the search for a unified understanding of the physical world. Remarkably, physicists are able to utilize their understanding of high energy particle physics and nuclear physics to extrapolate back to 10 - 4 3 second, an infinitesimally small fraction of a second, from the beginning of the Universe, called the Planck time. The establishment of the expansion of the Universe by Edwin Hubble from the cosmological redshift, the discovery of the existence of a cosmic radiation background, the understanding of primordial nucleosynthesis and the production of heavier elements within supernovae to establish the detected levels of elements within the Universe from spectroscopy, and the recent discovery that the expansion of the Universe is in fact accelerating from ancient supernovae data have established cosmology as a legitimate scientific pursuit that is enriching our comprehension of the laws of physics.

Cosmology has established itself on the cutting edge of science because the extreme conditions of the early Universe are not reproducible experimentally and those extreme conditions indicate the limitations of our current pillars of modern science, relativity and quantum mechanics, because they result in mathematical singularities. In order to progress, we must find a deeper comprehension of reality to unify our current understanding of the nature of the cosmos. Consequently, cosmology has established itself as a driving force in modern science and is guaranteed to be central to the advancement of scientific knowledge. Therefore, we would be remiss as educators, especially science educators, not to introduce our students to the stimulating and intellectually expansive, cutting-edge knowledge of current cosmology.

School Demographics

I teach at a comprehensive public high school in Pittsburgh, Pennsylvania. Peabody High School is located in the east end neighborhood of the city and serves six surrounding neighborhoods. The student body is predominantly African American (95% African American, 4% Caucasian, 1% other) with an enrollment of 660 students. 90% of the students receive free or reduced lunches. Information is based on the low socio-economic community in which the students live. Our school has been identified as an at risk high school. This means that our freshman class does not meet the state standards in reading and or mathematics. The benchmark year for testing in the state of Pennsylvania is during the junior year. The large majority of students have failed the PSSA tests in math, reading, and writing, and most scored below basic. At PHS tracking is implemented for all academic subjects; therefore, I teach two levels of physics. One course is designated for students who meet the state's gifted standards. The other is for regular education students. The students in my gifted class score significantly higher on the PSSA but some still failed. My honors students (3.0 GPA) in physics are above average for the school but likely failed the Pennsylvania System of State Assessment (PSSA) in math, reading and writing. My 9 th grade general science students are representative of the school population.

Background Cosmological Information

The Universe began with an event called the Big Bang. Based on the Big Bang theory the Universe began in an unimaginably hot, inconceivably dense fireball that began as a single point. This single point comprised the entire Universe. Then the space expanded and the Universe got larger. As the Universe got larger the temperature cooled. Over the next 13.7 billion years the Universe has continued to expand. In the last two billion years, surprisingly, the expansion of the Universe has begun to accelerate from the repulsive affect of Dark Energy. It appears that the Universe will continue to expand forever, getting ever colder and colder.

The Big Bang

In scientific explanations of the Big Bang we can only go so far back in time. In essence we are rolling back the film of the Universe. We are able to do this because we have formulas that enable us to determine the trajectory of the Universe and the laws of physics are valid in reverse. However, because the Universe appears to go back to a single point, our projection back into time can only go so far before the math reaches a singularity, or breaks down. Currently, our understanding of the Universe reaches its limit and we cannot explore any earlier that that time, which is known as the Planck time. Remarkably, though, we are able to go back to 10 - 4 3 second, or about one billionth of a billionth of a billionth of a billionth of a billionth of a second! That is nearly the beginning of time, but earlier than that we can not say what occurred. It is difficult to imagine, but at that time the entire Universe was shrunk down to a size smaller than a single atom and we can determine that the temperature was around 10 3 2 degrees Kelvin or an unimaginably hot, one hundred billion, billion, billion degrees (Weinberg, 146). The Universe which had been concentrated at one point underwent an "explosion" that continues to this day, 13.7 billion years later. This explosion is different than what we normally think of though, because space itself is actually what is expanding! Thus, the Universe did not "explode" out into space, but instead the space itself continues to expand so that the Universe does not have any edge or boundary.

Primordial Nucleosynthesis

Nucleosynthesis is any process that builds up heavy elements. Nuclear synthesis requires millions of degrees and only occurs in the extreme heat of the early universe, known as primordial nucleosynthesis, and in the center of stars, which is known as stellar nucleosynthesis. The early Universe was a fireball that "expanded with space" and as it did the energy also was spread out. The energy density is directly related to the temperature so as the Universe expanded the temperature dropped proportionally. As the energy dropped, matter gradually formed. Eventually, about three minutes after the Big Bang, when the Universe had cooled sufficiently to about nine hundred million degrees, protons and neutrons were able to undergo primordial nucleosynthesis (Freedman and Kaufmann, 668), which is the formation of the helium and traces of lithium and beryllium from the fusion of hydrogen and neutrons. Before this time, there was sufficient energy from collisions of particles to combine together but there was so much energy that the particles were torn apart again. This is known as the deuterium bottleneck.

