Cosmic Times Teachers' Guide

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1919 Cosmic Times

In this first edition of *Cosmic Times*, several concepts are introduced which will be revisited and built upon in future editions. The first concept is the idea of Einstein's General Relativity and its first confirmation. In addition, the idea of the size of the Universe is introduced. In 1919, the Universe was viewed to contain only the stars in the Milky Way. Other galaxies had not yet been resolved into their constituent stars, so it was not apparent that some of the fuzzy nebula were, indeed, outside our own galaxy. The Universe was a much smaller place than it is today, but change was just on the horizon.

The language in the 1919 *Cosmic Times* mimics the style of writing that would have appeared in a real 1919 newspaper. The poster also mimics the layout of newspapers of the time. We have, however, taken some creative license to make it more readable in a classroom setting. Real newspapers of the time would have had 5-7 narrow columns. The size of the text in each column would have gotten smaller and smaller as you read down the column, so the more details you wanted, the harder you would have had to work to read it.

Age of the Universe: Infinite

COSMIC TIMES

1919

Size of the Universe: 300,000 Light Years

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This article discusses the first confirmation of Einstein's Theory of General Relativity. He had introduced the theory several years earlier (1915); however, since General Relativity reduces to Newtonian Gravity except in cases of extreme speeds (i.e. close to the speed of light) or in strong gravity, the tests of General Relativity were somewhat limited.

Sidebar: Why a Total Eclipse?

In day-to-day life, Newtonian gravity is enough to predict how objects will behave. In order to see the effects of General Relativity, extraordinary conditions are needed – either high speeds, close to the speed of light, or strong gravity. In the early 1900s, the most accessible test for General Relativity was to watch the behavior of starlight as it passes very near the Sun.

Mount Wilson Astronomer Estimates Milky Way Ten Times Bigger Than Thought

In 1919, astronomers did not realize that there were galaxies in the Universe besides our own Milky Way. That discovery did not happen until 1924. At the time, they thought that stars and nebulae populated the Universe uniformly. Astronomers had observed nebulae, some of which appeared spiral, but they could not resolve these nebulae into stars. There was a debate going on at the time of this issue of the *Cosmic Times*, as to whether these nebulae were indeed just gas and dust or if they were comprised of stars. The telescopes of the time were not sensitive enough to settle the question.

Expanding or Contracting?

When applied to the real Universe, the equations of General Relativity predict that the Universe cannot be static – it must be either expanding or contracting. While an expanding Universe is an accepted concept today, it was a radical idea in 1919. Certainly they knew that the heavens were not unchanging, but it was largely believed that the Universe, as a whole, was static.

In Their Own Words

This column includes excerpts from various papers that introduce concepts that will be built upon in future issues of the *Cosmic Times*. The quotes may be a little difficult to understand, as they are taken directly from published papers by the listed authors.

Notes on the 1919 Articles

Sun's Gravity Bends Starlight

The primary message of this article is that all theories, even Einstein's, have to undergo testing before they become widely accepted. This test of General Relativity established not only his theory of gravity, but also Einstein's fame.

This article discusses the first confirmation of Einstein's Theory of General Relativity. He had introduced the theory several years earlier (1915); however, since General Relativity reduces to Newtonian Gravity except in cases of extreme speeds (i.e. close to the speed of light) or in strong gravity, the tests of General Relativity were somewhat limited.

The best test accessible to the scientists at the time was to look at starlight passing by a massive object. The closest object with sufficient mass was, of course, the Sun. However, in order to view starlight passing close to the Sun, observations had to take place during a total solar eclipse – otherwise, the light of the Sun drowns out the starlight.

Both Newtonian and Einsteinian gravity predict that the Sun will bend the starlight, but the extent of that bending is different. The test proposed by Eddington would observe how much the gravity of the Sun would cause the starlight to bend.

One possible point of confusion for students is why does Newtonian gravity predict the bending of starlight at all. Light is composed of "photons", and photons are massless. Therefore, since Newtonian gravity depends on the masses of the bodies involved, it is generally assumed that Newtonian gravity would predict that the Sun would not affect light at all.

To help understand this question, here is a brief history of how scientists viewed the possibility of the bending of light:

- Newton suggests the bending of light in his 1704 treatise, *Opticks*.
- Henry Cavendish calculates the bending of light due to Newtonian gravity in 1784, but does not publish the result. The only evidence of his calculation only surfaced in the 1900s.
- Johann von Soldner calculates the bending of light as it passes by a massive object in 1801, taking 25 pages to do it! The calculation uses Newton's theory of light as a stream of corpuscles (which have mass). However, the mass of the corpuscle (photon) drops out of the calculation, and the angle only depends on the mass of the object and the closest approach to that object.

- The angle of deflection turns out to be

$$a \sim \frac{2m}{r}$$

  where
  - $m = GM/c^2$ (G is the gravitational constant, c is the speed of light)
  - M is the mass of the sun
  - r is the closest approach distance of the photon to the sun.
- This solution is an approximation, because it's the first term in a series. All of the other terms in the series are much smaller. Von Soldner's calculation is very close to Cavendish's, and to a first-order approximation, they are the same.
- In early 1800s, Thomas Young's double-slit experiment showed that light must behave as a wave, rather than a particle. At this point, it was realized that light must be massless. Clearly, a massless particle, in Newtonian gravity, would experience no deflection due to gravity.
- Albert Einstein, in 1911, published a paper called "On the Influence of Gravitation on the Propagation of Light" (published in German), which calculated the effect of gravity on light using the equivalence principle, and with did not depend on light having mass. His answer in this paper was identical to von Soldner's approximation. However, this calculation did not include all of the equations of General Relativity.
- In 1915, Einstein finished his theory of general relativity, and found that the prediction for the deflection of starlight due to the Sun would be twice the prediction he published in 1911.
- In 1919, Arthur Eddington led one expedition to observe the total solar eclipse, and found that the light was bent by the amount predicted by General Relativity.

Based on this timeline, prior to the 1919 eclipse, astronomers could have expected one of three results: no deflection at all, assuming a massless photon and Newtonian gravity; some deflection, assuming massless photon that was still accelerated in a Newtonian gravity well; or full deflection, assuming a massless photon in General Relativity.

It's interesting to note that there is some question as to whether or not the equipment and results of the 1919 eclipse expeditions really had the sensitivity to detect the starlight deflections that Eddington claimed. It may be that the researchers injected some of their expectations into the reported results. However, many subsequent (and more robust) observations have been performed, all of which confirm the reported deflection of starlight as that predicted by General Relativity.

Scientists continue, even today, to put General Relativity to the test, and all of those tests have added further evidence in favor of General Relativity.

Sidebar: Why a Total Eclipse?

The primary message of this article is that nature offers us opportunities to test our theories, and scientists take advantage of those opportunities. The circumstances of the solar eclipse were right for scientists to test Einstein's theory of General Relativity.

In day-to-day life, Newtonian gravity is enough to predict how objects will behave. In order to see the effects of General Relativity, extraordinary conditions are needed – either high speeds, close to the speed of light, or strong gravity. In the early 1900s, the most accessible test for General Relativity was to watch the behavior of starlight as it passes very near the Sun.

According to General Relativity, light passing near any object with mass will be deflected, but only the Sun has enough mass for that deflection to be detectable from Earth, using the technology available in 1919. However, in order to observe starlight bending near the Sun, astronomers had to wait for a total solar eclipse. The best way to visualize why is to consider what the daytime sky looks like. Clearly there are stars still shining over the entire sky, but none are visible during the daytime. This is because the light from the Sun is scattered by our atmosphere, giving us our familiar blue skies. For the same reason, astronomers cannot observe starlight near the Sun on just any day – the Sun is too bright, and the blue sky obscures any attempted observations.

Therefore, to observe stars near the Sun, astronomers needed to wait for a total solar eclipse. Only during a total solar eclipse is the light of the Sun blocked out, making stars visible in the daytime.

However, observations during the eclipse alone, would not tell astronomers if the starlight had been bent. They also needed images of those same exact stars without the Sun in the way. Then, by comparing the two images – one taken without the Sun between the stars and the Earth, and one taken during the solar eclipse – they could determine if the Sun had any effect on the starlight. In addition, if the starlight had been bent by the Sun, they could determine by how much.

Mount Wilson Astronomer Estimates Milky Way Ten Times Bigger Than Thought

The primary message of this article is that at the beginning of the 1900s, astronomers believed that the Milky Way galaxy comprised the entire Universe. A secondary message is that astronomers must use indirect methods to determine distances in the Universe.

In 1919, astronomers did not realize that there were galaxies in the Universe besides our own Milky Way. That discovery did not happen until 1924. At the time, they thought that stars and nebulae populated the Universe uniformly. Astronomers had observed nebulae, some of which appeared spiral, but they could not resolve these nebulae into stars. There was a debate going on at the time of this issue of the Cosmic Times, as to whether these nebulae were indeed just gas and dust or if they were comprised of stars. The telescopes of the time were not sensitive enough to settle the question.

We now know that some of the nebulae were, indeed, separate galaxies and there are great distances between the Milky Way and these distant "nebula". However, some of the nebulae are bound clouds of gas and dust residing in our Milky Way. This question, and its resolution, will be discussed further in the 1929 issue of the Cosmic Times.

This article also contains the first mention in the Cosmic Times of Henrietta Leavitt and Cepheid Stars. These stars become more important in the 1929 and 1955 issues of the Cosmic Times. The 1929 issue discusses Leavitt's observations and their importance in more detail. Cepheid stars are variable stars that are seen to brighten and dim with a regular period. Leavitt saw that the period of the variation was related to the average brightness of these stars. The stars with the shortest period were dimmer and the longest period stars were brighter. Leavitt was observing stars in the Small Magellanic Cloud, so they could all be considered to be at the same distance. This meant that they could be used as distance indicators, if only a few Cepheids could be found with a known distance. Shapely was attempting to calibrate this Cepheid period-luminosity distance scale.

Expanding or Contracting?

The primary message of this article is that as he originally developed it, Einstein's theory of General Relativity requires that the Universe be either expanding or contracting. Because at the time there was no evidence for such a Universe, Einstein added a correction factor to keep the Universe static.

When applied to the real Universe, the equations of General Relativity predict that the Universe cannot be static – it must be either expanding or contracting. While an expanding Universe is an accepted concept today, it was a radical idea in 1919. Certainly they knew that the heavens were not unchanging, but it was largely believed that the Universe, as a whole, was static.

The cosmological constant that Einstein added to the questions of General Relativity did not affect the results of the 1919 eclipse. However, Hubble later discovers that the Universe is, indeed, expanding (as will be discussed in the 1929 issue of the Cosmic Times). George Gamow, in is autobiography, *My World Line*, says, "Much later, when I was discussing cosmological problems with Einstein, he remarked that the introduction of the cosmological term was the biggest blunder of his life."

In Their Own Words

The primary message of this column is that it is sometimes enlightening to read a description of the discovery by the scientist who made it.

This column includes excerpts from various papers that introduce concepts that will build upon in future issues of the Cosmic Times. The quotes may be a little difficult to understand, as they are taken directly from published papers by the listed authors. Here is a little more on these excerpts and why we have chosen to include them:

- "Periods of 25 Variable Stars in the Small Magellanic Cloud" – Miss Henrietta Leavitt

  Cepheid variables are mentioned briefly in the article titled "Mount Wilson Astronomer Estimates Milky Way Ten Times Bigger Than Thought". Their true significance will be realized in the 1929 issue of the Cosmic Times. Leavitt discovered that the Cepheid variables she looked at in the Small Magellanic Cloud (a companion galaxy to our own) had a remarkable and predictable relationship between their period (the time it took to cycle once from bright to dim back to bright) and their luminosity. This might not be remarkable, except that since they were all part of the Small Magellanic Cloud, they could be considered to be at approximately the same distance. This, in turn, meant that the relationship was intrinsic to the stars and not a trick of the eye. See the 1929 and 1955 issues for more on this relationship and its significance.

- "Spectroscopic Observations of Spiral Nebulae" – V. M. Slipher

  Vesto Slipher discovered, in 1912, that Andromeda, a spiral nebulae (which we now know is another galaxy) had a redshift, meaning that it had a velocity with respect to the Earth. He continued to measure the spectra of other spiral nebulae, and found that they had a net positive velocity. In other words, they had a net velocity *away* from the Earth.

- "The Relation of the System of Stars to the Spiral Nebulae" – G. F. Paddock

  As mentioned above, astronomers did not know that the spiral nebulae were galaxies separate from our how; however, some astronomers had speculated as much, but the evidence was scant. This research suggests another small piece of evidence in favor of the spiral nebulae as entities outside our galaxy. Slipher had found that the spiral nebulae had an average radial velocity of +400 km/sec. However, no other type of object in our galaxy had a radial velocity of over +50 km/sec. This was a huge discrepancy.

1929 Cosmic Times

This poster is the second edition of the *Cosmic Times*, and the articles in this edition build on the concepts introduced in the 1919 edition. The headline story is that Edwin Hubble has discovered that the Universe is expanding. The idea of an expanding Universe is contrary to Einstein's assumption of a static Universe, and while Einstein was not convinced of the veracity of Hubble's results, the astronomical community generally accepted them. This discovery was built on a second important discovery that the Milky Way is one of many galaxies in the Universe. This settled a debate among astronomers, which Harlow Shapley and Heber Curtis had expounded upon in a formal debate in 1920. This edition also contains brief biographies of Edwin Hubble and his assistant Milton Humason.

The language in the 1929 newspaper mimics the style of writing that would have appeared in a real 1929 newspaper. Like 1919, the language and sentence structure of this edition are more difficult than modern newspapers. The poster mimics the newspapers of the time, however, we have taken some creative license to make it more readable in a classroom setting. Real newspapers of the time would have had 5-7 narrow columns of small type.

Age of the Universe: *2 Billion Years*

COSMIC TIMES

1929

Size of the Universe: *140 Million Light Years*

Andromeda Nebula Lies Outside Milky Way Galaxy

Spiral Nebulae are indeed "Island Universes"

Universe is Expanding

"Red Shift" is Proof of Einstein's General Theory

"Great Debate" Resolved

Classifying Nebulae

The Minds atop Mount Wilson

In Their Own Words

Summary of the Articles

Andromeda Nebula Lies Outside Milky Way Galaxy

Up until the early 1920's, astronomers did not have definitive proof that galaxies existed outside our Milky Way Galaxy. It was through the use of Cepheid variable stars and the 100-inch telescope at Mt. Wilson that Edwin Hubble determined the distance to Andromeda, and found it to be outside our own Galaxy.

Universe is Expanding

This article describes Edwin Hubble's discovery of that the universe is expanding. Hubble put together his distances to the spiral nebulae with the redshifts measured in their spectra. The linear relationship between these two quantities showed that the Universe is expanding.

"Great Debate" Resolved

Hubble's measurement of the distance to the Andromeda Nebula settled a debate that had long raged among astronomers. This article reviews both sides of this issue that were brought to light in a debate staged between Harlow Shapley and Heber Curtis in April 1920.

The Minds atop Mount Wilson

The story of science is as much about the scientists involved as it is about the science itself. These two brief biographies highlight the different lives of two of the astronomers who shaped our understanding of the Universe in the early 20th century.

Classifying Nebulae

The first step to understanding many different phenomena can often be to classify them. To this end, Hubble looked at a large sample of galaxy images and classified them according to their features. The general classifications he used were: spiral, elliptical and irregular.

In Their Own Words

This quote from Edwin Hubble is from an article in the Fresno Bee, which appeared Oct 23, 1927, and offers his own perspective on his discoveries.

Notes on the 1929 Articles

Andromeda Nebula Lies Outside Milky Way Galaxy

The primary message of this article is that until 1924, astronomers did not know that the Milky Way Galaxy was just one of many galaxies in our Universe. A secondary message is that determining distances to the stars in other galaxies was only possible due to improvements in technology and due to the discovery, by Henrietta Leavitt, of the period-luminosity relationship of Cepheid variable stars.

During the time of the 1919 Cosmic Times, astronomers did not have definitive proof that galaxies existed outside our Milky Way Galaxy. Observers had seen fuzzy patches in the sky, but they could not resolve them into anything more than fuzzy patches. Without further evidence, astronomers could only call these regions "nebulae", which was generally associated with a cloud of gas and dust in space. The notes on the article titled *"Great Debate" Resolved* talk a little more about these nebulae and what astronomers thought they were. Here we'll talk more about how Hubble revealed the true nature of some of these nebulae.

Standard Candles

Since astronomers cannot simply pull out giant measuring sticks to determine distances to objects in the Universe, "standard candles" have become a holy grail of sorts for studying the Universe. A standard candle is any object that has a known brightness. With a known brightness, astronomers can then infer a distance based on the observed brightness of the object and the $1/r^2$ law.

Cepheid variables

In the early 1900s, Harvard astronomers employed women as “computers”. They took on tedious tasks such as determining the brightness of stars on photographic plates and searching photographic plates for variable stars.

Henrietta Leavitt was tasked with searching for variable stars in photographic plates taken between 1893 and 1906 at Harvard College’s observatory in Peru. In 1908 she published a catalog of over 1777 variable stars. For 16 of these stars, she was able to measure a period for their variability, and she noticed that the brighter stars of this sample had longer periods.

By 1912, Leavitt had determined the period for a total of 25 variable stars. She saw that the relationship she had observed in her 1908 catalog held up with these 25 stars. In fact, since all of the stars were in the Small Magellanic Cloud, they could be considered to all be at nearly the same distance. Given that, the relationship between their period and luminosity was intrinsic to the stars, and not just a trick of viewing stars at different distances.

These stars showed a similarity to another known variable star called Delta Cepheid (the fourth brightest star in the constellation of Cepheus), so they are collectively called Cepheid variables.

The one thing that Leavitt was missing was a distance to these Cepheid variables in her sample. She had a period-luminosity relationship, but no "zero point" for that relationship. It needed to be calibrated against something with a known distance.

Calibrating the Cepheid scale

Ejnar Hertzsprung was the first person to try and calibrate the period-luminosity scale for Cepheid variables. Using his calibration, he came up with a distance to the Small Magellanic Cloud of 30,000 light years (actually, the published value was 3,000 light years, but is believed to be a typo which Hertzsprung either did not catch or did not correct for some reason).

The next attempt to calibrate the Cepheid scale came with Harlow Shapley in 1918. Shapley included "Cepheids" from globular clusters in his calibration of the period-luminosity relationship, which will become important in the next issue of the Cosmic Times. It was this calibration of the relationship that Hubble used when he observed Cepheid variables in the Andromeda Nebula.

Observing Andromeda

In 1924, Hubble was able to resolve the spiral arms of the Andromeda Nebula into stars. Some of the stars that Hubble resolved were Cepheid variables, for which Hubble was able to determine periods. Armed with these periods and the calibrated period-luminosity relationship from Shapely, Hubble was able to estimate the distance to Andromeda, and found that it was 860,000 light years away – further than the furthest measured stars. At the time, the Milky Way was estimated to be about 300,000 light years, which we now know to be a huge overestimate, but even with such an overestimate of the Milky Way's size, Andromeda was far beyond the boundary.

Interestingly, even though Andromeda is generally thought to be the first definitive observation of a star system far outside the Milky Way, Hubble actually published results on NGC 6822 first. NGC 6822 is an irregular galaxy that Hubble estimated to be about 700,000 light years away, also very well outside Shapley's estimated size of the Milky Way. It is thought that this result got very little attention because Hubble had already published preliminary results for the spiral nebulae, so the astronomical community generally agreed that there were other galaxies in the Universe.

Other resources

The following web pages have more detailed information on the women computers and the Cepheid distance scale:

- The Cepheid Distance Scale: A History: http://www.institute-of-brilliant-failures.com/index.htm
- The Harvard Computers: From Pickering's Harem to Astronomy's Stars: http://www.womanastronomer.com/harvard_computers.htm
- Pickering's Harem: http://cfa-www.harvard.edu/~jshaw/pick.html

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Universe is Expanding

The primary message of this article is that the Universe is expanding, as shown by a linear relationship between the distance of a galaxy and the velocity at which is receding discovered by Edwin Hubble. A secondary message is that the cosmological constant, which Einstein added to his equations of General Relativity to account for a static Universe, may not be necessary, showing that even Einstein can be wrong occasionally.

This article introduces the idea of an expanding Universe. When we left the Cosmic Times in 1919, Albert Einstein had added the Cosmological Constant to his equations of General Relativity to prevent the Universe from expanding. The idea of an expanding Universe was against his philosophical viewpoint, and adding this Cosmological Constant to his equations violated nothing.

Redshift

One key concept to understanding Hubble's results is understanding the idea of redshift. Often this idea is introduced alongside the Doppler effect for sound because students are much more familiar with this – it is what causes the pitch of a siren to appear to drop as it passes by a listener. For light, when a source is emitting light while it is moving away from us, the wavelength of the light as we see it will be shifted toward the red, or toward longer wavelengths.

When astronomers look at light from distant galaxies, they can identify signatures of certain elements in the form of "spectral lines". By looking at how much these signatures are offset from their "at rest" wavelengths, astronomers can tell how fast the object that emitted them was moving. If the object is moving away from the observer, the light is shifted toward the red, or toward longer wavelengths, and this is often called "redshift". If the object is moving toward the observer, the light is shifted toward the blue, which is often called "blueshift".

In 1917, an astronomer named Vesto Slipher discovered that the light from several "nebulae" (later found to be galaxies) was "redshifted". It is commonly thought that Hubble discovered the redshift of galaxies, but this is not true. Hubble found the relationship between redshift and distance that is discussed in this Cosmic Times article, but he was not the first to see the redshift itself.

Distance

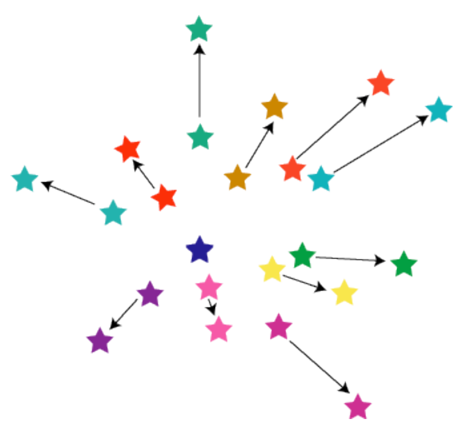
The thing that Hubble added to the picture was determining both the distance and redshift of galaxies. The distance determination was made using a standard candle, called Cepheid variables. The importance of these stars and how they are used in distance determinations are discussed in more detail in the notes for the *Andromeda Nebula Lies Outside Milky Way Galaxy* article.

Expanding Universe!

When Hubble plotted up the distance of the galaxies in his sample versus the redshift of those galaxies, he found that there was a trend – the further a galaxy was, the faster it was moving away. This is exactly what would be expected if the Universe was expanding.

This is one concept that your students might struggle with – why does an expanding Universe imply that the further a galaxy is from us, the fast it would be moving away from us. To help illustrate this, imagine that this picture shows several galaxies in the Universe as they were in the past:

Let's say that our galaxy is the blue star near the middle of the picture. Then let the Universe expand for a while and look at what's happened:



We are the blue galaxy, so we haven't moved. However, all of the other galaxies appear to have moved *away from us*. And, if you examine the size of the arrows from the original galaxy positions to the new ones, it is clear that the further a galaxy was away from us, the faster it appears to have moved, *in the same amount of time*. That means that the further away the galaxy was, the faster it appears to move away from us as the Universe expands.

One misconception that your students may have is that because all of the galaxies appear to be moving away from us that mean that we must be the center of the Universe. This is not true. Any galaxy would actually perceive the same thing. Let's say that instead of being the blue galaxy in that image above that we are the yellow galaxy. The picture we would see after the expansion would then be this:

The yellow galaxy also sees all of the other galaxies moving away from it, and the further the galaxy started from the yellow galaxy, the more it moved.

The fact that we see the galaxies all moving away from us is indicative of the expanding Universe, but *not* that we are the center of the Universe. In fact, the expansion happens *everywhere*.

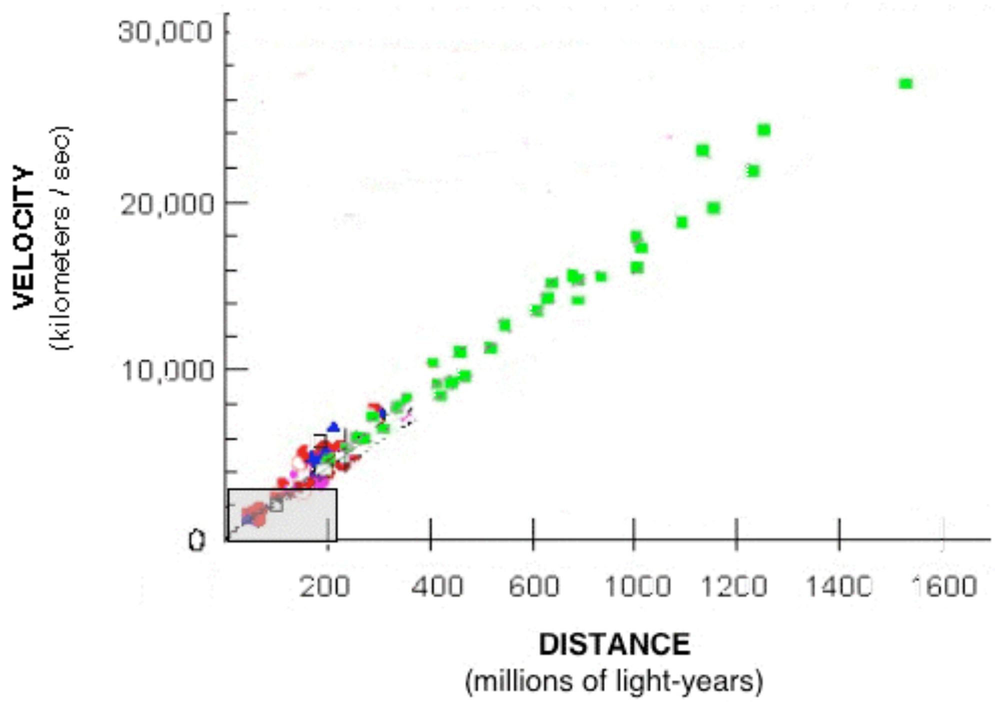
Einstein still didn't believe

If you read the 1919 edition of the Cosmic Times, you know that Einstein did not like the idea of an expanding Universe. In fact, even though his equations of General Relatively suggested an expanding Universe, Einstein added his "Cosmological Constant" to those equations to prevent expansion.

As of the publication date of this edition of the Cosmic Times, Einstein is still not convinced of Hubble's results. However, in 1930, Einstein travels to Mount Wilson to talk with Hubble and see his work first-hand. After meeting with Hubble, Einstein does become convinced that the Universe is, indeed, expanding.

Hubble's work holds up

Hubble's results have proved to hold over much greater distances than Hubble himself could probe. As we've developed larger and more sensitive telescopes and as we've determined more ways to pinpoint distances in further and further objects, we have continued to find that the further a galaxy is from us, the faster it is moving away, as this image shows for just a sample of the currently available data:



The relationship between a galaxy's distance and its speed holds far beyond what Hubble originally measured. This diagram uses modern measurements to show the same relationship. The gray box shows the region that Hubble probed. Data from the Hubble Space Telescope Key project, courtesy Prof. John Huchra.

Sidebar: "Great Debate" Resolved

The primary message of this article is that theories in astronomy, as any other science, are based on evidence. When there are two leading theories for the same phenomenon, astronomers must look objectively at the available evidence for both theories to determine which is more plausible. A secondary message is that science knowledge changes over time when new evidence comes to light.

Prior to Hubble's measurement of the distance to the Andromeda Nebula, the nature of "spiral nebulae" was not definitively known. By 1920, there was a growing number of scientists who believed that the spiral nebulae were actually systems of stars outside our own galaxy, which could not be resolved because of their great distances. However, other scientists still believed that these spiral nebulae were clouds of gas within the Milky Way.

To shed light on this debate in the astronomical community, two astronomers on either side of this issue – Harlow Shapley and Heber Curtis – held a debate on April 26, 1920 at the Smithsonian Museum of Natural History.

Shapley argued that the whole of the Universe was contained in the Milky Way, which was about 300,000 light years in size. The spiral nebulae were clouds of gas held within the Milky Way galaxy. One theory about the spiral nebulae was that they were solar systems in the process of forming. In addition, astronomer Adriaan van Maanen claimed to have observed rotation in the spiral nebulae. Shapley argued that the speeds for such rotation would have to be too high if the nebulae were outside the Milky Way. (Note: this claim of observed rotation in the spiral nebulae is certainly wrong, though at the time it was an accepted observation.)

Curtis argued that the Sun was part of a smaller system of stars measuring about 30,000 light years across. He believed that the spiral nebulae were *island universes* – systems of stars external to our own Milky Way. He demonstrated that the spectrum from these spiral nebulae were indistinguishable from the spectrum from the Milky Way, suggesting that they are similar in nature.

It was generally accepted that Shapley had won the debate with more observations supporting his claims. However, we now know that Curtis was correct on the nature of spiral nebulae. As technologies and observations improve, our understanding of the Universe around us also improves.

Other resources

The following web pages have more information on "The Great Debate":

- The Shapley-Curtis Debate - What is our Place in the Universe?: http://astronomy.nmsu.edu/nicole/teaching/ASTR110/lectures/lecture27/slide01.html
- The Scale of the Universe: http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate20.html

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The Minds atop Mount Wilson

The primary message of this article is that the story of science is as much about the scientists involved as it is about the science itself. The stories of Hubble and Humason show that there are many different roads to a science career.

The story of science is as much about the scientists involved as it is about the science itself. These two brief biographies highlight the unusual lives of two of the astronomers who helped to shape our understanding of the Universe in the early 20th century.

Edwin Hubble was a PhD astronomer with a wide range of interests from Roman law to water polo to astronomy. Milton Humason, on the other hand, dropped out of school when he was in eighth grade. Yet, both of these men have their names connected to one of the seminal discoveries about our Universe – the Universe is expanding.

There are lots of interesting characters in science, from the well known to the unknown, from Einstein to the women computers in "Pickering's Harem".

Sidebar: Classifying Nebulae

The primary message of this article is that often the first step to understanding many different phenomena can be to classify them.

The first step to understanding many different phenomena can often be to classify them. To this end, Hubble looked at a large sample of galaxy images and classified them according to their features. The general classifications he used were: spiral, elliptical and irregular. However, each main classification also had sub-classes based on other similarities.

Hubble's classification is often depicted in a diagram called the "Hubble Tuning Fork". Hubble proposed that this classification scheme may have been an evolutionary sequence for galaxies – that galaxies may evolve from one type to another throughout their lifetimes. Today, this classification scheme is viewed as overly simplistic and the evolution of galaxies is far more complex. However, Hubble's classifications were the first step in understanding galaxy formation and structure, and the classifications are often still used to describe galaxies.

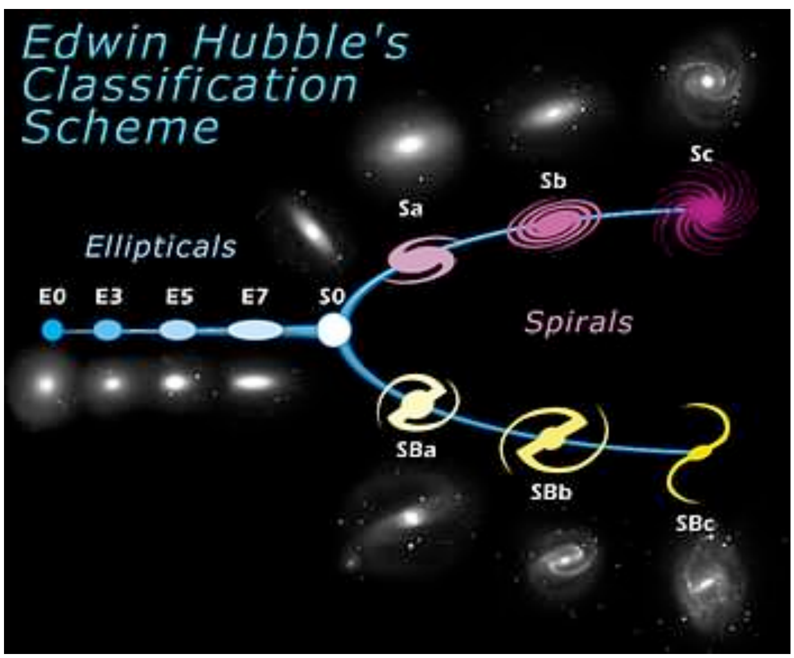

Illustration of Hubble's classification scheme, often called the Hubble Tuning Fork.
More information available here:
http://hubblesite.org/newscenter/archive/releases/1999/34/image/o/.
Image credit: NASA

Spiral Galaxies

Perhaps the best-known type of galaxy is spiral galaxies. These include those where the spiral arms are clearly visible, such as M 31 pictured below:

This is a composite image of the "grand-design" spiral galaxy M 81.
More information available here:
http://hubblesite.org/newscenter/archive/releases/2007/19/.
Image credit: Hubble data: NASA, ESA, and A. Zezas (Harvard-Smithsonian Center for Astrophysics); GALEX data: NASA, JPL-Caltech, GALEX Team, J. Huchra et al. (Harvard-Smithsonian Center for Astrophysics); Spitzer data: NASA/JPL/Caltech/Harvard-Smithsonian Center for Astrophysics.

However, spirals encompass a larger range than just those for which we can see the spiral arms. One way to think of a spiral type galaxy is a galaxy with a central bulge and a disk. The spiral arms are contained within the disk of the galaxy. If we observe such a galaxy edge-on, we don't see the spiral arms. Here is an example of an edge-on spiral galaxy:

The Sombrero Galaxy is a spiral galaxy where we are observing the disk edge-on. The dark line through the galaxy is actually the disk. More information available here: http://hubblesite.org/newscenter/archive/releases/2003/28/. *Image Credit: NASA and The Hubble Heritage Team (STScI/AURA).*

In addition, about half of the spiral galaxies have a bar-like structure in the central bulge of the galaxy.

NGC 1300 is a classic example of a spiral galaxy with a "bar" in the central bulge. More information available here: http://hubblesite.org/newscenter/archive/releases/2005/01/. *Image Credit: Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)*

Hubble sub-classified spiral galaxies based on a combination of how tightly the spiral arms appeared to be wrapped around the bulge and the relative size of the bulge compared to the disk. Type Sa galaxies (spiral, sub-type a) have large bulges and are tightly wrapped, while type Sc galaxies have small bulges and loosely wrapped arms. The barred spiral galaxies are similarly sub-classified.

Ellipticals

Elliptical galaxies are those that appear, well, elliptical. The shape of an elliptical galaxy can appear to be anywhere from perfectly round to cigar shaped. Hubble sub-classified elliptical galaxies based on their "ellipticity," which is defined as 10 times the eccentricity. Or:

$$ellipticity = 10 \times \frac{major\ axis - minor\ axis}{major\ axis}$$


Two types of elliptical galaxies. The image on the left is M 87, an elliptical that appears nearly circular and is classified as an E0 galaxy in the Hubble classification scheme. The image on the right is M 101, an elliptical that appears more elongated and is classified as an E5 galaxy in the Hubble classification scheme.
Image credits: Both images are from Jarrett et al., Astronomical Journal 125, 525 (2003).

It should be noted that the apparent shape of an elliptical galaxy in the sky is more dependent on our line-of-sight to that galaxy than any intrinsic properties of the galaxy itself. If a galaxy were intrinsically cigar shaped, and we viewed it edge-on, it would appear circular.

Irregular Galaxies

Hubble found that not all galaxies fell neatly into the "spiral" or "elliptical" categories. They don't show obvious spiral structure, nor do they show a central bulge, so they are not spiral galaxies. In addition, they lack symmetry, so are not elliptical galaxies. These hard to classify galaxies were lumped into a separate category – irregular galaxies.

NGC 1427A is an example of an irregular galaxy. It does not have any hint of spiral structure, a bulge or symmetry. In fact, this image, from the Hubble Space Telescope, shows that this galaxy is falling headlong into the Fornax galaxy cluster, and will not survive long as a recognizable galaxy. More information available here: http://hubblesite.org/newscenter/archive/releases/galaxy/irregular/2005/09/image/a/. *Image credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA).*

Additional Resources

- Galaxy Classification Activity: http://www.astro.lsa.umich.edu/undergrad/Labs/GalClass/GalClassShort.html
- Galaxy Classification: http://www.astr.ua.edu/keel/galaxies/classify.html

1955 Cosmic Times

This poster is the third edition of the *Cosmic Times*, dated to coincide with Einstein's passing. Much has happened since 1929, with developments in previous stories and completely new discoveries. Astronomers discovered there were two populations of Cepheid variables, leading to a re-calibration in the use of the Cepheids as standard candles and a doubling of the size of the Universe. A debate raged between whether the Big Bang or the Steady State theory correctly described the origin and nature of the Universe. Also, astronomers not only recognized the distinction between novae and supernovae, but there different types of supernovae. Finally, astronomers get their first "glimpse" of objects emitting in a region of the electromagnetic spectrum other than optical light.

The language in the 1955 newspaper mimics the style of writing that would have appeared in a newspaper at that time. While this is getting closer to familiar language and sentence structure of modern newspapers, it may still be a bit difficult for students to read. The poster also shows a layout that mimics the papers of the time. However, we have taken some creative license to make it more readable in a classroom setting.

Age of the Universe: 6 Billion Years

COSMIC TIMES

1955

Size of the Universe: 4-8 Billion Light Years

'Yardsticks' in Neighbor Galaxy Double Universe's Size

Origin of Everything: Hot Bang or Ageless Universe?

Death of a Genius

Hoyle Scoffs at "Big Bang" Universe Theory

It's a Star! It's a Nova! It's Super-Nova!

Radio 'Ear' on the Universe Being Built

Summary of the Articles

'Yardsticks' in Neighbor Galaxy Double Universe's Size

This article describes how astronomers discovered a miscalibration in the Cepheid distance scale. This arose from the discovery of the existence of two populations of Cepheids with two different period-luminosity relationships. When this miscalibration was corrected, the size of the Universe doubled overnight.