Deuterium is a proton and a neutron combined together and is an essential building block for the creation of elements. When two deuterium elements combine they form Helium, which is a stable nucleus that can be used to form heavier nuclei. At the energies present before this time deuterium did not survive long enough to be fused into helium. Before this point there were 13% neutrons, which decay quickly when free, and 87% protons. Primordial nucleosynthesis fused virtually all of the neutrons into helium resulting in a composition of 26% helium and the rest was hydrogen, with just traces of lithium with three protons and beryllium with four protons (Weinberg, 110). It turns out that all of the heavier elements in our periodic table are created from the processes of supernovae, but primordial nucleosynthesis is the only way to account for the cosmic abundance of helium. Nucleosynthesis also occurs in stars. Although stellar nucleosynthesis, the nuclear process in stars, produces helium, this helium is "locked up" inside white dwarf stars. The majority of stars end up as low mass white dwarfs, so unlike supernovae which explode, the helium within these stars is permanently contained within the star.

The Last Scattering Surface

For the next 380,000 years the Universe continued to cool until it reached about three thousand degrees. At a point, known as recombination, the decreased energy of the particles allowed the Coulomb attraction of the protons to capture the electrons, forming atoms for the first time. This is simply the result of positive and negative charges attracting one another. Up until this point, the tremendous amount of radiation that was traveling through the Universe at the speed of light had been scattered by the ionic charged "soup" of the Universe. The formation of atoms virtually eliminated the free charged particles, bonding all protons and electrons into small atoms. The photons interact easily with free electrons, but very little with neutral atoms. Consequently, the photons which are scattered when they collide with charged particles, very rarely encountered these bound charged particles and the Universe is said to have become transparent to radiation.

Radiation is said to have decoupled from matter so from this point on radiation was free to move through the Universe without being scattered by electrons. This radiation from what is known as the last scattering surface has continued to radiate unimpeded for the last 13.7 billion years and remarkably can be detected today. This radiation is known as the cosmic background radiation (CMB) and permeates the Universe in every direction that we look with a constant temperature of 2.7 degrees Kelvin (which is 2.7 degrees above absolute zero). This radiation has remained the same except for the effect of cooling, resulting from the stretching of space, which has resulted in the drop in temperature. The CMB is a perfect black-body spectrum, which means that it achieved thermal equilibrium. The CMB was first detected in the early 1960's and is definitive proof of the Big Bang!

Redshift of the Cosmic Background Radiation

Once decoupled the CMB radiation was only affected by the expansion of space itself. The expansion of space affects radiation (any form of light) by stretching out the wavelength just as a rubber band is stretched by pulling it out in space. This stretching results in a longer wavelength, which is the same thing as a lower frequency. In light, blue is a shorter wavelength and red is a longer wavelength, so the radiation is said to be redshifted. This redshift which is the result of the expansion of space is an equivalent effect to the Doppler shift which is caused by the motion of a source. An example of the Doppler Effect is the change in pitch that we experience when a car is moving past us. As the car approaches the pitch increases and after it passes us the pitch drops. This is caused by the compression of the waves as the source moves toward you and the dilution of the waves as the source moves away. The effect is increased with the speed of the source and can be used to accurately calculate the velocity of the source. Astronomers have determined that the light from virtually all of the galaxies in the Universe are redshifted. This means that all of the galaxies in the Universe are moving away from us. So the Universe is expanding! And we can calculate that the rate of expansion, known as the Hubble constant, is 22 km per second per million light years. From this redshift we can determine how fast galaxies are moving away from us and how far away they are.

The Formation of Galaxies Due to Gravity

As the Universe expanded and cooled, gravity acted on matter to increase the slight variations of density that had existed in the early Universe. Over time, gravity caused matter to coalesce into more dense regions. This attraction of matter into higher density regions eventually resulted in the formation of superclusters, clusters, galaxies and stars. Stars, like the sun are the result of matter achieving high enough densities and temperature sufficient to initiate nuclear fusion (5 million degrees) and the emission of light and other radiation. One of the critical ideas in studying the Universe is known as the cosmological principle. This principle states that the Universe is both isotropic and homogenous over large distances. Isotropic means that the Universe looks the same in every direction, and homogenous means that every region is the same as every other region. So although there are variations in density on small scales, the Universe on the scale of one hundred million light years appears to be the same!

Now, how do we know anything about the Universe, such as where things are in the Universe and how big it is when we are stuck on this little rock floating through space? The key is the light and other radiation that reaches us from luminous objects. Astronomers, or sky watchers, have been analyzing the light from stars nearly since the beginning of human history. The light that reaches us from the stars is, in fact, a sort of time machine that records history. Since light travels at a constant speed (of 300,000 km/s) it takes time for light to reach us. Consequently, the light that reaches us gives us information about what the star was like when the light left the star! The light from the closest star to us, the Sun, is eight minutes old. The light from the next closest star, which is Proxima Centauri, takes three and a half years to get to us. The oldest light that we are able to see comes from galaxies, which contain about a hundred billion stars, and has been traveling for billions of years. The oldest radiation that can be detected is the CMB which has been traveling for over 13 billion years and has been stretched by the expansion of space so that its energy has gone from billions of degrees to a mere three degrees above absolute zero. We can only see back to the last scattering surface, so we can only see as far as light has been able to travel since this time, which is known as our cosmic light horizon.

Determining Distances Using Parallax and Standard Candles

So how do we determine how far away luminous sources are? This is a very challenging problem. The most straight forward way is to use geometry to calculate distance. The method used is called parallax and is the same process that we use with our two eyes for depth perception. The idea is that each eye has a different line of sight. We look at an object with each eye and our brains compare how much the object changes relative to the background to estimate how far away the object is. If the object moves a lot relative to the background, then we know that the object is very close, whereas if the object moves little relative to the background then we know that the object is far away. This observation can be done mathematically using geometry to determine distances with great precision. This is done astronomically by viewing objects from two different locations.

You may ask, how can we do this since we are stuck on this Earth, and the distance from one side of the Earth to the other is not significant enough to determine the parallax? We must make two observations from as far away from each other as possible. So, we make measurements six months apart. Thus we are half way around our orbit of the sun and therefore, we are at a distance equal to the diameter of our orbit! Another method is to measure how much of the light is getting to us from luminous objects whose light production we know. This is based on the knowledge that the apparent brightness of a star diminishes as the reciprocal of the square of the distance from that star. So if we know how bright a star actually is and we measure how bright it appears to us on Earth, we can calculate the distance to that star. So the million dollar question is How do we know what the intrinsic brightness of any luminous object is? This is a very challenging endeavor, but there are luminous objects that emit a calculable amount of light and are, therefore, known as standard candles.

The two main types of standard candles that are particularly useful because they are incredibly bright objects and can be seen from great distances are Cepheid variable stars and type1A supernovae.

Cepheids are pulsating stars that produce periodic light curves, whose intrinsic luminosity is directly related to its period, and can be calculated (Freedman and Kaufmann, 480). The second type of standard candle, which is magnitudes brighter than cepheids, is the type 1A supernova. A supernova is an exploding star that can rival the luminosity of an entire galaxy of a hundred billion stars for a short period of time. Type 1A supernovae are singularly useful because in addition to their incredibly high luminosity, the luminosity is also standard because this type of supernova produces the same amount of light. A Type IA supernova can be identified by its light curve. The reason for this is that type 1A supernovae are binary stars in which a white dwarf draws matter from its companion star until it exceeds an exact mass, known as the Chandrasekhar limit, which is 1.4 Solar masses. At this point the white dwarf star can no longer produce enough pressure to resist its gravitational attraction and the star goes "supernova" and explodes. The mass is the critical value associated with the brightness of the star, so the luminosity of these type 1A supernovae also are constant. The distance to these stars can then be calibrated using the information from cepheids and nearby type 1A supernova and the use of redshift to determine the distance to supernovae billions of light years away!

Two major challenges in using standard candles is to calculate their luminosity by differentiating them from other types and also increasing the reliability of distances to nearby objects (Kirshner, 35). The light, or radiation, reaching us can be analyzed using spectroscopy, which allows us to decipher information about the source. Spectral emission and absorption lines, which are a type of celestial light fingerprint of stars, tell us the chemical composition of the source and help us distinguish the properties of individual stars. Analysis of the spectral lines and how much they are displaced, or shifted in frequency, is the method used to measure the cosmic redshift.

Dark Matter

The existence of Dark Matter was postulated to account for the "missing" matter of the Universe and has only been verified in the last decade. The amount of visible matter in the Universe, predominantly in the form of galaxies, is only about one sixth of the amount that we expect from our calculations of the amount of gravitational forces (caused by mass) in the Universe.

There are two main sources of the evidence that there has to be more matter for which we cannot account. The first source of evidence is based on Kepler's Third Law that the velocities of object revolving around a center of mass decreases as you move away from the center, by the formula: formula 05.04.04.01. So, when you get beyond the galaxy where all of the visible mass is, the velocity should fall off as formula 05.04.04.02. However, this does not happen. Instead the velocities continue relatively constant, and this can only be accounted for if there is mass beyond the galaxy that we do not see! The second source of evidence that there must be Dark Matter involves the velocity of galaxies within clusters of galaxies. Galaxies in clusters have a velocity dispersion that can be measured. Based on the mass and distances between the galaxies, it is possible to determine the escape velocity, which is the velocity at which the galaxy would break its bounds to the cluster and go flying off into space. You have all experienced this if you have been on a merry-go-round at a playground and go so fast that you cannot hold on, and go flying off. We have, in fact detected that galaxies are going much too fast, well beyond their escape velocity for the visible mass, and this can only be accounted for if the mass in the clusters is much greater than the visible matter in all the galaxies. These two sources of evidence have led to the calculation that 85% of the mass of the Universe is Dark Matter!

So what is Dark Matter? There are currently two proposed candidates for Dark Matter, amusingly named, MACHOS, which are familiar objects, such as dead stars, that produce no radiation, and WIMPS, which are particles that only respond to the forces of gravity and the weak force, and include neutrinos and theoretical particles. MACHOS are able to account for less than twenty percent of the required mass within the Milky Way. Therefore, it has been determined that Dark Matter is non-luminous matter that, unlike all of the matter we are familiar with, is not made of baryons (protons and neutrons) and is detectable by its gravitational effect. Although neutrinos seemed a promising candidate because they have been shown to have a rest mass and are pervasive through the Universe, from current calculations they can account for less than a half of a percent of the cosmic density (Adams, et al, 345-351). There is much that we still do not know about Dark Matter, but the search is on to learn more.