Origin of Everything

As of 1955, there were two equally likely theories for the origin of the Universe – the steady-state theory and the evolutionary Universe theory (later known as Big Bang theory). Although predictions were made by both theories, at the time, the observational evidence was insufficient to decide between them.

Hoyle Scoffs at "Big Bang" Universe Theory

Ironically, the biggest detractor of the evolutionary Universe theory ended up coining the phrase by which it is became to be known – the Big Bang. Hence, everyone seems to contribute to the progress of science!

Death of a Genius: Albert Einstein 1879 - 1955

This article shows how Einstein's death was felt the whole world over.

It's a Star! It's a Nova! It's Super-nova

This article begins the important story of supernovae by picking up with the discovery made that these stellar explosions can be classified into two types: novae and super-novae. Further, these super-novae can be split up into two different kinds – Type I which show no signs of hydrogen in their spectrum and Type II which do show hydrogen.

Radio 'Ear' on the Universe Being Built

By the mid-1950s technologies inherited from World War II allowed astronomers to look at radio waves emitted by objects in the Solar System and beyond. Hence astronomy was no longer confined to the realm of optical observations.

Notes on the 1955 Articles

"Yardsticks" in Neighbor Galaxy Double Universe's Size

The primary message of this article is that a miscalibration of the Cepheid distance scale, stemming from the existence of two populations of Cepheids with two different period-luminosity relationships, resulted in an underestimation of distances in the Universe. When this miscalibration was corrected, the size of the Universe doubled overnight.

Before we discuss the problem with the Cepheid variable distance scale that was discovered in the 1940s, researchers had already seen evidence of a problem with the distance scale. Astronomers are always looking for different types of "standard candles" – objects of known brightness for which a distance can then be calculated using the observed brightness. One such object that astronomers tried to use in the early days of extra-galactic observations was the globular clusters of a galaxy. Globular clusters are a type of star cluster that tend to lie in the halo of a galaxy. In 1931, Hubble compared the brightest globular cluster in our galaxy to the brightest one in Andromeda, and found that the one in Andromeda was intrinsically much dimmer than the one in ours.

Later, he compared the globular clusters in our galaxy to those in Messier 33 (M 33), another spiral galaxy that is further than Andromeda. He found that the globular clusters in M 33 were still fainter than those in Andromeda, based on the distances he had earlier found. Hubble recognized that it was possible for globular clusters to vary from galaxy to galaxy, but it seemed unlikely that they would preferentially get dimmer the further they were from our galaxy. This pointed to a problem with the distance scale, but Hubble did not have an explanation for the origin of the problem.

When Baade discovered that there were, in fact, two different populations of stars, it did not take researchers long to connect the dots between the discrepancy that Hubble was seeing in the globular clusters of distant galaxies and the Cepheid distance scale. Baade's images of Andromeda and Andromeda's two companion galaxies, Messier 32 and NGC 205, showed that there were two populations of stars, which he called "Type I" and "Type II" – Type I stars were bluer and brighter whereas the Type II were redder and fainter. He recognized that the globular clusters were rife with Type II stars, whereas the disk of the galaxies tended to have both Type I and II stars.

As it happens, the Large Magellanic Cloud, the location of the Cepheid variables that Henrietta Leavitt observed, is populated with Type I stars. However, when Shapley calibrated the Cepheid period-luminosity relationship, he was using observations of Cepheid variables in globular clusters – where Type II stars reign. The Cepheid variables that Hubble observed in the Andromeda nebula were Type I, but he unknowingly used Shapley's calibration that were calibrated for Type IIs. The problem lies in the fact that there are two different calibrations of the period-luminosity for the two different populations of Cepheid variables.

The re-calibration of the Cepheid scale for the Type I Cepheids showed that the distances to the Type I Cepheids was off by about a factor of 2. In other words, astronomers were finding distances that were half as far as they should have been. Andromeda suddenly went from being a "mere" 800,000 light-years away to being about 1,800,000 light-years away. With this new distance, the brightest globular clusters in Andromeda were now about the same intrinsic brightness as those found in our own galaxy.

To bring this discussion into a more modern note, astronomers have studied the differences between Type I and Type II stars in more detail. Typically, these are now referred to as Population I and Population II instead of Type I and Type II. Astronomers have found that one difference between Population I and II stars it the amount of heavy elements in the stars. Population II stars show very little heavy elements where Population I have more. It is thought that Population II stars are, therefore, older stars, formed earlier in our Universe's lifetime. This is because the Universe started as mainly hydrogen and helium. This is still true, but the abundances of the elements heaver that hydrogen and helium have slowly increased as stars fuse hydrogen into heavier and heavier elements. Population I stars were likely formed out of the remains of earlier, Population II stars.

Other resources

The following web page has additional information:

- Characteristics of Galaxies: http://imagine.gsfc.nasa.gov/docs/teachers/galaxies/imagine/characteristics.html

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Origin of Everything: Hot Bang or Ageless Universe?

The primary message of this article is that as of 1955, there were two equally probable theories for the origin of the Universe – the steady-state theory and the evolutionary Universe theory (later known as Big Bang theory). At the time, the observational evidence was insufficient to decide between the two theories.

In the 1950s there were two theories regarding the nature of the universe: the Steady State and the Big Bang. At that time, there was not sufficient observational evidence to clearly favor or disprove either of them.

The British astronomer Fred Hoyle was the champion of the Steady State theory. He, Tommy Gold, and Hermann Bondi developed this theory after seeing the movie *Dead of Night*, which ends the way it begins. Hoyle thought that the universe could be unchanging but dynamic. So as the universe expands, matter is created to fill the space. It would require only 1 hydrogen atom per cubic meter every 300,000 years (comparable to "a few hundred atoms per year per galaxy"). Hoyle developed the "Perfect Cosmological Principle", which states that the universe is the same at any place and at any time.

The "Evolutionary" model for the universe (a.k.a. "Big Bang") was built on theoretical work in the 1920s and 1930s. In the 1940s, George Gamow was trying to solve the problem of the origin of the chemical elements. He determined that most elements could not form in the early universe - the right conditions of temperature and density would not last long enough. With Alpher, he showed that hydrogen and helium would form (and in the right proportions), but nothing heavier. (Later astronomers figured out how heavier elements could be made in the dense hot core of stars.). In doing this, Gamow developed many of the fundamental ideas about the early "evolutionary" universe. He developed the relation between temperature and mass density, recognized that atoms (not just nuclei) would form only after the universe had cooled sufficiently, and developed the theory of early galaxy formation. In 1949 Alpher and Herman redid these calculations, and in doing so predicted a "relic primordial radiation" with a temperature of about 5 K. They didn't think this would be detectable, and indeed instruments at the time could only detect a background radiation of only 20 K.

Both theories made predictions. Some are described in the table below

Issue	Steady State	Big Bang
Density of the Universe	The density is constant	The density changes, but do known physical laws apply at early time of very high density?
Age of the Universe	Ageless	In 1955, Big Bang gave an age less than known age of solar system
Rate of Expansion	Expansion is constant	Expansion should slow
Ages of Galaxies	Old and young Galaxies should be mixed in space	Galaxies age with time
Background Microwave Radiation	There should be none	It should exist, with a temperature of about 5 K

In the 1950s, the evidence was mixed. A number of observations seemed to favor the Big Bang, but it was not definitive. The fact that the age derived for the Big Bang was less than the known age of the Solar System was a major problem. However, there was no conclusive evidence for one theory or the other.

Interestingly, the presence of the Steady State as a competing theory provided the impetus to make the observations to test the theories.

Side Notes:

- Interestingly, one of Thomas Bondi's major contributions to astronomy came with the discovery of pulsars in 1967. He was the first to explain them as rotating neutron stars, which turned out to be correct.
- As a bit of joke, Gamow asked Hans Bethe if his name could be included on the paper Gamow was writing with Alpher. Bethe, who had not participated at all in the research, agreed. So the initial paper on the Big Bang was authored by Alpher, Bethe and Gamow, reminiscent of the first three letters of the Greek alphabet, Alpha, Beta, and Gamma.
- Alpher was Gamow's graduate student, and only after many years did he get full credit for working out Gamow's ideas, and predicting the cosmic microwave background. In the mid-1950's Alpher and Herman's theories were challenged by supporters of the Steady State. Alpher and Herman were nearly forgotten when Penzias and Wilson discovered the cosmic microwave background in 1965 (although Penzias mentioned their work in his Nobel lecture in 1978). Alpher received honors starting in the 1970's culminating with the National Medal of Science (the highest scientific honor in the US) two weeks before he died in 2007.

Other resources

The following web pages have more detailed information:

- Arno Penzias' Nobel Prize Lecture : describes the development of the Big Bang theory and how astronomers wrestled with the problem of the origin of the chemical elements: http://nobelprize.org/nobel_prizes/physics/laureates/1978/penzias-lecture.html
- Big Bang or Steady State? - an article from the American Institute of Physics describing the issues surrounding these two theories: http://www.aip.org/history/exhibits/cosmology/ideas/bigbang.htm

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Sidebar: Hoyle Scoffs at "Big Bang" Universe Theory

The primary message of this article is that the biggest detractor of the evolutionary Universe theory ended up coining the phrase by which it is became to be known – Big Bang theory.

Hoyle was no fan of the "evolutionary" model of the universe. He coined the term "Big Bang" on a BBC radio broadcast of *The Nature of Things* in 1949. The term took about another decade to really catch on. Once it did, however, the term stuck. Attempts have been made to rename it, since it mistakenly leaves the impression that the universe started with an explosion. For example, in 1993 Sky and Telescope magazine ran a contest to rename it, and received many interesting ideas. More amusingly (but still perpetuating the explosion misconception), Bill Watterson in his *Calvin and Hobbes* comic strip referred to it as "The Horrendous Space Kablooie!"

Death of a Genius: Albert Einstein 1879-1955

The primary message of this article is that Einstein's death was felt the whole world over.

There were many obituaries and reminiscences when Einstein died, and this brief article attempts to capture just a small portion of that.

Einstein spent the last thirty years of his life working on "the theory of everything", which would attempt to unify gravity and quantum mechanics. During those years, he was about the only person working on the problem, and he did not succeed. However, that question is still pursued today.

It's a Star! It's a Nova! It's Super-Nova!

The primary message of this article is that stellar explosions can be classified into two types: novae and super-novae. And that super-novae can be split up into two different kinds – Type I that show no signs of hydrogen in their spectrum and Type II that do show hydrogen.

Astronomers had long been observing new stars, or novae. These are newly visible stars whose brightness changes by hundreds or millions of times (increasing between 5 to 15 magnitudes). They had been observed in our galaxy, and in the "spiral nebulae". Once Hubble determined the distance to the Andromeda Nebula, he realized that the bright nova that had been observed to have occurred there in 1885 must have been much more luminous than those occurring in our own galaxy. By 1934 there was growing evidence from other bright novae in distant galaxies that there were two types of phenomena. Walter Baade and Fritz Zwicky were apparently the first to coin the term "super-nova". Minkowski studied the spectra from these supernovae and determined there were two types.

We now know novae to be an event that happens on a white dwarf. A white dwarf is the remnant of a star like our sun after it has used all its nuclear fuel. White dwarfs may be at the center of planetary nebulae, or in orbit around another star. When in a close orbit around another star, the white dwarf can accumulate matter from its companion. With enough material on the surface of the white dwarf, there is an episode of nuclear burning of the accumulated hydrogen. This happens rather quickly, and the star brightens.

Supernovae are much more violent events, and hence much brighter.

- Type Ia supernovae (a subclass of the Type Is discussed in the article) is the total destruction of a particular type of white dwarf. Here enough material accumulates on the white dwarf that it reaches the upper allowed limit of its mass, 1.4 times the mass of the sun (a limit discovered by Chandrasekhar). Once this limit is reached, carbon and oxygen in the core of the white dwarf fuse, completely detonating the star.
- Type II supernovae result from massive stars that have come to the end of their lives. Stars that start with more than 8 times the mass of the sun go supernova

when their cores start to fill with iron, the last step in a long chain of fusion processes. Since iron does not generate energy by nuclear fusion, the core collapses under its own weight. The rest of the star falls onto the collapsing core, and then bounces back, creating the supernova explosion. The energy of the explosion is enough to create heavy elements beyond iron. The explosion leaves behind a neutron star or a black hole (depending on the original mass), as well as a gaseous remnant (known as a supernova remnant).

Side Note

- The style of this article plays off the popularity of Superman in the mid-1950s. The Superman comic books debuted in the 1930s, and were wildly popular by the early 1940s. In 1955, the television series "Adventures of Superman", starring George Reeves, was in its heyday.

Other resources

The following web pages have more detailed information:

- Supernovae - basic information about supernovae: http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html
- Supernovae - more information about supernovae: http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html
- Teachers Guide to the Life Cycles of Stars: http://imagine.gsfc.nasa.gov/docs/teachers/lifecycles/LC_title.html
- "What is Your Cosmic Connection to the Elements?" - a teachers guide to the origin of the chemical elements, including a section on supernovae: http://imagine.gsfc.nasa.gov/docs/teachers/elements/elements.html

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Radio 'Ear' on the Universe Being Built

The primary message of this article is that astronomy is no longer confined to the realm of optical observations – new technologies allow astronomers to look at radio waves emitted by objects in the Solar System and beyond.

Radio was the first non-optical portion of the electromagnetic spectrum to be explored by astronomers. This article introduces students to this fact, and that radio astronomy was flourishing in the 1950s. This article sets the stage for the further expansion of astronomy into the X-ray and microwave regions of the spectrum, which become quite important in the 1965 and 1993 issues of Cosmic Times.

Radio astronomy had its origins in the early 1930s, when Karl Jansky was investigating the sources of noise in a radiotelephone system at Bell Telephone Labs in New Jersey. He linked the source of the noise to something in the sky, rather than the immediate surroundings. He identified the source to be the center of our Galaxy. Most astronomers took little notice of this discovery. Grote Reber, a radio engineer and amateur astronomer, learned of the discovery in 1933 and built his own radio telescope. By the early 1940s Reber had made detailed maps of the radio sky.

The impetuses for the advancement of radio astronomy were the necessities and technological advances from World War II. The necessities included classified work by the British to determine the source of the jamming of British radars – which turned out to be the Sun. New receivers built for the War provided the basis for new radio telescopes after the War. By the early 1950s, Martin Ryle and Antony Hewish had started the Cambridge catalogues ("2C" and "3C") of radio sources. By the mid 1950s, radio astronomy was flourishing.

Jodrell Bank, which is 25 miles south of Manchester, England, was first used for radio astronomy when Bernard Lovell brought surplus WW II radio equipment there in 1945. Jodrell Bank Observatory was expanded in 1952, offering a place to build the Mark I telescope.

The Mark I telescope at Jodrell Bank was completed in 1957, and later became known as the Lovell Telescope, named for the observatory's founder. Shortly after its completion, it tracked the booster rocket that carried Sputnik 1 into orbit. The Lovell Telescope remains the third largest steerable radio telescope in the world.

The Lovell Telescope has been used to track a number of planetary probes. It has been used extensively for astronomy research, including the study of pulsars, star-forming regions, quasars, and gravitational lenses.

In the Cosmic Times article, the "brightest radio emitter ... in the constellation Cassiopeia" is Cassiopeia A, later found to be a supernova remnant. Cassiopeia A is now extensively studied to understand the nature of supernova explosions, formation of chemical elements, and how the remnant interacts with the surrounding interstellar gas.

Other resources

The following web pages have more detailed information:

- Jodrell Bank Centre for Astrophysics - for current research done at Jodrell Bank and other radio observatories run by University of Manchester: http://www.jb.man.ac.uk/
- Lovell Telescope - Wikipedia article: http://en.wikipedia.org/wiki/Lovell_Telescope
- Jodrell Bank Observatory - Wikipedia article: http://en.wikipedia.org/wiki/Jodrell_Bank_Observatory
- Cas A and Other Supernova Remnants: http://chandra.harvard.edu/xray_sources/supernovas6.html

1965 Cosmic Times

This edition, the fourth of the series, *Cosmic Times*, coincides with the discovery of the cosmic microwave background (CMB), the remnant radiation from very early in the Universe. This new discovery clearly makes the Big Bang the lead theory on the origin of the Universe. The realm of astronomy has grown, with the addition of observations of X-rays from outside the Solar System, and, indeed, outside of the Galaxy. Astronomers have also just gotten their first glimpse of the invisible dark matter.

The language in the 1965 newspaper mimics the style of writing that would have appeared in a real 1965 newspaper. The style is very close to modern-day newspapers, and should not be as difficult for your students as previous papers. However, the concepts may be more difficult than in the previous *Cosmic Times* editions. The layout of the poster also mimics the newspapers of the time. However, we have taken some creative license to make it more readable in a classroom setting.

Age of the Universe: 10 - 25 Billion Years

1965

Cosmic Times

Size of the Universe: 25 Billion Light Years

MURMUR OF A BANG

Big Hiss Missed By Others

Galaxies Still Misbehaving

QUASARS: Express Trains To Netherworlds

SUPERNOVAE LEAVE BEHIND COSMIC X-RAY GENERATORS

Summary of the 1965 Articles

Murmur of a Bang

A pair of astronomers, Penzias and Wilson, stumbled upon the discovery of the cosmic microwave background. This discovery played a pivotal role in overthrowing the Steady State theory. This article shows that science does not always take the expected route – unexpected discoveries are sometimes the richest discoveries.

Big hiss missed by others

Other scientists had the potential to discover the cosmic microwave background, but were not able to connect the observation and theory.

Supernovae Leave Behind Cosmic X-ray Generators

Not all wavelengths of light are able to penetrate the Earth's atmosphere, so astronomers must use satellites to expand astronomy beyond optical and radio wavebands. This article reinforces the idea of multiwavelength astronomy that was introduced in the 1955 Cosmic Times article, *Radio 'Ear' on the Universe Being Built*.

Quasars: Express Trains to the Netherworld

Astronomers have discovered objects near the edge of the known Universe that appear to be speeding away from us due to the expansion of the Universe. In addition, we see the shear power these objects must have if we are able to observe them across such great distances.

Galaxies Still Misbehaving

This article illustrates that there is mass in this universe that we cannot account for by studying light alone. In fact, there isn't just a little more matter, but a lot more. This article shows that we can observe phenomena in our universe by their influences on other parts of the universe – in this case, we observe the presence of dark matter through its affect on the motions of galaxies and galaxy clusters.

Notes on the 1965 Articles

Murmur of a Bang

The primary message of this article is the introduction of the cosmic microwave background and its role in overthrowing the steady state theory. A secondary message of this article is the idea that science does not always take the expected route – unexpected discoveries are sometimes the richest discoveries.

Serendipitous Discovery

The "Holmdel horn" had been built by Bell Labs to test telecommunications with the Echo satellite, but was no longer needed for that job as of mid-1962. With its primary task finished, the Holmdel horn was made available to Arno Penzias for astronomical observations. Robert Wilson was hired to help out.

To use the Holmdel horn for astronomical purposes, Penzias and Wilson first needed to characterize the "noise" in the telescope. For astronomers, "noise" refers to light that enters a telescope from a source other than the object of study. Noise can come from many places, such as the detector itself, nearby lights from a city, or sources in the sky that lie close to the object of interest. By characterizing the noise sources, astronomers can better determine the signal that came from the object they wish to study. Astronomers must track the noise in all astronomical instruments to be confident in their observations and conclusions. For the Holmdel horn, Penzias and Wilson identified all possible noise sources, including cleaning pigeon droppings from the horn itself, but found they had remaining noise that they could not trace.

As discussed in the article, *Big Hiss Missed by Others*, other researchers had been looking for the remnant radiation from shortly after the Big Bang. The Big Bang model was already the front-runner for the model of our Universe, but finding the remnant radiation was seen as the smoking gun that would effectively squash any other model (such as the steady state model). It is interesting to note that Penzias and Wilson were not among the researchers actively seeking out the remnant radiation of the Big Bang.

While Penzias and Wilson were contemplating the possible remaining source of noise, they heard about work done by Princeton researchers Dicke and Peebles. Dicke sent them a draft of his group's paper on radiation in the universe. The theoretical work by Dicke's group on the remnant radiation from the Big Bang was just the thing that Penzias and Wilson needed to pin down their extra "noise" source. The noise they hadn't been able to characterize was not coming from any local sources – it was the Universe itself!

The two teams published their papers in the same volume of the *Astrophysical Journal* in 1965:

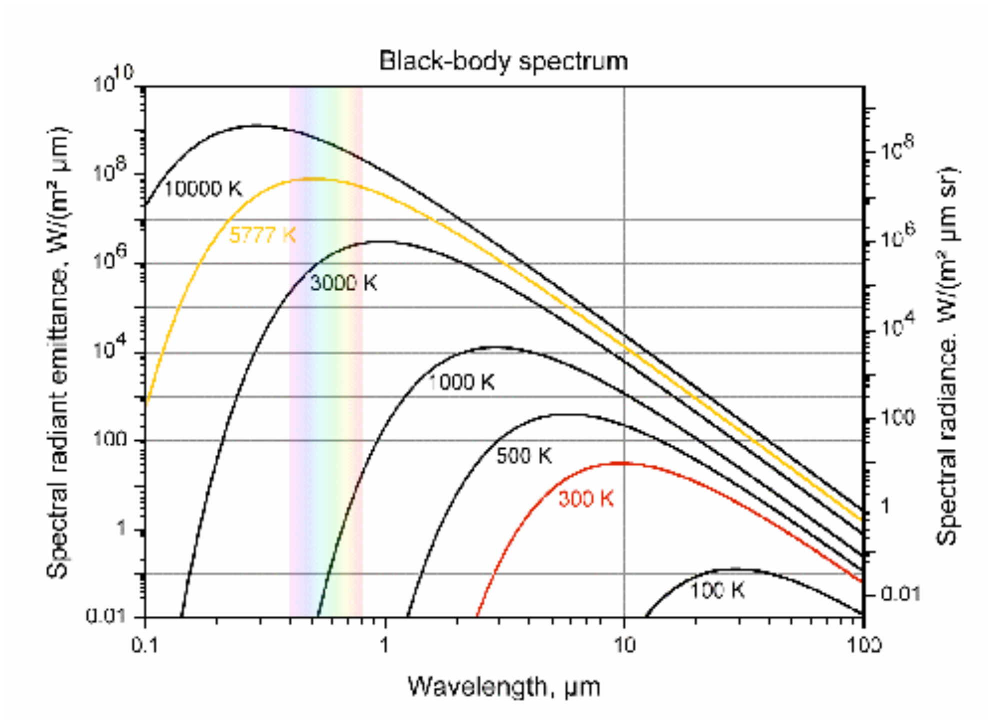
- "Cosmic Black-Body Radiation" by Dicke, Peebles, Roll, and Wilkinson, D. T. appeared in *Astrophysical Journal*, volume 142, pages 414-419 (1965)

- "A Measurement of Excess Antenna Temperature at 4080 Mc/s" by Penzias and Wilson appeared in *Astrophysical Journal*, volume 142, pages 419-421 (1965)

Signature Radiation

The Cosmic Times article discusses how "the remnants of the Big Bang have cooled in a way that channels energy into specific bandwidths". This is our writer's way of saying that the remnant radiation has a specific spectrum – that of a black body. In fact, the black-body spectrum of the remnant radiation was predicted by the theorists, and was, indeed, what Penzias and Wilson saw in their "noise".

Black-body radiation has a specific spectrum. Black bodies radiate at all wavelengths, but the spectrum has a peak at a wavelength where most of the energy radiates. This peak wavelength (or energy) completely characterizes the black-body spectrum. The remnant radiation from the Big Bang peaks in the microwave range of the electromagnetic spectrum, so it is now called the "cosmic microwave background" or CMB for short.



Blackbody spectrum for several different characteristic temperatures. The 3K spectrum like that of the CMB is not shown on this plot.

Significance of the Discovery

The discovery of the cosmic microwave background (CMB) was the final straw for the steady-state model of the universe. The steady-state model cannot account for the CMB without major backbreaking efforts. Most scientists had already seen that the Big Bang model was the more reasonable theory, with more hard evidence. With the discovery of the CMB, however, all but a few die-hard hangers-on abandoned the steady state theory.

This story illustrates two important processes in science – first, the idea that serendipitous observations often yield the most interesting science, and second, that often one person's trash is another person's treasure. Penzias and Wilson never intended to find the CMB – they were only hoping to use the Holmdel horn for astronomical purposes. In order to do that, they needed to characterize all of the noise in the system. The so-called noise, however, was a gem in the field of cosmology, and has become the cornerstone for understanding the nature of the universe.

The CMB is so important, that studying and mapping it became the focus of two NASA satellite missions. The results of the first mission are discussed in the 1993 edition of Cosmic Times.

Other resources

The following web pages have more detailed information:

- Short autobiography of Arno Penzias on the Nobel Prize website: http://nobelprize.org/nobel_prizes/physics/laureates/1978/penzias-autobio.html

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Big hiss missed by others

The primary message of this article is to point out that theory and observation must both coordinate to advance our understanding of the Universe. A secondary message is that not all discoveries are planned – many of the richest discoveries happen by accident. It's one of the things that keeps science fun!

While the tools to find the echo of the Big Bang were known and could have been found by others, it is no big surprise that other researchers missed it. Theorists had been pursuing the cosmic microwave background (CMB), but most believed that it would be too faint to be detected.

Another factor that made the CMB difficult to find was that some theorists estimated a higher temperature for the CMB than was actually found. As discussed in the notes for the article *Murmur of a Bang*, the spectrum of light of the CMB is that of a black body. A black-body spectrum is characterized by the wavelength at which it peaks, corresponding to a characteristic temperature. Without knowing the characteristic temperature of the CMB, the signal would be easy to miss.

Perhaps if Penzias and Wilson had not seen the paper by Dicke, they would have written the excess noise off to some "unattributable source", and continued with astronomical observations, oblivious to cosmological gem they had at their fingertips.

And as a side-note, a few other things in science that were discovered by accident include penicillin and gamma-ray bursts. It may be fun to have students find other examples.

Other resources

The following web page has more detailed information:

- Cases of Accidental Scientific Discoveries at Trivia-Library.com: http://www.trivia-library.com/cases-of-accidental-scientific-discoveries/index.htm

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Supernovae Leave Behind Cosmic X-ray Generators

The primary message of this article is that astronomer need to put telescopes in orbit in order to study the wavelengths that don't pass through the Earth's atmosphere. This article also reinforces the idea of multiwavelength astronomy that was introduced in the 1955 Cosmic Times article, "Radio 'Ear' on the Universe Being Built".

For thousands of years, the only form of astronomy observation was optical observation – the light we could see with our eyes. All telescopes, lenses and cameras were sensitive only to optical light. The 20th century saw the advent of astronomy in other wavelengths. Radio astronomy began in the 1930s (as we found in the 1955 Cosmic Times article titled *Radio 'Ear' on the Universe Being Built*), with the first sky-survey in radio wavelengths conducted in the 1950s. The subject of the main 1965 article, *Murmur of a Bang* describing the discovery by Penzias and Wilson of the cosmic microwave background, was done with an antenna sensitive to microwave wavelengths.

There is a limit, though, to the portions of the electromagnetic spectrum that can be studied from the Earth's surface. Earth's atmosphere stops many wavelengths of light from reaching the Earth's surface – lucky for us, because many of these wavelengths are harmful to humans. However, this means that for the wavelengths stopped by the atmosphere, observations must take place above the atmosphere.

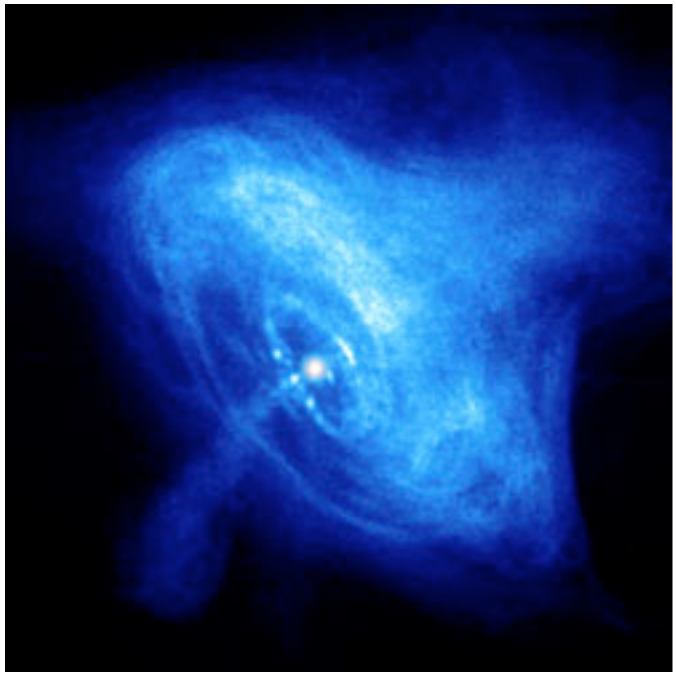
A sounding rocket

X-ray wavelengths are among those stopped by the atmosphere, so must be observed above the Earth's atmosphere. The 1960s saw the birth of X-ray astronomy, with rockets, called "sounding rockets", to put instruments above the bulk of the atmosphere. A "sounding rocket" is one that is used to perform research, and is named after the nautical term *to sound*, meaning, "to take a measurement". A sounding rocket has a typical science observing time of 5-40 minutes (in other words, the rocket remains above the bulk of the atmosphere for between 5 and 40 minutes, depending on the rocket and how high it flies).

When astronomers first thought about X-rays from astronomical sources, the general opinion was that extra-solar sources would be too faint to be detectable. The first X-ray detector flown on a sounding rocket was set to look at the moon, under the idea that heavy particles from the sun would cause X-ray fluorescence of the moon's surface. They did not detect the moon. Luckily, it just so happened that an X-ray source was near enough to the moon that the detector could "see" it. This source is now called Scorpius X-1, because it was the first X-ray source observed in the direction of the constellation Scorpius. It was clear that Scorpius X-1 came from outside our solar system – disproving the idea that extra-solar sources would be too faint to see!

This article discusses two specific X-ray sources in the sky, Taurus XR-1 and Ophiuchus XR-1. Early X-ray observations were named after the constellation in which they were found, and numbered in the order that they were discovered. So Taurus XR-1 was the first X-ray source found in the constellation Taurus. Similarly, Ophiuchus XR-1 was the first X-ray source observed in the constellation Ophiuchus.

As previously mentioned, astronomers originally thought that cosmic X-ray sources would be too weak to be observed, so the appearance of numerous X-ray sources was a bit of a mystery. This article reports one of the first attempts to unravel the mystery, pointing out the similarity between the distributions of supernovae remnants in our Galaxy and that of the observed X-ray sources. This view was bolstered by the possibility of two X-ray sources coinciding with known supernova remnants.



X-ray image of the Crab nebula as observed by Chandra. The details seen in this image are only possible with modern instrumentation – the original observations of the Crab would have been in the form of a spectrum, rather than an image. More information on this image available here: http://chandra.harvard.edu/photo/2002/0052/
Image credit: NASA/CXC/ASU/J. Hester et al.

Taurus XR-1 was conclusively tied to the Crab nebula – a remnant of the supernova of 1054. The Crab nebula is currently one of the most-studied objects in the sky, exhibiting emission at all wavelengths from radio to gamma-ray. It is unclear, however, if Ophiuchus XR-1 turned out to be from the remnant of SN 1604, also known as Kepler's Supernova. Ophiuchus XR-1 was only conclusively observed by one rocket observation. However, later observations did find X-ray emission from SN 1604. It is possible that the first observation was merely noise.

We now know that supernova remnants can leave behind X-ray sources (neutron stars or black holes); however, supernova remnants are hardly the only source of cosmic X-rays. X-ray astronomy has grown since the 1960s, with several dedicated satellites, including the well-known Chandra observatory.

Other resources

The following web pages have more detailed information:

- What is a Sounding Rocket?: http://www.nasa.gov/missions/research/f_sounding.html
- A Brief History of High Energy Astronomy: http://heasarc.gsfc.nasa.gov/docs/heasarc/headates/heahistory.html
- Constellation Ophiuchus: http://seds.org/Maps/Stars_en/Fig/ophiuchus.html
- Constellation Taurus: http://seds.org/Maps/Stars_en/Fig/taurus.html
- Supernova 1054 - Creation of the Crab Nebula: http://seds.org/messier/more/m001_sn.html
- SN 1604, Kepler's Supernova: http://seds.org/~spider/Spider/Vars/sn1604.html
- Chandra website: http://chandra.harvard.edu/

Quasars: Express Trains to the Netherworld

The primary message of this article is the idea that there are objects near the edge of the known Universe that appear to be speeding away from us due to the expansion of the Universe. Secondary messages include the use of Hubble's law to determine distances and the shear power of some of the objects in the Universe that we are able to see them given the huge distances involved.

Quasars were first observed with radio telescopes in the 1950s – they were seen in radio wavelengths with no corresponding visible object. When the first quasar was tied to an optical source (a source called 3C 48), its visible spectrum showed odd emission lines. Remember that different elements have signature emission lines, so it was unusual to see an object with unidentified lines.

In 1962, a second object, called 3C 273, was connected to an optical source. Astronomers subsequently made a detailed optical spectrum which showed unusual emission lines, similar to 3C 48. The unusual lines turned out to be hydrogen lines redshifted more than any other object had shown. The reason the lines looked unusual was not because they had not been seen before, but because they had not been seen in the observed waveband before.

One of the most important concepts in this article is how the "speed" of an object, or its redshift, is related to the distance of that object. In the 1929 edition of the Cosmic Times, we introduced this idea with Hubble's Law relating the redshift of an object to its distance. Quasars are an example of how this redshift-distance relationship was used in astronomy to determine the nature of an object. Using the large redshifts measured from the "unusual" spectra, astronomers determined that quasars lie at the edge of the known universe. The size of the Universe listed in the 1965 Cosmic Times is based on quasar distances.

After 1965, astronomers have identified quasars as a class of active galactic nuclei. A galaxy with an active nucleus is one that exhibits a high amount of emission from its nucleus, often so high that it outshines the galaxy itself. An active galactic nucleus is powered by a supermassive black hole (a black hole with the mass of a million, or more, suns). The black hole itself does not radiate, since once a black hole has swallowed something, even light, it can never return. However, as the black hole pulls in material, it forms a disk and the material experiences a lot of friction as it travels in that disk toward the central black hole. Hot matter can radiate a lot of energy.

Other resources

The following web pages have more detailed information:

- Active Galaxies and Quasars: http://imagine.gsfc.nasa.gov/docs/science/know_l1/active_galaxies.html
- Gene Smith's Astronomy Tutorial Quasars & Active Galaxies: http://cass.ucsd.edu/public/tutorial/Quasars.html

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Galaxies Still Misbehaving

*One message of this article is that there is mass in this universe that we cannot account for by studying light alone. In fact, there isn't just a little more matter, but there is **a lot** more mass. A secondary message is that we can observe phenomena in our universe by their influences on other parts of the universe – in this case, we observe the presence of dark matter through its affect on the motions of galaxies and galaxy clusters.*

This article is the first that deals with the idea of dark matter in the Cosmic Times. However, astronomers had discovered evidence of dark matter, or "unseen matter" in the 1930s. The location of dark matter observed in the 1930s was a bit different than that reported here (a cluster of galaxies versus a single galaxy), but the reasons for concluding that something was missing, something that we couldn't see, were similar for each discovery.

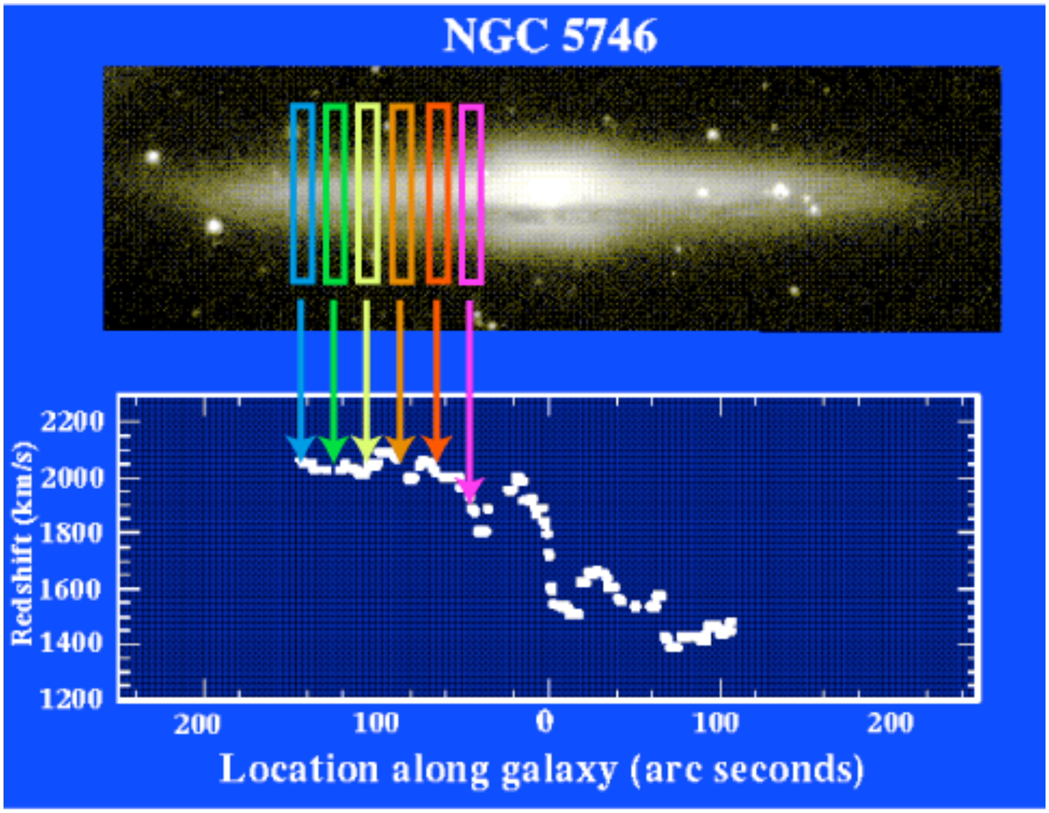
Observations Leading to the Idea of Dark Matter

Fritz Zwicky published the earlier discovery in 1933. Zwicky had observed the Coma cluster of galaxies, and seen that the speed of the galaxies in the cluster was too great for the amount of mass he could account for. By his calculation, the galaxies in the cluster should have been flung free of the cluster.