Dark Energy

As much as we do not know about Dark Matter, we know even less about Dark Energy. What we do know is that Dark Energy comprises most of the Universe, about 73%, and it provides a repulsive force that can account for the acceleration of the expansion of the Universe! Dark Energy is a source of negative pressure that overcomes the effect of gravity and results in the acceleration of the expansion of the Universe. It fills the entire Universe like a fluid. Currently, there are three proposed explanations for Dark Energy. For the first two, Dark Energy remains constant as the Universe expands. The first is that Dark Energy is the cosmological constant proposed by Einstein that is a constant, like the gravitational constant, that defies explanation.

The second possibility, based on the Heisenberg uncertainty principle of quantum mechanics, is that there is a vacuum energy. Vacuum energy is negative pressure that is the consequence of the continual creation of virtual particles in "empty space" and is supported by the phenomenon known as the Casimir effect. The third possibility is quintessence which is a very exotic form of matter that is equivalent to an energy density that fills the Universe. Unlike vacuum energy, quintessence is variable (Adams, et al, 352-355). These are the best theories that physicists are currently able to imagine that agree with the limited evidence that we have concerning the nature of Dark Energy. This is the frontier of exploration in physics and presents an unlimited opportunity for discovery. Understanding Dark Energy is the essential key to determining the fate of our Universe!

Advanced Background Information

Geometry of Space

There are three possible geometries of space. Space is closed, flat or open. In a closed Universe the geometry of space is equivalent to living on a globe. If you travel in a straight line, eventually you will return to the same place. In a flat Universe, the geometry is like living on a flat sheet of paper. An open Universe, like a closed Universe is curved, but light traveling in a straight line diverges. The geometry of this space looks like a saddle. It has been determined that our Universe has a flat geometry.

Inflation

Inflation was an episode of extremely rapid and accelerating expansion in the early Universe. At 10 -3 7 second from the beginning the Universe underwent inflation and increased in size by an inconceivable factor of 10 5 0! It is possible that this may have happened just before the end of grand unification, as the result of the development of a "false vacuum" with a high density of vacuum energy. There is no accepted explanation for why this would have happened but inflation solves several perplexing problems.

Inflation resolves the horizon problem. The horizon problem is the issue that without inflation the universe would not have been able to be in thermal equilibrium at the time of the last-scattering surface. Consequently, the CMB radiation at a constant temperature of 2.725 K within 1 in 10,000 is unexplainable without inflation, which enables the early universe to have the time and the proximity to be in thermal equilibrium before the tremendous expansion.

Another problem that inflation resolves is the flatness problem. The Universe has an energy density that is almost exactly equal to the critical density that determines whether the Universe will eventually contract or expand forever. It has been determined that the energy density is almost exactly equal to the critical density with an unimaginable accuracy. If the energy density was even slightly different than the critical density in the early universe, the value would have diverged very rapidly. This is equated to trying to stand a pencil on its point. The pencil will stand on its point initially, but the pencil will lean in the direction that it started because it is not perfectly centered at its center of gravity. This effect is magnified by gravity the more that the pencil leans so the pencil accelerates in its fall. So how could the Universe have existed in this state of balance for 13.7 billion years? It is statistically impossible and we know of no reason why the Universe would have started with a value so nearly equal to the critical value.

Inflation also presents an explanation for the origin of cosmic structure. In Inflation, a very small part of the Universe expanded to become our entire known universe. The expansion of this small region would actually have magnified the quantum fluctuations known in quantum mechanics. This gives an explanation for how the fluctuations of matter could have resulted in the known variations in matter density that resulted in the formation of galaxies and clusters.

Although Inflation is a very challenging concept, it is a very attractive theory because it is able to explain a wide variety of problems that otherwise elude explanation. There are variations on the inflationary theory, but it appears that there is sufficient circumstantial evidence to validate the theory. (Guth)

Alternative Theories to the Big Bang

There are alternative theories to the Big Bang. The Steady State Model was popular. The Steady State Model suggested that the Universe was static. Later variations included the possibility that the Universe was expanding but that matter was created to maintain a constant density. Albert Einstein was so convinced that the Universe was static that when his formula indicating a non-static universe he inserted the cosmological constant, L, to force his formula to be static. He later acknowledged the error of this approach, but ironically, his cosmological constant is one of the leading explanations for the repulsive force that is the predominant constituent of our Universe.

The Unification of the Four Forces

The explorations into the events of the early Universe are defining the very nature of the Universe and suggest that the four fundamental interactions were unified in the tremendous temperatures within the first second of the Universe. In these extreme early conditions matter and energy were interchangeable and even the four fundamental forces of physics (gravity, electromagnetic, the strong and the weak interactions) were unified. The equivalence of "phase transitions" were removed and symmetry was restored (Weinberg,149; Freedman and Kaufmann,664).

Black Body Spectrum

In a perfect black body spectrum photons do not involve radiation, but rather photons permeate space. There is an implication that time is involved and photons are energy that has been spread out, but they do not arrive. They have always existed where they are but space has expanded, causing them to be a lower frequency.

The CMB can be calculated using Wein's law formula 05.04.04.03. So if we know the current wavelength, we can project backwards to calculate the temperature at various times in the early universe.

Gravitationally Bound Objects

High matter density region, like within galaxies, do not expand because the Coulomb force and gravity prevent their expansion.