This story in the 1965 Cosmic Times reports that astronomers have found two galaxies that are rotating faster than they should be able to based on the mass calculated from the luminous matter (or matter that shines on its own, such as stars). In fact, the measurements indicated that if there was not more mass in these objects than meets-the-eye, the outer reaches of the galaxy should have been flung free of the galaxy long ago.

How the Presence of Dark Matter is Detected

In both observations of missing mass, astronomers observed that an object (galaxy or cluster of galaxies) was rotating too fast for the amount of mass in luminous matter. In the case of a galaxy cluster, the rotation can be measured approximately by measuring the redshifts galaxies in the cluster. For the case of a galaxy, astronomers can measure the rotation of a galaxy by measuring the redshift of different "slices" of the galaxy, as illustrated below.



This illustration shows how an astronomer might take redshift measurements of different slices of a galaxy to construct a rotation curve. (The center of the galaxy does not have a redshift (or rotational velocity) of zero because the galaxy has an intrinsic redshift due to the expansion of the Universe.)

Using redshifts for many slices of a galaxy, astronomers construct a "rotation curve" for the galaxy, plotting the distance from the center of the galaxy versus the rotation rate.

Now, if most of the mass is concentrated at the center of the galaxy, as is observed with the stars of a galaxy, we would expect that the stars at the outer edges of the galaxy would rotate slower and slower as you moved out. Instead, the observed rotation curves flatten out at the outer edges of the galaxy. This observation implies that the amount of matter in the galaxy does not taper out in the same manner that the luminous matter tapers out. In other words, there must be a lot of matter in the galaxy that is not seen as luminous matter.

It was not unexpected that some matter would be unseen in galaxies. Certainly, astronomers knew that stars died, and stopped shining, leaving behind non-luminous corpses. However, it was expected that luminous matter would be a tracer of all matter in a galaxy – in other words, the corpses of stars, which might account for much of the unseen matter, should lie in regions where stars have formed and are still shining. Instead, they found that there was much more mass than could be accounted for by the observed luminosity from the galaxy, and the distribution of that mass did not follow the distribution of light in the galaxy.

In 1965, dark matter is a growing mystery in astronomy. We will revisit dark matter in both the 1993 and 2006 editions of Cosmic Times. In fact, scientists continue to puzzle about the nature of dark matter, even today.

Other resources

The following webpages have more detailed information:

- RotCurve – a site with a Java applet that allows you to play with the different components of a galaxy to see that there is no way to fit the observed rotation curves with luminous matter as the tracer of matter in the galaxy: http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/main.html

1993 Cosmic Times

This edition, the fifth of the series, features the discovery of anisotropies in the cosmic microwave background (CMB). These tiny variations in the remnant radiation from very early in the Universe eventually formed the structures that we see around us today. By the early 1990s, astronomers have extended the Big Bang theory to include a period of inflation to make the theory better align with observations. The distance scale has been refined based on a class of supernova, allowing distance determinations to ever-further galaxies. In addition, the Nobel Prize for physics awarded to a pair of scientists who discovered proof of gravitational waves.

The language in the 1993 newspaper mimics the style of writing that would have appeared in a newspaper at that time. The style is similar to modern-day newspapers, and should be easier to read than previous editions; though, the concepts continue to get harder. The poster also shows a layout that mimics the papers of the time (note the introduction of color); however, we have taken some creative license to make it more readable in a classroom setting.


Age of the Universe: 12-20 Billion Years

COSMIC TIMES

1993

Size of the Universe: 30 Billion Light Years

Baby Universe's 1st Picture

Inflation in the Universe

Dark Matter Hunt Heats Up

Pancake or Oatmeal Universe - What's for Breakfast?

Pulsar Gravitational Waves Win Nobel Prize

Fool-Proofing Galactic 'Candles'

Summary of the 1993 Articles

Baby Universe's 1st Picture

In the early 1990s, the COBE satellite confirmed the spectrum of the cosmic microwave background to be a perfect black body, as predicted by astronomers. It also made the first complete map of the tiny fluctuations in the temperature of the background. This discovery was a watershed event. Astronomers had known that this remnant radiation from the Big Bang could not be infinitely smooth. This is because we have a "lumpy" universe now, with clumps of matter that form structures we see today. The discovery of the anisotropy confirmed astronomer's ideas about the Big Bang.

Pancake or Oatmeal Universe – What's for Breakfast?

Despite the fluctuations discussed in the "Baby Universe" article, the microwave background is remarkably smooth. This brief sidebar discusses the differences between the apparent smoothness of the distribution of matter in the early universe to lumps of matter (in the form of galaxies) we see today. It sets up the "Inflation in the Universe" article.

Inflation in the Universe

This article explains how inflation theory addressed a problem faced by the Big Bang – the universe is too big for the cosmic microwave background to be as smooth and uniform as it is. To solve this, astronomers introduced a very short period of very rapid expansion just after the Big Bang. An underlying message of this article is that theories, such as the Big Bang, often undergo revision and changes.

Dark Matter Hunt Heats Up

In the 1990s, the evidence for dark matter expanded to include observations of hot X-ray gas in a group of galaxies. The observations showed that the visible mass of the galaxies was insufficient to hold such energetic gas in place. Hence, dark matter must be present. While previous *Cosmic Times* editions have touched on dark matter, we find that exploring in wavelengths other than visible light provides compelling new evidence.

Fool-Proofing Galactic 'Candles'

This article continues the story of how astronomers refine their "standard candles" to determine distances to far away galaxies. This article picks up the story of supernovae and different types of supernovae discussed in the 1955 edition of *Cosmic Times*. In the early 1990s, astronomers refined their understanding of Type Ia supernovae so that they could be more reliably used as standard candles. Type 1a supernovae can be observed in objects at much further distances that the other standard candle, Cepheid variables, discussed in earlier editions of *Cosmic Times*. This development sets up a key tool that will play an important role in the 2006 edition of *Cosmic Times*.

Pulsar Gravitational Waves Win Nobel Prize

In 1993, the Nobel Prize for physics was awarded to Russell Hulse and Joseph Taylor of Princeton University. The prize was awarded for their discovery of the first pulsar in a binary system and subsequent work using the arrival times of pulses from the pulsar to give the first evidence of gravitational waves. This article illustrates that scientists continually test their theories, and that after nearly 80 years Einstein's theory of relativity continues to pass those tests.

Notes on 1993 Articles

Baby Universe's 1st Picture

The primary message of this article is that the discovery of tiny variations in the cosmic microwave background was a watershed event. Astronomers had known that this remnant radiation from the Big Bang could not be infinitely smooth. This is because we have a "lumpy" universe now, with clumps of matter that form structures we see today. The discovery of the anisotropy confirmed astronomer's ideas about the Big Bang.

Helping your students understand the concepts

The ideas presented in this article may be easier for your students to understand if they have first read and discussed the 1965 Cosmic Times article on the cosmic microwave background, *Murmur of a Bang*. The 1965 Cosmic Times lesson plan titled " Cosmic Microwave Background" may also help your students develop a solid understanding of the CMB.

In addition, we suggest that the lesson plan titled "What's the Problem with Isotropy" used after reading this article may help students understand the main concepts presented in this article.

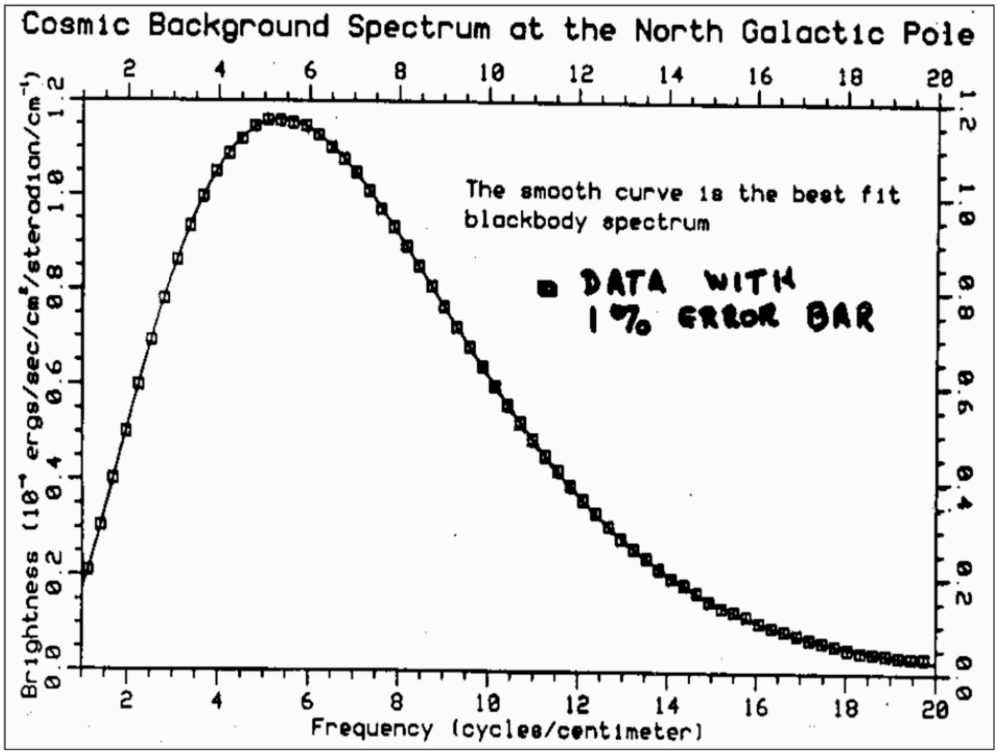
The COBE satellite

The 1965 Cosmic Times introduced the observation by Penzias and Wilson of a radiation background left over from a time just after the Big Bang bathing the entire Universe. As with any astronomical discovery, the first observations serve to prove that a phenomenon exists. Astronomers scramble after such a discovery to develop methods and technologies to study the phenomenon in greater detail. The cosmic microwave background (CMB) is no different. NASA solicited for proposals for small- or medium-sized space missions in the early 1970s, and received three independent proposals to study the CMB. This sent NASA the message that the astronomical community wanted to study the CMB in greater detail, and that they had many ideas about how to carry out those studies. NASA responded by selecting members from each of the three teams to join together for a unified mission. The end result was Cosmic Background Explorer (COBE), which launched in 1989.

The three instruments COBE carried were designed for two primary tasks: measuring the CMB spectrum and mapping the CMB. One instrument made a detailed spectrum of the CMB. The other two instruments mapped the CMB across the entire sky.

The COBE spectrum

Using just the first 9 minutes of data from the spectrometer, COBE scientists were able to make a spectrum of the CMB. Shown below.



This is the spectrum that John Mather presented at the January 1990 meeting of the American Astronomical Society Meeting. It is the spectrum based on the first 9 minutes of data from COBE. The solid line shows a theoretical blackbody, and the squares show the COBE data. The error bars for the data are contained within the squares.

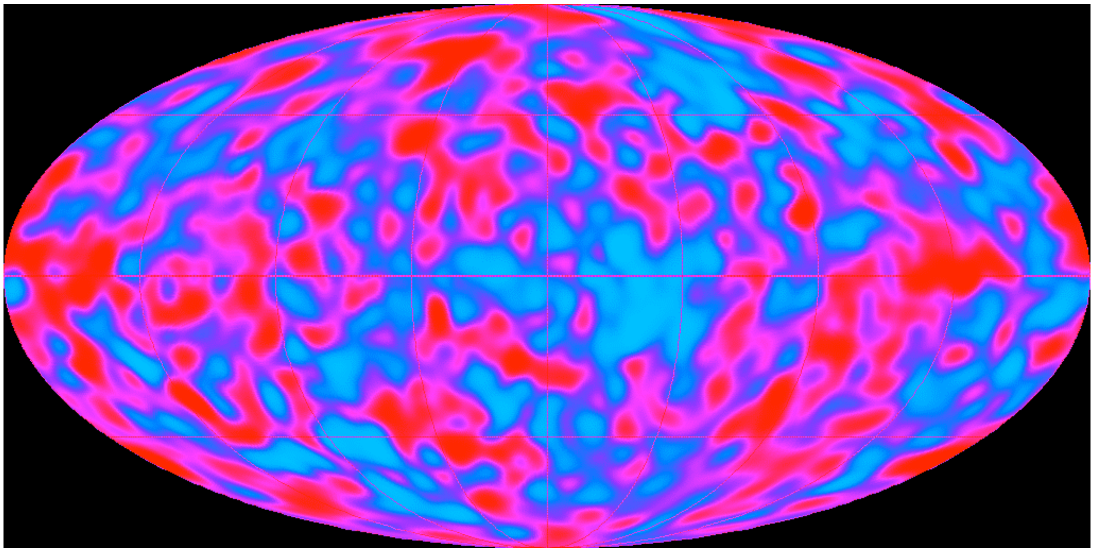
One thing to notice about the plot is that the theoretical blackbody (solid line) and the data (squares) match *precisely*. Astronomers rarely see data and theory matching so precisely. In fact, when John Mather presented this very plot at the 1990 meeting of the American Astronomical Society Meeting, it was greeted with a standing ovation.

This spectrum was the first result from COBE, and it was enough to make some astronomers a little nervous. Why is that? Because the data is *too* smooth. Let's take a quick inventory of the Universe around us. There are planets, stars, galaxies and cluster of galaxies. In a word, it's clumpy. In other words, the matter is generally found in gravitationally bound structures.

The structure we see today must have come from seeds in the early Universe. But the CMB is a reflection of that early Universe, so those seeds must be present in the CMB or we would not see structure today. The smooth spectrum contained no hints of those seeds. The astronomical community would have to wait another 2 years to see if the maps made by COBE's other instruments contained the seeds that needed to be there to produce our present-day Universe.

The COBE Map

In 1992, George Smoot's team published COBE's map of the CMB, and for the first time astronomers saw the "lumps" in the CMB. These anisotropies, as astronomers call them, were at the very limit of COBE's capabilities, but were large enough to eventually form the structure that we see in the Universe today. The map is shown below:



COBE cosmic microwave background radiation (CMB) map.

The different colors show places where the very early Universe had temperature differences, which are equivalent to density differences. Higher density regions were the places where gravity started to form structures. We know that these anisotropies must be the seeds of structure that we see today, but the details of COBE are too coarse to identify specific seeds with present-day structures.

One important point is that while we talk about "lumps" in the early Universe, the size of those density differences was tiny. They represent changes of the order of 1 part in 100,000. Changes of this size are a bit like locating a single mosquito on a stretch of road a mile long. That's a small difference in density! In fact, the background was so smooth that other problems with Big Bang Theory arose even before these COBE results. However, these other problems are solved with inflation, as is discussed in the article titled "Inflation in the Universe".

Perhaps the most important point for students to walk away with is that on the one hand, we have very, very small changes in the background, but those changes turn out to be essential to the Universe we observe today. Big Bang theory would have been in a heap of trouble if astronomers hadn't seen those tiny changes in the CMB.

Other resources

The following web pages have more detailed information:

- COBE website: http://lambda.gsfc.nasa.gov/product/cobe/
- Discovery Education Streaming – if your school has an account with Discovery Education Online, they have several videos and clips discussing the cosmic microwave background and the expanding universe: http://streaming.discoveryeducation.com/
- The Beyond the Solar System DVD has a few clips that deal with the cosmic microwave background and how the structure we see in the CMB were transformed into the Universe we see today. This DVD can be requested from the following web page: http://cfa-www.harvard.edu/seuforum/btss/dvd/

Sidebar: Pancake or Oatmeal Universe – What's for Breakfast?

The primary message of this article is to further differentiate the definitions of "smooth" and "lumpy" as they pertain to the cosmic microwave background.

The articles about the comic microwave background (CMB) in this edition of Cosmic Times talk about it being lumpy and being smooth, so this sidebar aims to clarify the different definitions as they apply to cosmology.

The first thing to remember is that when astronomers talk about structure in the CMB, they are really talking about structure in the Universe shortly after the Big Bang. By most definitions, the CMB is quite uniform (or smooth). In fact, the level of uniformity caused some problems for cosmologists, which we discuss in the article on Inflation Theory, "Inflation in the Universe". The anisotropies, or "lumps", that astronomers found in the CMB were tiny. The magnitude of the anisotropies was just 1 part in 100,000, which in length scales would be is like the width of a human hair compared to a full-sized school bus.

Most of the matter that we see in the Universe around us now is in the form of "clumps": planets, stars, nebula, star clusters, galaxies, and clusters of galaxies. This is a huge difference from the early Universe as seen in the CMB. It is important for students to understand these distinctions.

Inflation in the Universe

The primary message of this article is to show that Big Bang theory has gone through changes since it was first conceived. Observations of the cosmic microwave background posed problems for the theory as it stood, so theorists developed Inflation Theory to better account for those new observations.

The Problem

In the article titled "Universe's 1st Baby Picture", we found that the cosmic microwave background was very, very smooth. There were density differences, but as we discuss in the article and the article notes, those differences are *very* small. In fact, the CMB was so uniform that it posed a problem for Big Bang theory. In cosmology, this is called the Horizon Problem. *

It is not unusual for a scientific theory to undergo revisions when new observations conflict with its predictions. In fact, this is the very heart of the scientific process. Students may be surprised that, more often than not, theories generally undergo revision rather than being discarded wholesale when new observations do not support the theory. Theorists work to incorporate the new observations into the theory with as little change as possible to the original theory, because the theory presumably worked pretty well for observations prior to the new observations.

Big Bang theory is no different from any other scientific theory, and even before the COBE results, it was becoming clear that the background was too uniform. The reason this was a problem was that regions of the CMB that should not have had time to "talk" to each other were essentially in thermodynamic equilibrium. This was a problem.

To better understand this problem, consider a mug of hot coffee. If we drop an ice cube into it, we know that eventually the ice cube will melt and warm up while the hot coffee will cool down a little, and liquid in the mug will come to the same temperature throughout. Once the liquid is all at the same temperature again, scientists would say that the liquid is in "thermodynamic equilibrium".

For this illustration, let's say that it takes 15 minutes for the liquid to come back to thermodynamic equilibrium. Up until that 15-minute mark, different areas inside the coffee mug will have different temperatures. Early on, the differences are especially pronounced. During the first minute, the coffee will be relatively cool near the ice cube, but the coffee toward the bottom of the mug will still be close to its original temperature. The way astronomers might describe this is that different parts of liquid in the mug have not had time to "communicate" with each other.

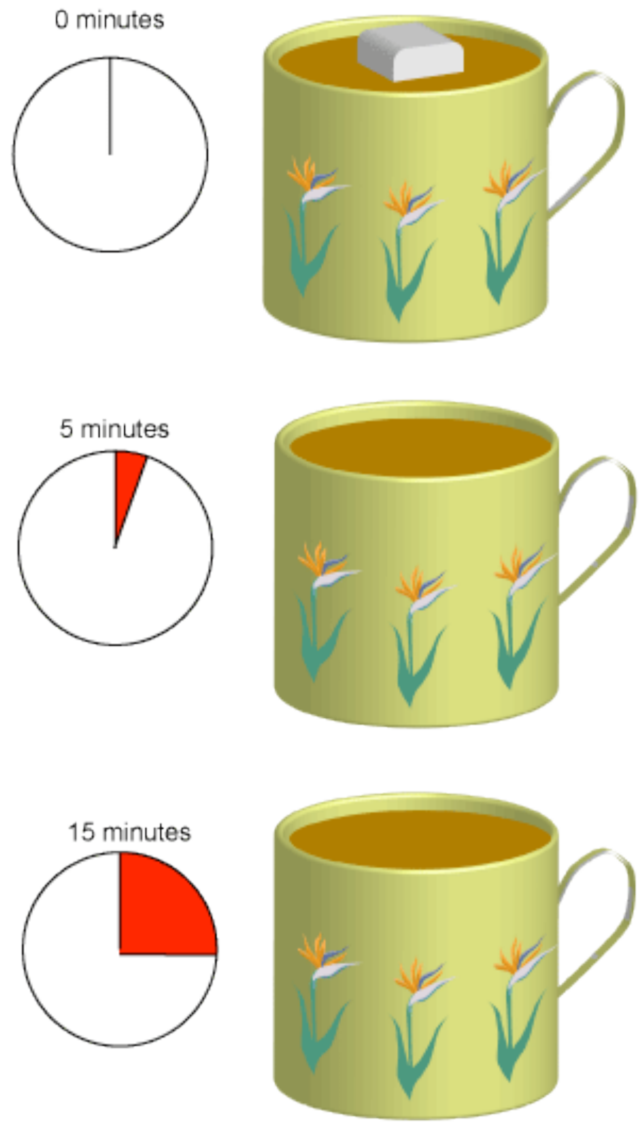
Thermodynamic Equilibrium in a Coffee Mug

Add an ice cube to a mug of hot coffee.

Just after the ice is placed in the mug, the coffee at the bottom of the mug will be close to its original temperature, while coffee immediately surrounding the ice cube will be cooler.

Right as the ice cube disappears, let's say at minute 5, there will be a temperature difference between coffee in different parts of the mug.

Eventually, all of the coffee in the mug will be at the same temperature. This final temperature will be slightly lower than the original temperature of the coffee. However, the final temperature will be significantly higher than the original temperature of the ice, because there is so much more coffee than ice.



Taking the coffee mug analogy one step further, let's imagine that we measure the temperature at all parts of the mug 10 minutes after adding the ice cube. We know that the liquid in the mug should be at different temperatures depending on where we measure, so if our measurement showed a uniform temperature everywhere in the coffee mug, we would be very surprised. The Big Bang model, as it existed before Inflationary

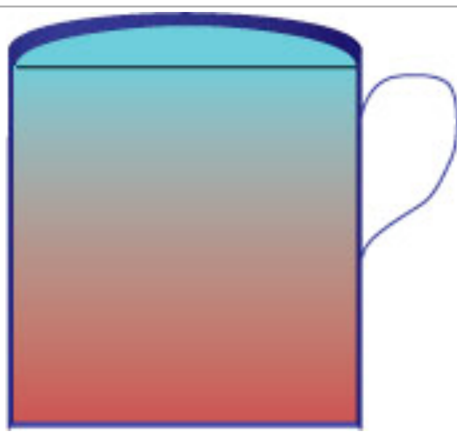
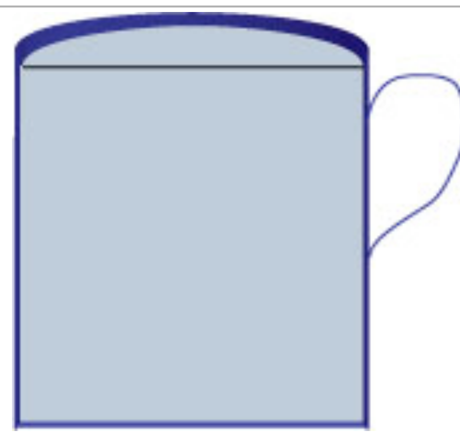
Theory, predicted that the Universe should not have been in thermodynamic equilibrium when the CMB was emitted. In other words, the Universe would be so large that parts of the Universe should not have been able to communicate before the CMB was created. So we had every reason to believe that the CMB measured in opposite directions should have shown different temperatures. The observations, however, found that the temperature was uniform in every direction.

<table>
<tr><th colspan="2">The Universe without Inflation:
Prediction versus observation</th></tr>
<tr><td>What we expected

Below is a cut-away of the coffee mug with colors indicating the temperature gradient that we might expect to measure 10 minutes after we add the ice cube. The liquid in the mug has not had time to reach thermodynamic equilibrium, so there is a temperature gradient, with blue indicating cooler temperatures and red indicating hotter temperatures.

Toward the top of the mug, the coffee is cooler because of the melted ice cube. Toward the bottom of the mug, the coffee is hotter because it has not had time to mix with the cooler liquid at the top of the mug.</td><td>What we measured

Below is a cut-away of the coffee mug with colors indicating the temperature gradient that we measured at 10 minutes after adding the ice cube. The consistent temperature was not expected because coffee should not have had time to come to thermodynamic equilibrium.

This is analogous to the measurements of the CMB prior to Inflation Theory – cosmologists needed to explain why the temperature was so consistent when the Universe should not have had time to come to thermodynamic equilibrium before the CMB was emitted.</td></tr>
<tr><td></td><td></td></tr>
</table>

The Solution: Inflation

Inflation Theory answers the Horizon Problem by proposing that early in the Universe's history, a small parcel of space expanded rapidly. This expansion increased the size of the

Universe by a factor of 10^{26} in a fraction of a second. This might sound like it violates relativity, because the expansion occurs faster than the speed of light. However, the expansion is of *space* only, with no matter or information carried between points at faster than the speed of light.

The Horizon Problem is solved with inflation because prior to the episode of inflation, those regions that are on different sides of the Universe today were actually much, much closer than they would have been without Inflation. That means that parts of the CMB that look very distant today actually would have had time to "communicate" early in the Universe's history because they were much closer then and in thermodynamic equilibrium. This explains why their temperatures are so similar now.

Returning to the coffee mug analogy, this time we will take a much smaller mug of coffee and add an ice cube. Because there is less liquid that needs to come to thermodynamic equilibrium, it will happen much faster. Imagine that thermodynamic equilibrium occurs 5 minutes after adding the ice cube. At 7 minutes after adding the ice cube, increase the size of the mug by a factor of 4, and measure the temperature everywhere in the mug a few minutes later. We wouldn't be surprised if the temperature was uniform throughout the coffee in the mug, because it was in thermodynamic equilibrium before the expansion. This is what happened in the universe, except the universe expanded by a factor of 10^{26}!

The Universe with Inflation

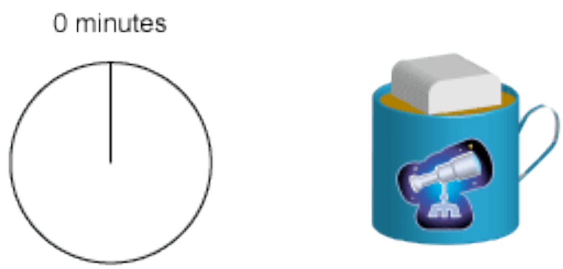
Add an ice cube to a small mug of hot coffee.

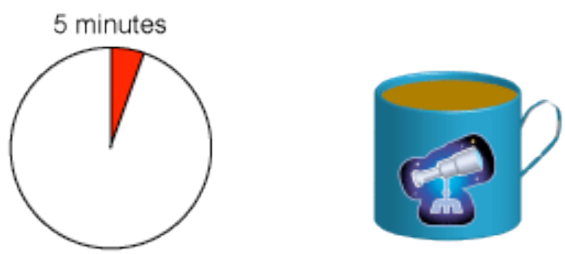
Just after the ice is placed in the mug, the coffee at the bottom of the mug will be close to its original temperature, while coffee very close to the ice cube will be at a lower temperature.

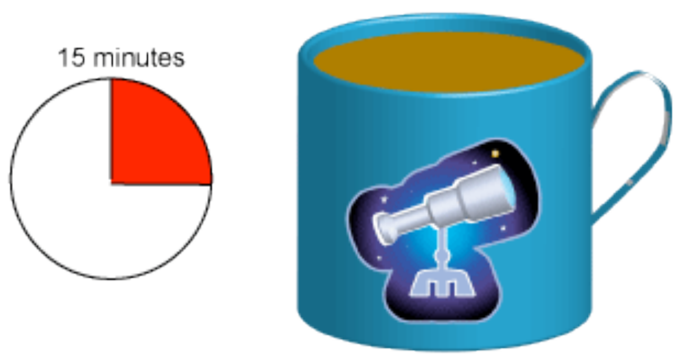
However, with a smaller mug, the coffee and ice cube will come to thermodynamic equilibrium much faster; let's say 5 minutes after dropping the ice cube into the mug. Now, all parts of the coffee are the same temperature.

In Inflationary Theory, after the early universe came to thermodynamic equilibrium, but before the cosmic microwave background was emitted, the universe underwent a rapid expansion. So, in our coffee-mug model, our small mug of coffee expands sometime after it comes to thermodynamic equilibrium.

Note: The illustration scale and timing are not to scale with the Universe's period of inflation.







*Big Bang Theory had three different problems that are accounted for in Inflation Theory: The Flatness Problem, The Horizon Problem, and The Monopole Problem. We concentrate on the Horizon Problem here because it is the easiest to understand. For more information on the other problems and how they are solved with Inflation Theory, follow the links under "Other Resources" below.

Other resources

The following web pages have more detailed information:

- What is Inflation Theory?: http://map.gsfc.nasa.gov/universe/bb_cosmo_infl.html
- Inflation for Beginners by John Gribbon: http://www.lifesci.sussex.ac.uk/home/John_Gribbin/cosmo.htm

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Dark Matter Hunt Heats Up

The primary message of this article is that evidence for dark matter has been found in the X-ray observations of a galaxy cluster. While previous Cosmic Times editions have touched on dark matter, this time we are finding evidence in a new wavelength.

Dark matter is one of the hot topics of the late 20th century (and today). In the Cosmic Times, we first encountered dark matter in the 1965 edition, with the rotation curves of galaxies. However, as we discussed in the notes to *Galaxies Still Misbehaving*, earlier evidence for dark matter came from Fritz Zwicky when he observed clusters of galaxies. Zwicky observed that galaxies in the cluster were moving too fast to be gravitationally bound to the visible mass in the cluster. X-ray observations have uncovered further evidence for unseen mass in clusters of galaxies.

The particular discovery discussed is this article is from the ROSAT satellite, an X-ray observing satellite that launched in 1990. ROSAT observed a group of galaxies and found a cloud of hot gas lying between the galaxies. Out in open space a cloud of hot gas would typically dissipate rather quickly. In order to keep a cloud of hot gas together for any length of time, the gas must be gravitationally bound to the galaxies in the group. However, the mass of the galaxies and gas were not enough to bind the hot gas to the group of galaxies. This observation led to the conclusion that there must be more mass in the group of galaxies than could be seen – further evidence for dark matter.

A back-of-the-envelope calculation can be done for the ROSAT data by comparing the kinetic energy of the hot gas to the gravitational energy of the mass of the galaxies plus gas. One of our lesson plans, “Dark Matter NASA Conference”, goes through the calculations using the real measurements from ROSAT.

Other resources

The following web pages have more detailed information:

- ROSAT data hint at a closed Universe: http://findarticles.com/p/articles/mi_m1200/is_n2_v143/ai_13324072
- ROSAT mission web page: http://heasarc.gsfc.nasa.gov/docs/rosat/rosgof.html

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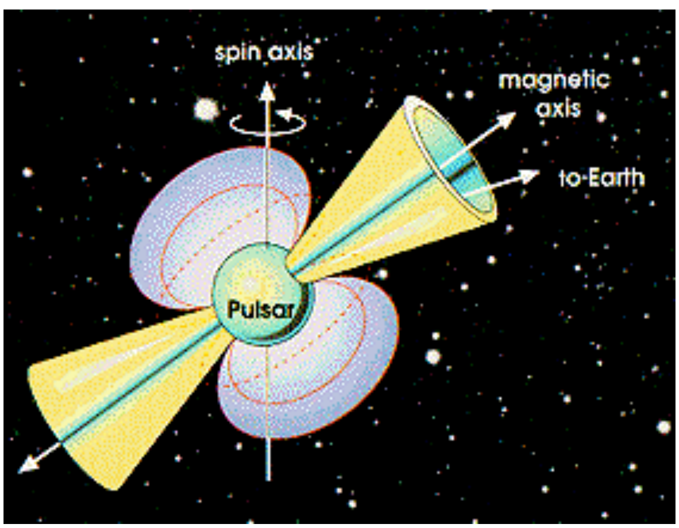
Pulsar Gravitational Waves Win Nobel Prize

The primary message of this article is that Einstein's theory of relativity continues to be tested, and it continues to pass those tests.

In 1993, the Nobel Prize for physics was awarded to Russell Hulse and Joseph Taylor of Princeton University. The prize was awarded for their discovery of the first pulsar in a binary system and subsequent work using the arrival times of pulses from the pulsar to give the first evidence of gravitational waves.

Pulsars

We can't introduce pulsars without first introducing neutron stars. A neutron star is one of the possible endpoints of stellar evolution. When a massive star dies in a supernova, the core that it leaves behind can either collapse into a black hole or into a neutron star (see links under "Other Resources" on stellar evolution for more information on how neutron stars form). Neutron stars are very dense – they have about 1.4 times the mass of our Sun smooshed into a volume with a diameter of about 20 km. Pulsars are neutron stars with strong magnetic fields, from which we observe pulses of radiation as the neutron star rotates (as illustrated below).



A diagram of a pulsar, showing its rotation axis and its magnetic axis

Hulse and Taylor's Discovery

Hulse and Taylor first observed the pulsar PSR 1913+16 in 1974 while they were searching for pulsars. They soon discovered that it was in a binary system with another star. In fact, PSR 1913+16 was the *first* pulsar to be found in a binary system. Hulse and Taylor knew that such a system would be very interesting, particularly in what it could tell us about relativity in an environment that we can't reproduce on or near the Earth.

PSR 1913+16 and its companion star orbit with a period of 7.75 hours. PSR 1913+16 rotates with a period of 59 milliseconds, as derived from the time between its pulses. Hulse and Taylor measured the arrival times of the pulses of light from PSR 1913+16 as they arrived at Earth. Using these arrival times, Hulse and Taylor could determine the orbital properties of the binary system. As the pulsar orbits its companion star, the pulsar is closer to Earth and the pulses arrive slightly sooner. When the pulsar is at periastron (the place in the orbit where the two stars are closest together), the pulses appear bunched together because the pulsar is moving fastest in its orbit at that point. By analyzing these pulses and the pulse patterns throughout the orbit of the pulsar, they were able to find the velocity of the pulsar in its orbit and subsequently calculate the orbit properties. They found the orbit is elliptical with a semi-major axis of 500,000 km.

Hulse and Taylor observed the orbit of PSR 1913+16 over time, and found the signatures of three different relativistic effects in the data. First, they found a signature of time dilation, such that when the stars neared each other in their orbit, the gravitational field is stronger, and the pulses slowed down. Second, they found evidence of the warping of spacetime, with the periastron of the orbit advancing by 4.2° each year (much faster than the advance of the perihelion of Mercury's orbit). Third, they found that the orbit itself was shrinking, based on their observation that the orbital period of PSR 1913+16 and its companion was decreasing over time. From this they determined that the size of the orbit was shrinking by 3.1 mm each orbit.

It's that shrinking orbit that was evidence for gravitational waves. In order for the orbit to shrink, energy had to be leaving the binary system. Einstein's General Theory of Relativity predicted that gravitational waves could carry energy from a system, but no one had seen evidence for gravitational waves prior to Hulse and Taylor's results. This was the first physical evidence of the existence of gravitational waves.

Note: The literature often refers to PSR 1913+16 as a "binary pulsar". Be aware that this does not necessarily mean that the two stars in the system are pulsars. Instead, it simply means that PSR 1913+16 is a pulsar that lies in a binary system. The term "binary pulsar" is not meant to reveal information about the companion star. In this case it is likely that the companion is a neutron star, but we do not detect pulses from it.

LISA and the future of gravitational waves

Even today gravitational waves have not been directly observed. Scientists have been working on the problem since this first discovery, but gravitational waves are exceedingly hard to detect. Essentially, a gravitational wave stretches and shrinks spacetime by a tiny amount. So far, there is one gravitational wave experiment that has conducted several experimental runs since 2002, but they have not yet seen the signature of gravitational waves. The next step in detecting gravitational waves is a space-based mission called LISA (Laser Interferometer Space Antenna).

Gravitational wave research is currently the very cutting-edge of astronomy and physics, and is one of the unsolved problems facing scientists today. With the projected launch of LISA in 2015, current middle- and high-school students may be the scientists and graduate students who will see the first direct evidence of gravitational waves.

Other resources

The following web pages have more detailed information:

- Press release announcing Nobel prize for Hulse and Taylor: http://nobelprize.org/nobel_prizes/physics/laureates/1993/press.html
- Taylor's Nobel Lecture: http://nobelprize.org/nobel_prizes/physics/laureates/1993/taylor-lecture.html
- Hulse's Nobel Lecture: http://nobelprize.org/nobel_prizes/physics/laureates/1993/hulse-lecture.html
- Neutron Stars and Pulsars: http://imagine.gsfc.nasa.gov/docs/science/know_l1/pulsars.html
- Gravitational Waves: http://imagine.gsfc.nasa.gov/docs/features/topics/gwaves/gwaves.html
- LIGO website for all audiences: http://www.ligo-la.caltech.edu/index.htm
- LISA Mission homepage: http://lisa.nasa.gov/

Fool-Proofing Galactic 'Candles'

The primary message of this article is that astronomers can use a certain type of supernova, Type 1a supernova, as a standard candle to determine distances in the Universe. Type 1a supernovae can be observed in objects at much further distances that the other standard candle, Cepheid variables, discussed in earlier editions of Cosmic Times.

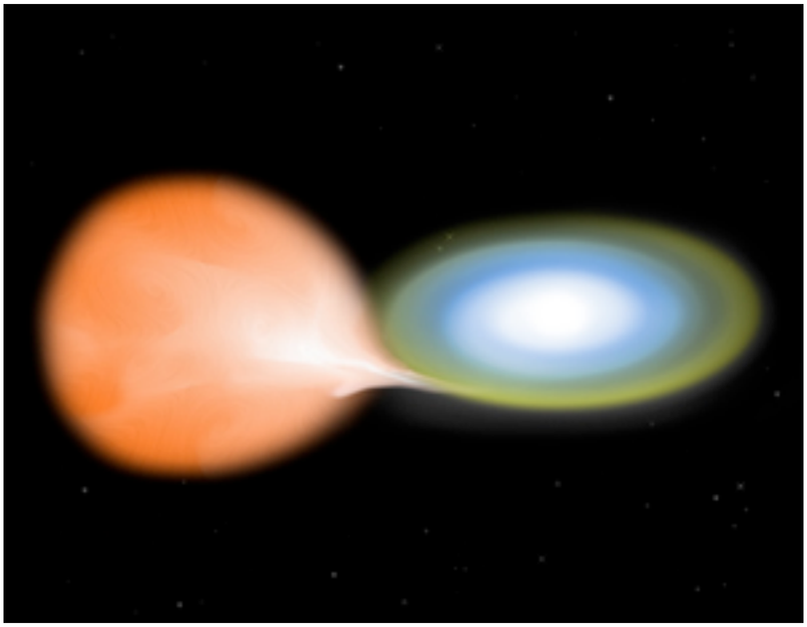
In this article, the Cosmic Times threads of distances in the Universe and supernovae come together as we discover that one type of supernovae, Type 1a supernovae, can be used as standard candles. The idea of standard candles comes up in nearly every edition of the Cosmic Times because the importance of standard candles in astronomy cannot be overemphasized – they are essential for determining distances to objects in the Universe.