Nature of Light

What is the nature of light? What does the limit of the speed of light tell us about the nature of reality? What does it tell us about the relationship of space and time? For an object traveling at the speed of light, time does not elapse. This is equivalent to the time dimension disappearing. For an object accelerating toward the speed of light, the mass and therefore the energy, relativistically goes to infinity. What does this tell us about the nature of light and the nature of reality itself? How can the limit of the speed of light have a unit of time when time is dilating (Heinz Ahlers, personal conversation)? Should it cause astronomers and physicists consternation that there is a limit to the speed of light? Is this limit telling us something fundamental about nature?

Determining Astronomical Distance

It is very difficult to determine astronomical distances. The process involves determining the distance to stars or galaxies using geometry by the method of parallax. Astronomers use the distance known as a parsec. A parsec is the distance that results in an angle of 1 arc second that encompasses 1 AU. One parsec is equal to 3.2 light years. In addition, astronomers use the intrinsic brightness of an object because the luminosity is related to the brightness and the distance from the object. The apparent brightness of an object as observed from Earth (technically referred to as energy flux) is L/4∏d 2.

Objectives

The students will get a basic understanding of the current knowledge of cosmology and be able to incorporate that knowledge into a greater understanding of physical science (S2). Students will improve their capacity for making discerning judgments about issues related to science and will be able to appreciate the scientific method as a valuable and useful approach to decision making. The students will be able to use their observations to evaluate the veracity of knowledge and be able to identify issues that are still unknown (S1, S5). The students will be able to understand the evolving nature of science and the method that scientist use to make truth claims (S7). The students will appreciate the role that the advances in technology have played in the advances in cosmology and be able to access internet resources (S9). The students will acquire the terms and language to discuss their elevated ideas regarding cosmology (C5). The students will be able to communicate their ideas, express their opinions, and defend the relative reliability of different theories. The students will engage in higher level class discussions (C6,C7,C8). The students will improve mathematical skills in understanding formulas, calculating results, representing their data graphically and comprehending the implication of mathematical expressions (M1, M2, M4, M5,M6).

Strategies

This unit is based on a constructivist, student-centered, hands-on approach in which students are encouraged to create models of the Universe that make sense to them. The students are asked to make qualitative and quantitative observations whenever possible, perform labs and calculate quantities and apply the knowledge that they acquire to facts that science has determined about the Universe. The goal is to develop enough scientific knowledge that the students are able to explain the main topics about what science currently knows about the Universe and how they know it, and to be able to make a discerning evaluation of scientific claims.

The knowledge of cosmology, and science in general, is evolving and the intent of this unit is to engage students in a scientific process to be able to appreciate how science knows what it claims to know. Partly, this will be achieved by guided questioning. It is my belief that instilling an enthusiasm for science through exciting hands on activities and relevant and challenging intellectual stimulation will produce more informed citizens who appreciate the utility of the scientific method.

Classroom Activities

5 Lesson Plans- How Do We Know What We Know?

Lesson 1: What is the Evidence for the Big Bang?

Objective: Students will be able to explain the evidence for the Big Bang Theory and discuss why it is our best current explanation.

Activities:

LAB: The Big Bang: An Analogy to an Expanding Balloon

Part 1: Observations

Give each group of 2 or three students a balloon. Have them mark dots on the deflated balloon to indicate the position of galaxies. This deflated balloon represents the early Universe (assuming that galaxies had already formed). Now have the students blow the balloon up slowly. Ask the students to discuss what happens to the galaxies (dots) as the balloon is inflated.

Determining the Expansion Rate of the Universe: Qualitative Analysis

Have the students blow up the balloon slightly. Tell the students to mark one "galaxy" ñ"US." Then put a number "1" on a "galaxy" close to "Us." Mark a "2" on a galaxy about a quarter of the way around. Lastly, mark a "3" on a galaxy as far away as possible (about half way around the balloon). Have the students deflate the balloon and tell them that the balloon represents the Universe (but if it were really accurate the balloon would shrink to a point). Have the students inflate the balloon a little. Now ask the students again what is happening to the distance between "US" and other "galaxies." What happens to the distance between "galaxies" that are close? What happens to the change in distance between galaxies that are far apart? Continue these steps a couple of times. Discuss with the students what is happening to the distance between galaxies.

Explain to the students that this is an analogy of our model of the Big Bang, and that their observation that the distance changes more the further you are away is true in the Universe. The further away galaxies are from us, the faster they are moving away from us! Collect the balloons and tell the students to remember this analogy and we will come back to it later.

Thought Experiment: Cosmic Microwave Background

In the 1960's, researchers detected microwaves coming to us from every direction with the same temperature, 2.7 degrees Kelvin. This is now known as the cosmic microwave background (the CMB). Where could this "light" have come from" Why is it all at the same temperature? Why is it microwaves? How is this proof of the Big Bang?

Thought Exercise: Redshift

Since we cannot measure the distance to galaxies directly, we must use another method. It turns out that in astronomy we use the same technique you use every day to cross the street. When you cross the street do you have to look to see if cars are coming? Is there another way to tell? Yes, you can listen. And what does it tell you? How can you tell if a car is coming? Can you tell if it is going faster or slower? Does it make a different sound as it goes past you? This is the Doppler Effect! An object coming toward you makes a higher pitch and an object going away from you makes a lower pitch. A faster object that makes a sound is received at a higher pitch and the slower object that makes a sound is received at a lower pitch. The Doppler Shift for sound is the same as the redshift for light! Measuring the change in the frequency of light is how we tell how fast stars are moving and in what direction.