Type 1a Supernovae

The last two editions of Cosmic Times have introduced the idea of supernova and different types of supernovae explosions. We know that supernovae are essentially exploding stars; however, there are two primary types of supernovae – those from a star at the end of its life and those from a white dwarf exceeding its critical mass. This latter type of supernovae, called Type 1a supernovae, is the type that we're interested in here.

A low-mass star (one with less than about 10 times the mass of our Sun) ends rather quietly when it exhausts its supply of material for nuclear fusion. Without nuclear fusion to hold the core up against gravity, the core collapses into a white dwarf. A white dwarf is held up against gravity by what is called "electron degeneracy pressure". There is a limit, however, to the amount of mass that electron degeneracy pressure can hold against gravity – 1.4 solar masses. When a white dwarf exceeds 1.4 solar masses, it will explode in a Type 1a supernova.

In general, a white dwarf all by itself in space will not gain mass very quickly. However, when a white dwarf is in a binary system, its companion may donate mass through two different mechanisms. If the white dwarf's companion is a massive star, it might put off a strong stellar wind (like our Sun's solar wind, but much stronger). Some of that stellar wind will be picked up by the white dwarf. A faster method for the white dwarf gaining mass is if its companion is a low-mass star that becomes a red giant star. If the two stars are close enough, the red giant may become "too big for its britches" and lose some of its outer layers of mass to the white dwarf (see image below).



Artist's impression of a binary star system with a white dwarf and a low-mass companion that has become a red giant. The red giant "donates" mass to the white dwarf. If the white dwarf's mass exceeds 1.4 solar masses, it will collapse and explode as a Type 1a supernova.

Image Credit: CXC/M.Weiss

Type 1a Supernovae as Standard Candles

No matter what the mechanism that causes a white dwarf to gain mass, once it exceeds 1.4 solar masses, it will explode in a Type 1a supernova. Because they all explode at approximately the same mass, the explosions should be pretty much the same, no matter where they occur in the Universe. This is why astronomers can use Type 1a supernovae as standard candles. Type 1a supernovae are quite bright, so they can be observed at very large distances – much further distances than Cepheid variables, opening up more of the Universe for detailed study.

This article discusses a correction to the standard candle scale for slight differences in Type 1a supernovae. These differences might arise because the progenitor white dwarfs have different abundances of materials, or perhaps their surrounding environments are different. Either way, astronomers have determined a correction that accounts for the differences and re-calibrates the Type 1a distance scale. This sets up Type 1a supernovae for their important return in the 2006 Cosmic Times, where they become critical in the discovery of dark energy.

Other resources

The following webpages have more detailed information:

- Background on the Life Cycles of Stars: http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/background-lifecycles.html
- White Dwarf Stars: http://imagine.gsfc.nasa.gov/docs/science/know_l2/dwarfs.html

2006 Cosmic Times

This edition is the last of the series, with the publication date chosen to encompass the discovery of dark energy, a puzzling new component of our Universe that had been undetected until 1997. Since that first discovery, astronomers have confirmed its presence and its overwhelming abundance in our Universe. This edition discusses some of the most recent pieces of evidence for dark energy and NASA's future plans for pinning down its elusive nature. In so doing, this edition returns to the cosmic microwave background (CMB), and shows a more detailed map of the early Universe as observed by the Wilkinson Microwave Anisotropy Probe (WMAP). In addition, the Nobel Prize is awarded to the pair of scientists responsible for the two main science results of COBE, which we introduced in the 1993 Cosmic Times.

The language in the 2006 newspaper mimics the style of writing of newspapers of today. Hence, it should be easier to read than previous editions; though, the concepts continue to get harder. We have taken some creative license to make the newspaper more readable in a classroom setting.


Age of the Universe: 13.7 Billion Years

COSMIC TIMES

2006

Size of the Universe: 94 Billion Light Years

Faster Walk On The Dark Side

Journey to Cosmos' Dark Heart

Seeds of Modern Universe

Biggest Mystery: What is Dark Energy?

'First Light' Wins Nobel

Sorting Out the Dark Stuff

Summary of the 2006 Articles

Faster Walk on the Dark Side

Recent observations have confirmed the 1997 discovery that the Universe is expanding at an increasing rate. The energy from this accelerated expansion makes up nearly 75% of the energy and matter in the Universe. This article describes the latest evidence for this "dark energy".

Seeds of Modern Universe

NASA's Wilkinson Microwave Anisotropy Probe (WMAP) has picked up where COBE (featured in the 1993 edition of Cosmic Times) left off by providing a more detailed baby picture of the Universe, with the seeds of modern structures finally coming through.

Biggest Mystery: What is Dark Energy?

The nature of dark energy is still a puzzle, with several theories in current contention, including the cosmological constant and quintessence. This article describes astronomers' attempts to understand this mysterious energy.

Sorting Out the Dark Stuff

This article clarifies the difference between two very different unseen components of the Universe: "dark energy" (seen as a speeding up of the expansion of the Universe), and "dark matter" (a type of matter whose effects we see gravitationally).

"First Light" Wins Nobel

The scientists responsible for the first detailed spectrum and map of the cosmic microwave background are honored with the Nobel prize for physics.

Journey to Cosmos' Dark Heart

NASA plans to study the nature of dark energy in more detail by collecting data for ever-more-distant supernovae. This article describes the three satellite missions that are currently being considered.

Notes on the 2006 Articles

Faster Walk on the Dark Side

The primary message of this article is that scientists have recently discovered a new component to the Universe, called dark energy. Dark energy is causing the expansion of the Universe to accelerate instead of decelerate, as would have been expected from the effects of gravity. A secondary message is that there are several lines of evidence for dark energy.

There seems to be a feeling that there are no longer any mysteries left to discover in the Universe. Up until a decade ago, astronomers and physicists seemed to think that the only thing left was to iron out all the details. When the discovery of dark energy came along, the entire scientific community got excited. This type of revolutionary discovery is something that scientists dream of working on.

In this article introducing dark energy, we used the Integrated Sachs-Wolfe effect as the anchor point, but it is not the most important message of the article. Rather, it is more important for your students to understand that there is something out there that we hadn't previously observed, nor did current theories predict its presence. The discovery is so new that astronomers do not yet have a good handle on what it is, but they can characterize its observable effects on the large-scale structure of our Universe.

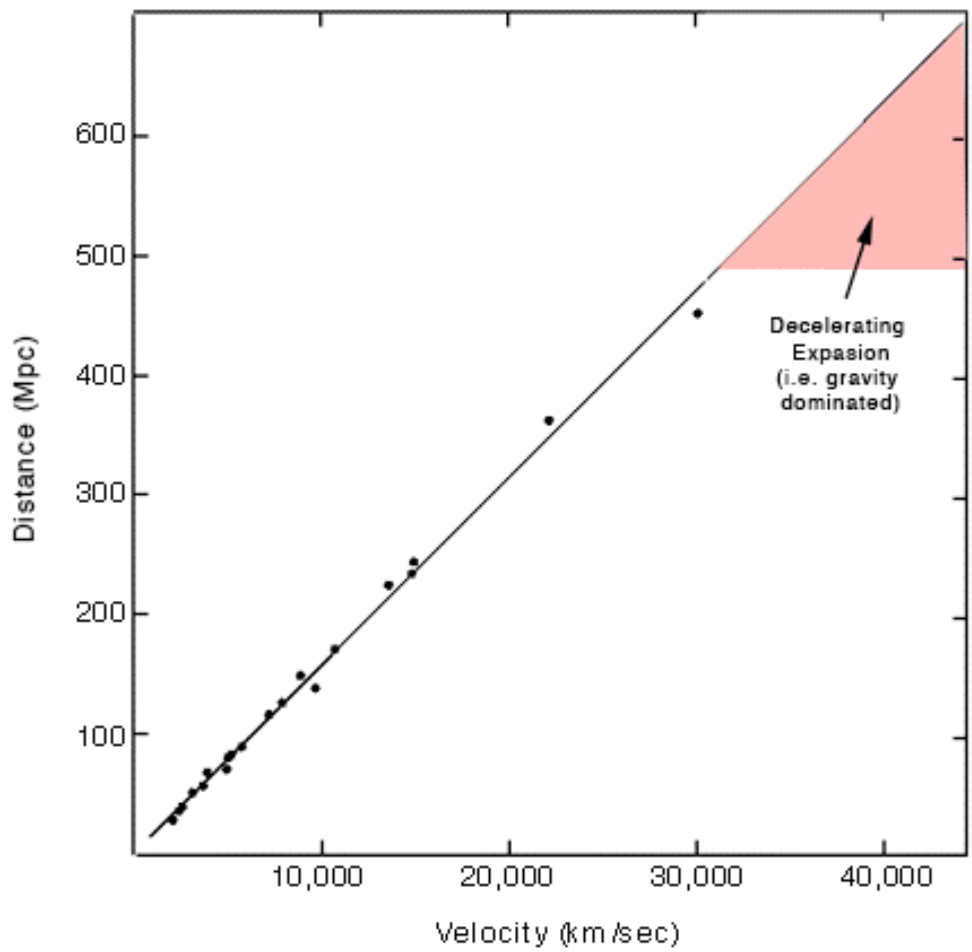
The Discovery

In the 1929 edition of Cosmic Times, Edwin Hubble had discovered that the further a galaxy was from the Earth, the faster it was receding. The relationship between distance and the velocity of a galaxy (or redshift of that galaxy) was a remarkably straight line. From this, we saw that the Universe was expanding. The straight line in the distance-velocity relationship indicates that the expansion occurs at an approximately constant rate over the timescales that we can measure.

Another thing to note about Hubble's Law is that when we look at further and further galaxies, we are really looking at slices of the Universe's history. This stems from the fact that light takes time to travel to us, so we really see objects as they were when the light was emitted. The light we receive from a galaxy that is 50 million light years away is showing us that galaxy as it looked 50 million years ago. In this way, astronomers will often use the ideas of distance and time in the Universe's past interchangeably.

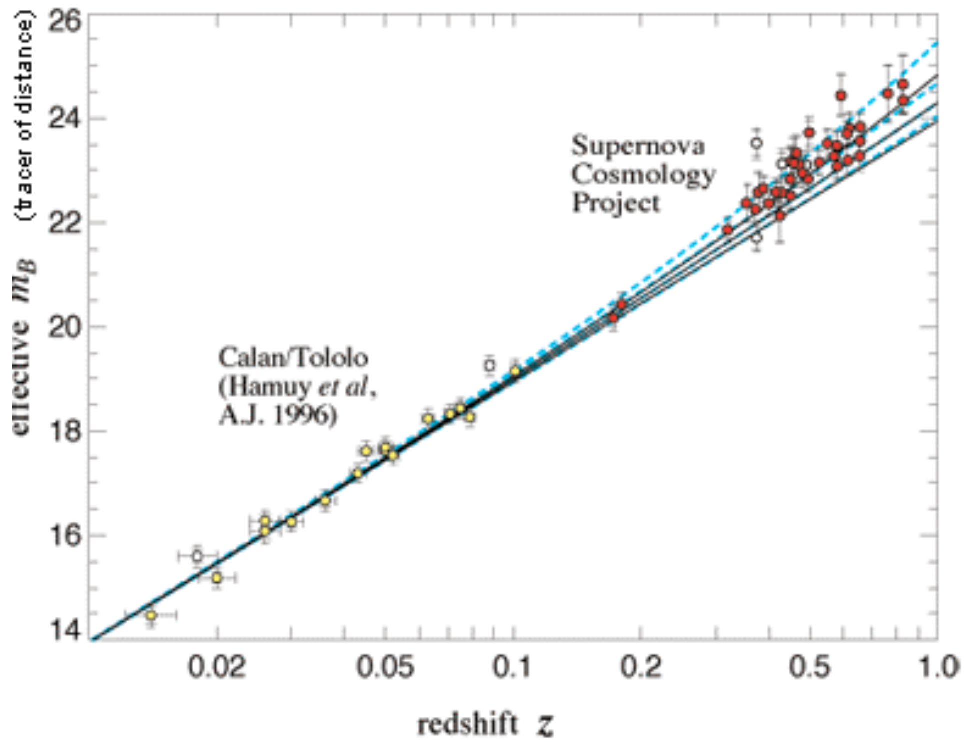
As mentioned above, the data prior to 1997 pointed to a fairly constant rate of expansion in the Universe. However, astronomers did not expect that to hold indefinitely because of the expected effects of gravity. Of all of the fundamental forces in physics, gravity works over the largest distances, and it tends to pull things together. So, over long timescales, we would expect the expansion to slow down. Astronomers knew that at some distance, we should start to measure deviations from Hubble's Law due to this slowing expansion.

A natural question is, what would the Hubble plot look like once we start seeing deviations due to slowing expansion, as we assumed we should see. Consider a given redshift, or recession velocity, and recall that we are looking into the past with these observations. If the expansion rate has been slowing down, then these galaxies should be closer than they would have with constant expansion. So, we expect that the points should start to fall below the line, as illustrated below.



Plot of Hubble's Law, with the red region showing where points would start to fall if the expansion of the Universe is decelerating from the effects of gravity.

Prior to 1998, this was what astronomer expected to find, if they could just observe galaxies at great enough distances. However, in 1998 two groups of astronomers measured distances to Type 1a supernovae in distant galaxies. (Recall that the 1993 Cosmic Times introduced the idea of using Type 1a supernovae as standard candles – it may be helpful to review the teacher's notes for that article). The groups also measured redshifts for the galaxies and added their data to a Hubble plot (distance versus redshift, or velocity). These new observations finally showed statistically significant deviations from the straight line normally seen in Hubble's Law. However, the deviation was not in the direction they had expected! Instead of the points starting to fall below the line, which would be expected from a slowing expansion due to gravitation, they found that the points started to fall *above* the line.



Hubble's Law showing the addition of distant Type 1a supernovae. Note that they all lie above the projected Hubble's Law (black line) from previous data.
Credit: Perlmutter et al., 1998, Astrophysical Journal, v. 516

Scientists are cautious when it comes to revolutionary observations, so the change in astronomers' thinking did not change right away. The data needed to be tested further, and more data was needed before the idea of an accelerating expansion was fully accepted. However, all subsequent measurements using different independent methods confirmed that the expansion of the Universe was speeding up, rather than slowing down. This discovery changed our understanding of the Universe.

Note that in one of the associated lesson plans, titled "Measuring Dark Energy", students reproduce the deviation from Hubble's Law for themselves with modern supernova data.

Integrated Sacks-Wolfe

One type of test of dark energy involves measurements of the cosmic microwave background (CMB). Recall that the CMB was created just a few hundred thousand years after the Big Bang (as discussed in the 1965 Cosmic Times article, *Murmur of a Bang* and the 1993 Cosmic Times article, *Baby Universe's 1st Picture*). Since the effects of dark energy become apparent only over the largest scales, more precisely over large timescales, the CMB is an ideal laboratory for dark energy studies.

As the article mentions, gravity is a property of matter, and often we depict a "gravitational well" around massive objects. Such a depiction is shown below.

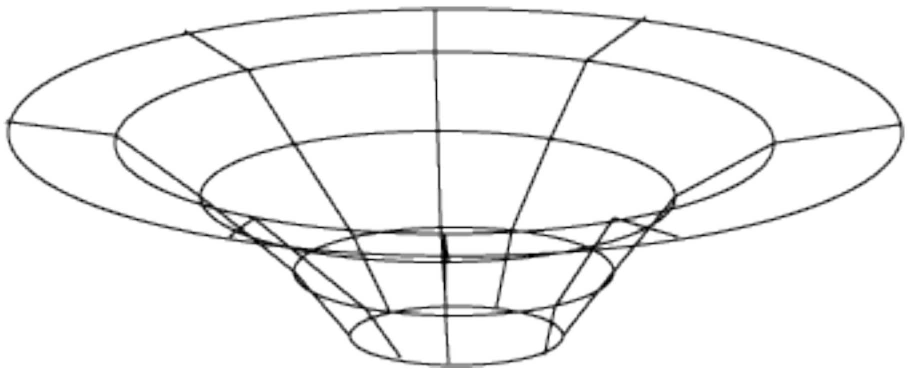
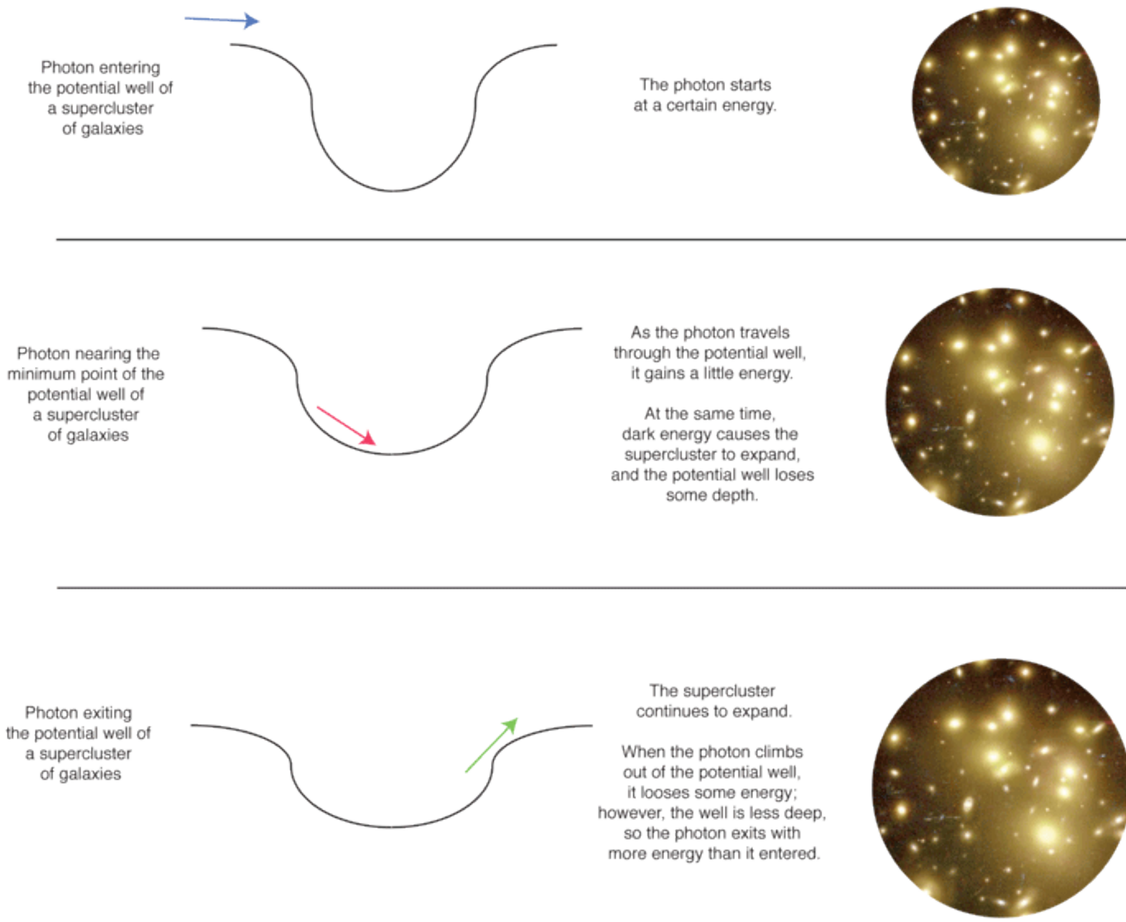


Illustration of a typical depiction of a gravity well in spacetime. The well represents a place in spacetime where a massive object "dents" spacetime, causing an attraction between the object and other objects. The "well" in spacetime also causes the paths of light beams to bend near the massive object.