Doppler Demonstration:

Demonstrate the Doppler Effect with the Doppler Demonstrator, which is just a noise maker at a constant pitch attached to a string. Swinging the Doppler Demonstrator over your head causes the listener to hear a higher pitch when the "noise maker" is coming towards them and a lower pitch when it is moving away.

Explanation of the redshift:

The redshift is graphed to determine the rate that galaxies and supernovae are moving away from us relative to their distance from us. The cosmic redshift is the same thing we saw with the balloon. The farther away you are the faster the objects are moving away. So like the balloon, we can run it in reverse to prove that the whole Universe would collapse down to one point! This is the Big Bang in reverse!

Discuss "The History and Fate of the Universe" CPEP Chart

Lead a discussion on what information is presented to us by the timeline of the early Universe to the present.

Lesson 2: How Old is the Universe?

Activities:

LAB: The Big Bang: An Analogy to an Expanding Balloon - Part II (See Lesson 1 for Part I)

So, we know from the theory of the Big Bang that the Universe is expanding. Today we are going to discuss the rate of expansion and how we can calculate what that exact rate is.

The students should then copy the following chart:

Determining the Expansion Rate

Distances to Distant Galaxies

	Distance between Galaxy and "US"		
	Galaxy 1	Galaxy 2	Galaxy 3
Step 1			
Step 2			
Step 3			
Step 4			

Hand out the marked balloons from Lesson 1, and give each group a length of string and a meter stick. Now, we are ready to begin.

Step 1: Using the string, have the students measure the distance between "US" and galaxy "1". Then measure the distance between "US" and galaxy "2". Measure the distance between "US" and galaxy "3".

Step 2: Using the string to measure, mark a distance twice the distance between "US" and galaxy "1". Now, blow up the balloon so that the distance between "US" and "1" are this far apart (twice the distance that "US" and galaxy "1" was in Step 1. Have the students mark this distance on their chart. Then, have the students measure the distance between "US" and galaxy "2", and measure the distance between "US" and galaxy "3".

Step3 and Step 4: Repeat step 2, measuring what the distance is between "US" and the three other "galaxies".

Graph Results:

Have the students plot the distance between galaxies vs. the step (which are proportional).

Find the slope of your line- this is your "Rate of Expansion"!

Conclusions:

What did you find? How do the distances vary as you get further away? Did you get a straight line? What is the slope of your line? What does a positive slope of a straight line indicate about your "Universe"? Your result is equivalent to the Hubble Constant, which gives us the rate of expansion of the Universe!

Activity: Calculating the Age of the Universe

As it turns out, the Hubble Constant is 22 kilometers per million light years away an object is from us. This is the result of the cosmological redshift.

Age of the Universe is simply the reciprocal of the Hubble constant, H 0.

$v = H_0 d$; $d = vt$; so by substitution $v = H_0 vt$. The v's cancel so $1= H_0 t$, So solving for t: the age of the Universe $t = 1/ H_0$!

The Hubble constant H_0 is 22 km/s/million light years:

First we must convert light years. A light year is a distance, but we will convert light year into km/s for 1 year for the ease of cancellation with the Hubble constant. (distance/time x time = distance)

1 light year = (3×10^5 km/s for 1 year)

So:

formula 05.04.04.04

If we do the math, $1/22/((10^6)(3\times10^5 \text{km})= 3 \times 10^{11} 1/22 = 1.36 \times 10^{10}$ years!

So the age of the Universe is 13.6 billion years!!!

Lesson 3: Are We at the Center of the Universe?

Activities:

LAB: Are we at the Center?

Repeat the Big Bang Lab (Part 2) in Lesson 2, but this time use "1" as your center and measure from "1" to the other galaxies. Does this change your results? Does it change your graph? If so, how? So, can you say which point "us" or "1" is at the center of the galaxy? What if we repeat the lab for galaxy "2". Do we get the same result?

Explain that every galaxy is moving away from every other galaxy, and they all "collapse" back to the center where the deflated balloon was, so no one point is the center! The center is the singularity, the point from which the Big Bang started.

Video Resources:

Show the students segments of the following videos to enhance their comprehension of our place in the Universe. View clips from Runaway Universe that indicate that the Universe is expanding and that the Hubble constant is the same anywhere in the Universe. Show the students clips of Steven Hawking's Universe to illustrate characteristics of the Universe. The Astronomers series indicates the approach scientist take to making astronomical discoveries. The segment on Robert Kirshner's search for supernovae is particularly engaging. And lastly, the eclectic and engaging Elegant Universe addresses the bizarre implications of quantum mechanics, which is essential to understanding the early universe. These video clips will stimulate the students' imagination and impress upon them the magnitude and wonder of the cosmos.

Lesson 4: What is the Evidence for Dark Matter?

a) Kepler's 3 rd Law with masses P 2=(4Π 2/(G(m 1+m 1))a 3

We would expect the velocity to decrease by formula 05.04.04.05 when you go beyond the galaxy because we are further from the mass, but it doesn't! Instead it remains constant. Therefore, there must be mass beyond the galaxy that we can't see!

b) the velocity of galaxies within clusters

the velocity of galaxies within clusters are greater than the escape velocity for the visible mass, but the galaxies continue to orbit, so there must be dark matter that we don't see.

Lesson 5: What is the Evidence for Dark Energy?

The recent supernova data for high z (redshifted) objects has shown a departure from the slope of H 0, that indicates an increase in the rate of expansion of galaxies starting about 5 billion years ago. So, the expansion of the Universe is accelerating!

Give the students a copy of a graph of current supernovae data showing that the expansion of the Universe is accelerating.

image 05.04.04.01

(NASA and A. Field)

Glossary

(Universe,G1-G18; An Introduction to Galaxies and Cosmology, 407-425)

baryonic matter- matter consisting of baryons (i.e. ordinary matter made of protons and neutrons)

Big Bang- An explosion of all space that took place roughly 13.7 billion years ago and that marks the beginning of the Universe.

blackbody- A hypothetical perfect radiator that absorbs and re-emits all radiation falling upon it.

cepheid variable star- a type of yellow, supergiant, pulsating star.

Chandrasekhar limit- The maximum mass of a white dwarf.

cluster of galaxies- A collection of galaxies containing a few to several thousand member galaxies.

cosmic microwave background (CMB)- An isotropic radiation field with a blackbody temperature of about 2.725 K that permeates the entire Universe.

cosmology- The study of the structure and evolution of the Universe.

dark energy- A form of energy that appears to pervade the universe and causes the expansion of the universe to accelerate, but has no discernible gravitational effect.

dark matter- Nonluminous matter that is the dominant form of matter in galaxies and throughout the Universe.

decoupled- no longer in thermal equilibrium with

deuterium bottleneck- The situation during the first 3 minutes after the Big Bang when deuterium (an isotope of hydrogen whose nucleus contains one proton and one neutron) inhibited the formation of heavier elements.

Doppler effect- The apparent change in wavelength of radiation due to relative motion between the source and the observer along the line of sight.

escape velocity- The velocity needed by an object to leave the gravitational field of a second object permanently and to escape into interplanetary space.

galaxy- A large assemblage of stars, nebulae, and interstellar gas and dust.

homogeneous- Having the same property in one region as in every other region.

Hubble Constant (H 0)- In the Hubble law, the constant of proportionality between the recessional velocities of remote galaxies and their distances. H 0 is equal to 22 km/s per million light years or 72 km/s per Mpc.

intrinsic brightness- the amount of radiation produced

isotropic- Having the same property in every direction.

last-scattering surface- The surface defined by the locations at which photons in the cosmic microwave background last underwent significant interaction with matter (with the exception of gravitational effects). This interaction was due primarily to electron scattering, and so last-scattering occurred at about the time of recombination.

light- Electromagnetic radiation in the visible spectrum.

light horizon- The boundary indicating how far light would have been able to travel.

luminosity- The rate at which electromagnetic radiation is emitted from a star or other object.

MACHOS- Massive Compact Halo Object- A dim star or low-mass black hole that may comprise part of the unseen dark matter.

microlensing- A phenomenon in which a compact object such as a MACHO acts as a gravitational lens, focusing the light from a distant star.

nuclear fusion- The process of combining elements to form more massive elements.

nucleosynthesis- The process of building up nuclei such as deuterium and helium from protons and neutrons.

parallax- The apparent displacement of an object due to the motion of the observer.

parsec (pc)- A unit of distance; 3.26 light-years.

Planck time- A time determined by a combination of physical constants that represents the earliest time in cosmic history at which currently established physical theory might be used to study the nature and evolution of the Universe.

primordial nucleosynthesis- The nuclear processes that were responsible for the initial formation of the nuclei of light elements (such as helium and lithium) in the early Universe. It is generally believed that primordial nucleosynthesis began when the age of the Universe was about 3 minutes, and that it continued for about thirty minutes.

recombination- A process in which an electron and an ion combine. The term recombination is also used to refer to the postulated episode in cosmic history in which the baryonic matter of the Universe made the transition from being predominantly plasma to predominantly neutral atoms. Recombination is believed to have occurred when the age of the universe was about 380,000 years.

redshift- The numerical quantity used to measure the shift in wavelength of a spectral line. The shifting to longer wavelengths of the light from remote galaxies; the Doppler shift of light from a receding source.

spectroscopy- The systematic study of spectra and spectral lines. Spectral lines are tremendously important in astronomy, because they provide reliable evidence about the chemical composition of distant objects.

standard candles- Any type of object whose luminosity is directly indicated by its observable properties, thus allowing its distance to be inferred from the difference between its apparent brightness and its true brightness.

supernova- A stellar outburst during which a star suddenly increases its brightness roughly a millionfold.

thermal equilibrium- A state in which there is a high level of interaction between matter and radiation which leads to the radiation having a black-body spectrum with a characteristic temperature that is the same as that of the matter.

Universe- The one known universe.

white dwarf- A low-mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth.

WIMP (Weakly Interacting Massive Particle) - A hypothetical elementary particle that has a relatively high mass and which only interacts by the weak interaction and gravity. A large population of such particles might account for a significant amount of (non-baryonic) dark matter.