For the largest structures in the Universe (such as a supercluster of galaxies), dark energy will have a noticeable effect on the energy of a CMB photon crossing through its gravitational well. The photon gets a boost in energy when entering the gravitational well. Normally, the photon would lose that extra energy as it climbs back out of the well. However, dark energy stretches, and slightly squashes, the gravitational well over the time it takes the photon to travel across large structures. It takes less energy for the photon to escape the well than it received on the way into the well. So the exiting photon keeps a portion of that extra energy.



This illustration shows how the Sachs-Wolfe effect works. As a photon from the cosmic microwave background enters the potential well of a supercluster of galaxies, it starts with a certain energy. As it travels through the supercluster, the photon gains energy until it is at the bottom of the potential well. In the absence of dark energy, the photon would lose all of its gained energy on its trip out of the potential well of the supercluster. However, dark energy will cause the supercluster to expand, slightly shrinking the potential well. The exiting photon will retain some of the energy it gained on its trip through the supercluster.

When astronomers look across the sky, the spectrum of the CMB will be slightly different in regions where those photons have crossed gravitational wells that have been shrinking.

Other resources

The following web pages have more detailed information:

- Integrated Sachs-Wolfe Effect, with a nice animation of the CMB photons gaining energy as they pass through a supercluster: http://ifa.hawaii.edu/cosmowave/supervoids/the-integrated-sachs-wolfe-effect/
- Dark Energy: Astronomers Still 'Clueless' About Mystery Force Pushing Galaxies Apart: http://www.space.com/scienceastronomy/astronomy/cosmic_darknrg_020115-1.html

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Seeds of Modern Universe

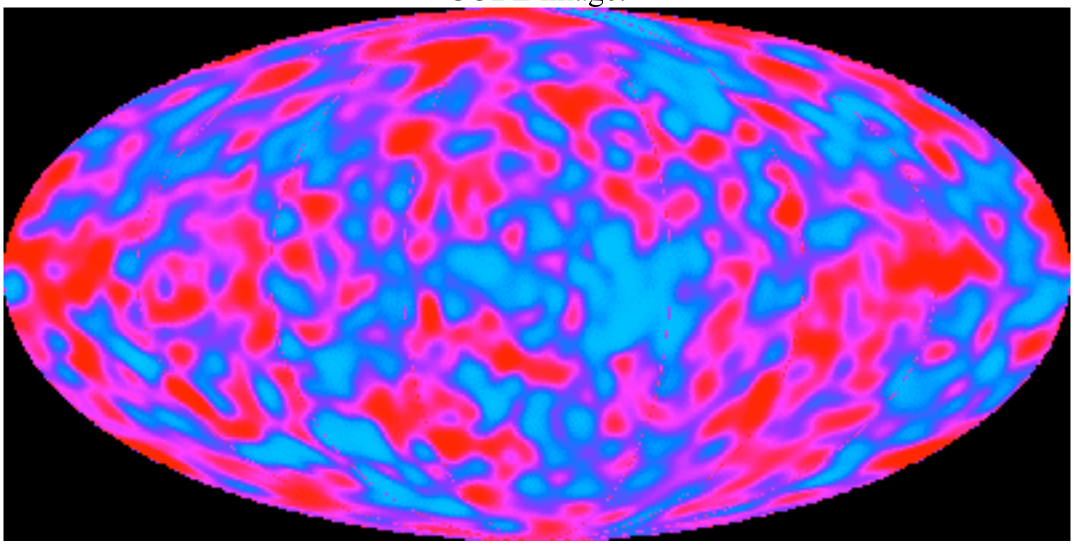
The primary message of this article is that a recent NASA mission, the Wilkinson Microwave Anisotropy Probe (WMAP) has returned a more-detailed map of the cosmic microwave background (CMB), which is allowing cosmologists to begin to connect early density differences with present-day large-scale structures in our Universe.

Wilkinson Microwave Anisotropy Probe (WMAP)

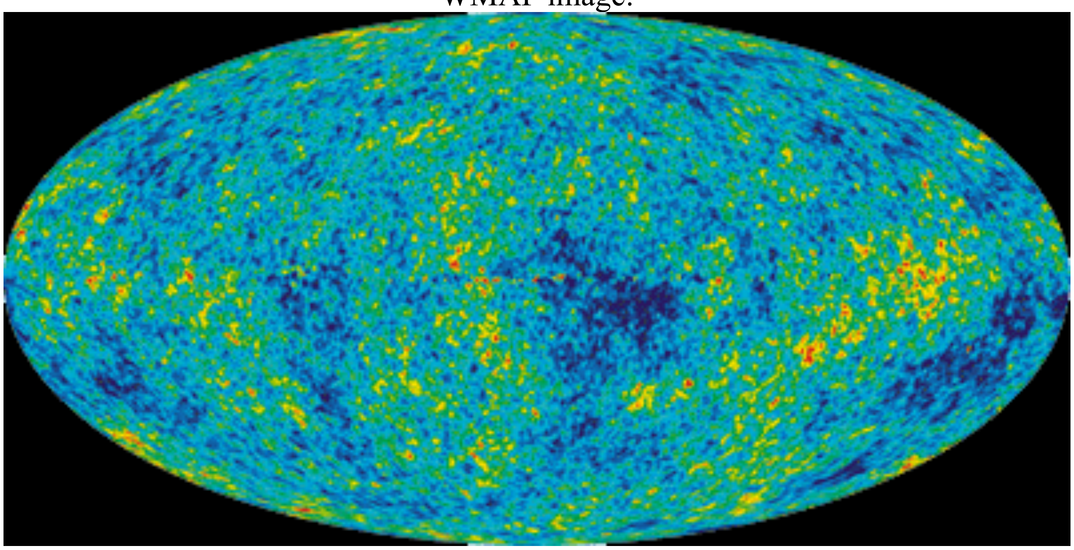
After the success of the COBE mission, as discussed in the 1993 edition of Cosmic Times, cosmologists wanted to follow-up with a mission that could map the cosmic microwave background (CMB) in greater detail. The result was the Wilkinson Microwave Anisotropy Probe (WMAP). The first WMAP map of the CMB was released in February 2003. A more refined map released in March 2006, which is the one highlighted in this edition of Cosmic Times. As of August 2008, WMAP continues to scan the sky, creating a more-and-more detailed map of the CMB.

The images below show the maps from COBE and WMAP to illustrate the increased detail in the WMAP data.

COBE image:



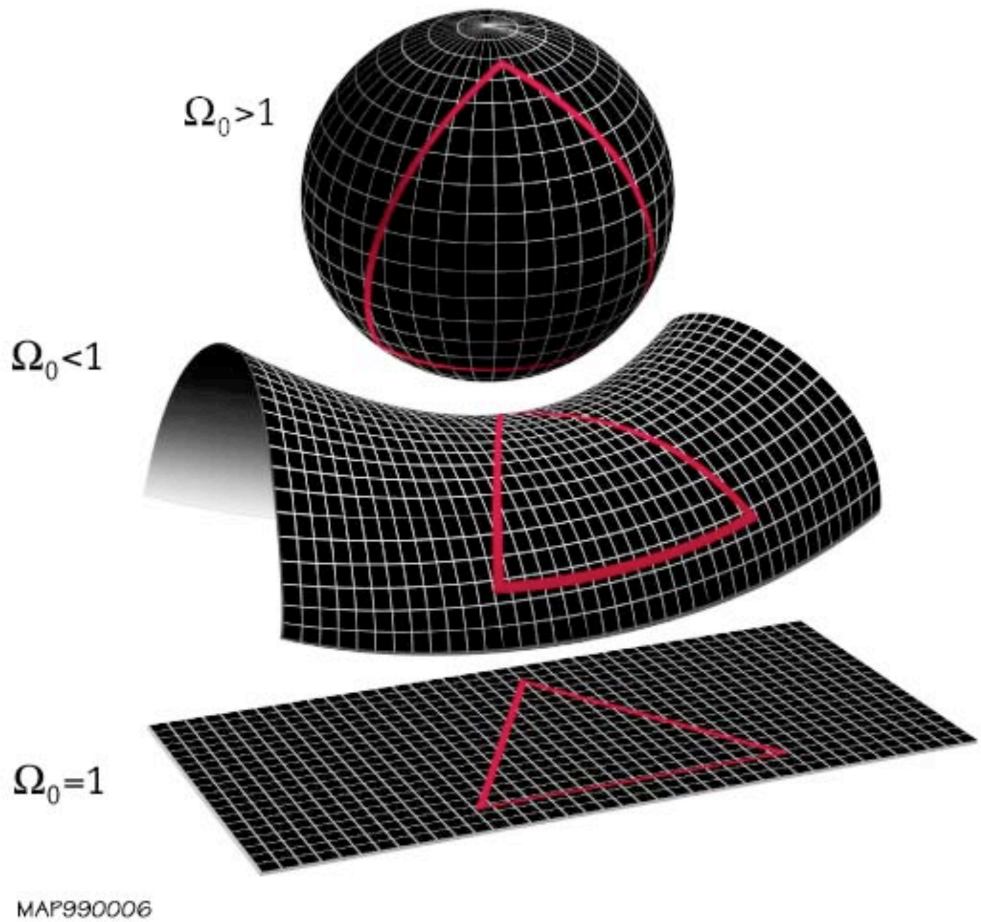
WMAP image:



Two maps of the cosmic microwave background.
Top: The map from COBE. (*Credit: COBE/NASA*)
Bottom: The map from WMAP. (*Credit: WMAP/NASA*)

Flat Universe

In the early 1990s, one un-answered question in cosmology was what the ultimate geometry of the Universe was. There were three possibilities envisioned: positively curved like the surface of a sphere, negatively curved like a saddle, or flat like a geometric plane. It is difficult to envision these geometries for our 4-dimensional spacetime, but the image below shows what they look like for 2-dimensionals.



Three possible geometries. The top shows a spherical geometry, which is characterized by a positive curvature and is finite in extent. The middle image shows a hyperbolic parabolic, or a saddle-like, geometry, which is characterized by a negative curvature and is infinite in extent. The bottom geometry is a plane, or flat, geometry, which is characterized by no curvature and is infinite in extent.
Credit: WMAP/NASA

Measurements at the beginning of this decade by balloon-borne instruments such as BOOMERANG and MAXIMA demonstrated that the geometry of the Universe is flat. WMAP confirmed these measurements. However, WMAP was able to go further. With the geometry of the Universe pinned down, WMAP was able to determine the relative abundances of the different components of the Universe. WMAP found that normal matter comprises 4%, of the Universe, dark matter at 23%, and dark energy at 73%.

Refined Picture of the Early Universe

After reading this article, one question that might linger is how are the CMB and inflation related? Indeed, the article discusses how the current map of the CMB can tell us about the period of inflation, but the two events – inflation and the emission of the CMB – occurred at different times in the history of the Universe.

The CMB was emitted about 400,000 years after the Big Bang, which is relatively close to the Big Bang, considering the 13 billion year age estimate of the Universe. However, inflation occurred within a few seconds of the Big Bang, so it might be hard to see how the CMB could tell us much about inflation.

When we discussed inflation in the 1993 edition of Cosmic Times, we said that it explained some of the problems with Big Bang theory, including the "smoothness" of the CMB. As it turns out, inflation also explains another problem of Big Bang theory – how structure in the Universe formed. Structure came about because of some quantum physics effects, namely the Heisenberg Uncertainty Principle. Because of this, not all regions of spacetime experienced the exact same amount of inflation. Tiny regions that experienced a little less inflation had higher densities than those that experienced a little more inflation. The higher-density regions represent places where gravity took hold and started the process of structure formation.

The WMAP picture of the early Universe can resolve some of these structures, allowing cosmologists to begin to associate density fluctuations in the early Universe with grand-scale structures that we see today.

Other resources

The following web pages have more detailed information:

- WMAP Website – there are teaching materials, animations and further information about cosmology which may be useful: http://wmap.gsfc.nasa.gov/
- Timeline of the Universe Image: http://wmap.gsfc.nasa.gov/media/060915/index.html
- BOOMERANG: http://cmb.phys.cwru.edu/boomerang/
- MAXIMA: http://cosmology.berkeley.edu/group/cmb/index.html

Biggest Mystery: What is Dark Energy?

The primary message of this article is that dark energy is an as-yet unsolved mystery in astronomy. When presented with such a mystery, scientists rally to develop theories to explain the mystery, which is also the case with dark energy.

When scientists are faced with a new mystery, they collect the available data and develop theories to explain the new data. Over time, new data will contradict some of those theories, and they will drop out of contentions. Others will be bolstered by the new data. This is the very process of science. Dark energy is no different from any other scientific mystery. Astronomers have theories for what it is, and develop new tests to differentiate those theories.

Astronomers have a few front-runners for what dark energy is, including the cosmological constant and quintessence, as discussed in this article. The primary difference between these two models is that the cosmological constant is a constant energy field filling all of space; whereas, quintessence allows for changes in the energy field over space and time.

Over time, new data will help astronomers determine which models work best. Some theories may require modification while others will be abandoned. We will all just have to wait and see.

Sidebar: Sorting Out the Dark Stuff

The primary message of this article is that our Universe is made up of three different components – normal matter, dark matter, and dark energy – but dark matter and dark energy are not the same thing, nor are they directly related.

With names like "dark matter" and "dark energy", it is easy to confuse the two and to assume that they have some direct relationship to each other. However, dark matter and dark energy are two very different beasts. This article is meant to help students differentiate between the two. Here is a brief description to help:

Dark matter: Dark matter is a type of matter that has been indirectly observed by its gravitational effect on large-scale objects in our Universe, such as galaxies and galaxy clusters. Without the gravitational effect of some additional kind of matter, the galaxies and clusters of galaxies that we see would not be held together. This additional matter is called dark matter, but it has not been directly observed.

Dark energy: Dark energy is a type of energy that has been indirectly observed through its effect on the expansion rate of the Universe. Without dark energy, we would expect that the expansion of the Universe would be slowing down over time, due to the mutual gravity of the matter and energy in the Universe. However, the expansion appears to be speeding up over time, leading astronomers to conclude that there is "something" out there that counteract gravity on the largest scales. That "something" is called dark energy, but it has not be directly observed.

What do they have in common? Both dark matter and dark energy have only been indirectly observed, and both have the word "dark" in their names.

What makes them different? Comparing dark matter with dark energy is a bit like comparing the earth and sunlight. The two are not the same type of object. One is a form of matter that gravitates just like any other matter in the Universe (dark matter). The other is a form of energy that acts differently from any other energy that we have encountered in the Universe (dark energy).

It is important to know that dark matter and dark energy are different, and their presence is seen in different types of observations. Astronomers know certain characteristics of each, but when it comes down to it, they aren't really sure what either one is yet.

'First Light' Wins Nobel

The primary message of this article is that the scientists responsible for the COBE instruments that measured the spectrum and mapped the cosmic microwave background back in 1993 were awarded with the Nobel Prize for physics.

In the 1993 edition of Cosmic Times, we featured articles on the results of the COBE mission, which produced a spectrum and mapped the cosmic microwave background (CMB). By measuring the CMB so accurately, they proved that cosmology could be a precise science, allowing scientists to test predictions of different theories of the origin of our Universe.

This article in the 2006 Cosmic Times updates the COBE story with the announcement of the awarding of the Nobel Prize for Physics to the COBE mission scientists. This honored the achievements of COBE and its contributions to the field of cosmology. The fact that this appears in the same edition as the WMAP results shows the continuity of science, and how one accomplishment builds on earlier ones.

For more information on the discoveries of COBE, please see the 1993 edition of *Cosmic Times*.

Other resources

The following web page has more detailed information:

- Nobel Prize for Physics 2006:
  http://nobelprize.org/nobel_prizes/physics/laureates/2006/announcement.html

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Journey to Cosmos' Dark Heart

The primary message of this article is that NASA and the Department of Energy are planning to continue the study of dark energy by launching a mission to detect a large number of distant supernovae.

When scientists encounter a mystery, it is in their nature to seek out an answer. Dark energy is one of the biggest mysteries that modern-day astronomers have faced, so they want to study it further. Agencies that run missions and telescopes, like NASA and the Department of Energy, respond by allocating funds to develop new technologies and to refine old technologies to study the mystery.

The first hints of dark energy came with observations of supernovae billions of light-years from Earth. One way to continue studying dark energy is to observe a larger number of supernovae across the Universe. That is the plan of JDEM, though the exact details of the mission have not yet been determined.

Process from mystery to mission

This article can be used to illustrate the process that NASA goes through to develop a mission. Long before a satellite is launched, a NASA mission begins with a question that astronomers want to answer. Some questions that have driven NASA missions include, "What powers a gamma-ray burst?" (Swift), "How is the cosmic microwave background distributed across the sky?" (COBE and WMAP), and "What is the nature of dark energy?" (JDEM). With a question in hand, astronomers determine the types of information they need to begin to answer the question. In response, NASA solicits the astronomical community to submit mission concept ideas. Teams of astronomers and engineers write proposals for telescopes and instruments that they believe will provide the information necessary to answer the question. These proposals have to demonstrate how each proposed mission concept would answer the question, and why a particular method might be better than others.

Using a mission concept, or a combination of mission concepts, NASA then develops a mission plan. NASA invites its own teams, teams from University laboratories, other government agencies, and industry (i.e. companies outside of the government and Universities) to write proposals to build the telescopes, instruments and spacecraft based on the mission plan. The teams that participate in the mission are chosen from this competitive process based on the team with the best combination of qualifications and skills to get the job done with a given budget.

Usually, construction of the flight instruments, telescopes, and spacecraft doesn't take place until years after the initial question was posed. Once construction starts, it can take another several years to complete. Each group is responsible for testing their own contributions to the final spacecraft, but NASA will also test the spacecraft once it is assembled into a complete mission. Only then will it be launched into space.

The process from a question to the launch of a mission can take 10 years or more (usually more). As of late 2008, JDEM is still in the mission-planning phase. If all goes as planned, JDEM may launch in a decade, with its first science results returned a year or so later.

Other resources

The following web page has more detailed information:

- JDEM Program: http://universe.nasa.gov/program/probes/jdem.html