Annotated Bibliography / Resources

Cited Works

Adams, David J. et al. An Introduction to Galaxies and Cosmology. Ed. Mark H. Jones and Robert J. A. Lambourne. New York: Cambridge University Press, 2004.

A thorough explanation of the issues of modern cosmology, dark matter and dark energy.

Kirshner, Robert. Extravagant Universe. Princeton: Princeton University Press, 2002.

Detailed explanation of Kirshner's contribution to utilizing 1A supernovae for high z redshifts to determine the Hubble constant. They can be used as standard candles because their peak luminosity can be determined from their light curves.

Freedman, Roger A. and William J. Kaufmann III. Universe. New York: W.H. Freeman and Company, 2005.

Guth, Alan. The Inflationary Universe. New York: Addison-Wesley Publishing Company, 1997.

Historical and conceptual explanation of Guth's role in developing the Inflationary Theory. Inflation is essential for explaining the horizon problem and flatness problem.

Weinberg, Steven. The First Three Minutes. New York: Basic Book, Inc., Publishers, 1977.

An excellent detailed explanation of the early Universe after the big bang.

Reading List

Feynman, Richard and Robert B. Leighton and Matthew Sands. The Feynman Lectures on Physics. Reading, Massachusetts: Addison-Wesley publishing Company, 1965.

Freshman lectures on physics. These include lectures on Quantum Mechanics, relativity and waves.

Feynman, Richard P. QED: The Strange Theory of Light and Matter. New Jersey: Princeton University Press, 1985.

An explanation of quantum electrodynamics, which are essential in the fluctuations in the early Universe that resulted in the formation of galaxies and clusters from gravitational effects.

Greene, Brian. The Elegant Universe. New York: Vintage Books, 2003.

An exploration of string theory, which is the best candidate for a TOE (theory of everything).

Hawking, Stephen. The Universe In a Nutshell. New York: Bantam Books, 2001.

A pictorial and conceptual explanation of cosmology and black holes.

Rees, Martin. Just Six Numbers: The Deep Forces That Shape the Universe. New York: Basic Books, 2000.

Description of the six cosmological constants that define the parameters of the cosmos.

Thorne, Kip S. Black Holes & Time Warps: Einstein's Outrageous Legacy. New York: WW Norton and Company, 1994.

The effect of extreme gravity on relativity and an explanation of black holes. The resulting singularity resulting from extreme gravity of black holes indicates the limitation of relativity and quantum mechanics.

Student Reading List

Weinberg, Steven. The First Three Minutes. New York: Basic Book, Inc., Publishers, 1977.

An excellent detailed explanation of the early Universe after the big bang.

Video Resources

Astronomers. KCET/ LOS ANGELES. 1991.

A seven part series on the innovations and discoveries of modern astronomers.

The Elegant Universe. WGBH/Nova. 2003.

An exploration of the implications of String Theory.

Runaway Universe. NOVA. 2000.

An excellent explanation of the accelerating expansion of the Universe.

Universe by Stephen Hawking. Thirteen/WNet/Uden/David Filkin Enterprises. 1997

A three part series on astronomical issues including the Big Bang and black holes.

http://www.cpepweb.org. The History and Fate of the Universe, "The Universe Adventure"

"The History and Fate of the Universe" CPEP Chart

Acknowledgements

This unit would not have been possible without the help of Dr. Sabatino Sofia, Dr. Richard Holman, and the CPEP (Contemporary Physics Education Project) members: Sam Lightner, Bob Reiland, Ted Zaleskiewicz and Cherie Harper.

http://teachers.yale.edu/curriculum/viewer/initiative_05.04.04_u

Appendix-Content Standards

PENNSYLVANIA SCIENCE STANDARDS

S1. All students explain how scientific principles of chemical, physical, and biological phenomenon have developed and relate them to real-world situations.

S2. All students demonstrate knowledge of basic concepts and principles of physical, chemical, biological and earth sciences.

S5. All students construct and evaluate scientific and technological systems using models to explain or predict results.

S7. All students evaluate advantages, disadvantages and ethical implications associated with the impact of science and technology on current and future life.

S9. All students demonstrate basic computer literacy, including word processing, software applications, and the ability to access the global information infrastructure, using current technology.

PENNSYLVANIA MATH STANDARDS

M1. All students use numbers, number systems, and equivalent forms (including numbers, words, objects and graphics) to represent theoretical and practical situations.

M2. All students compute, measure, and estimate to solve theoretical and practical problems, using appropriate tools, including modern technology such as calculators and computers.

M4. All students formulate and solve problems and communicate the mathematical processes used and the reasons for using them.

M5. All students understand and apply basic concepts of algebra, geometry, probability and statistics to solve theoretical and practical problems.

M6. All students evaluate, infer, and draw appropriate conclusions from charts, tables and graphs, showing the relationships between data and real-world situation.

PENNSYLVANIA COMMUNICATION STANDARDS

C5 All students analyze and make critical judgments about all forms of communication, separating fact from opinion, recognizing propaganda, stereotypes, bias and recognizing inconsistencies and judging the validity of evidence.

C6 All students exchange information orally, including understanding and giving spoken instructions, asking and answering questions appropriately, and promoting effective group communications.

C7 All students listen to and understand complex oral messages and identify the purpose, structure, and use.

C8 All students compose and make oral presentations for each academic area of study that are designed to inform,