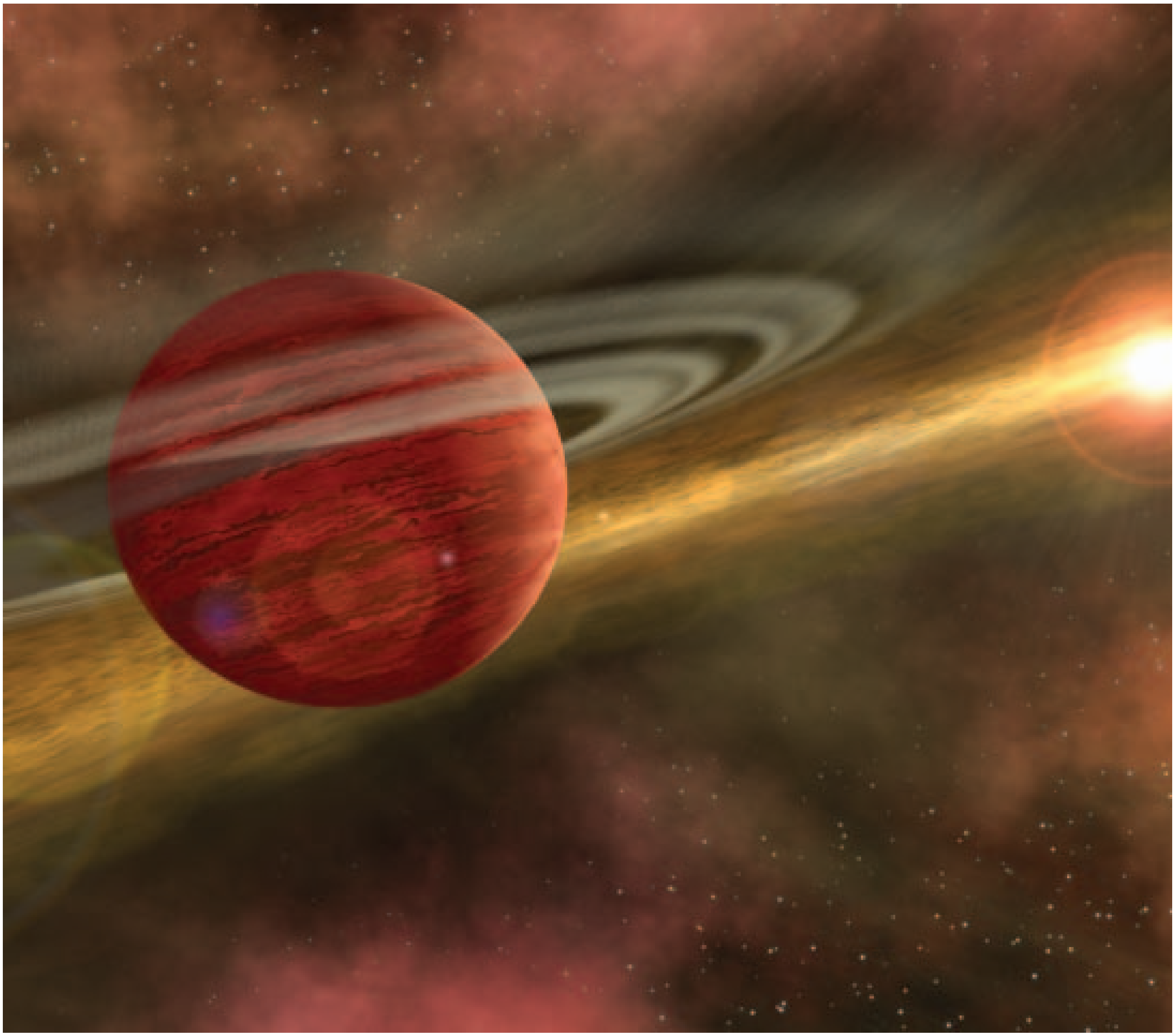
An Ancient Universe

How Astronomers Know the Vast Scale of Cosmic Time



A Guide for Teachers, Students, and the Public

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Credits

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Introduction

In the past 150 years, scientists have greatly advanced our understanding of the natural world. We know that we live on an ancient planet, that life on Earth has evolved in its diversity and complexity, and that the universe itself has evolved from a hot and dense early state. These assertions are supported by a web of evidence, and the ideas behind them can be and have been tested with a wide range of experiments. The understanding of our place in the universe and our place in the scheme of living creatures is one of the greatest achievements of the human intellect.

Many good books and articles have been published for teachers and the public on the scientific basis of evolutionary ideas in biology. But rather little is available to help explain *how* we know that the galaxies, stars, and planets are really old. In this booklet, we want to give you some of the background on how scientists have been able to measure ages so vast that human history is a mere blink of an eye in comparison. We also provide some references to classroom activities, and resources for further exploration of some the astronomical ideas we discuss.

As part of our discussion, we want to emphasize the methods by which scientists study cosmic age and evolution, and how this relates to the interwoven structure of scientific knowledge. We note that science and religion deal with different aspects of human existence. For example, science cannot answer such questions as *why* there is a universe or whether the universe has a "purpose". What science is very good at, however, is searching out physical laws that describe the behavior of matter and energy in the universe, and seeing how such laws make stars, planets, and 7th grade students possible.

A small, but vocal, minority of religious individuals has been urging a major revision of how evolution is taught in U.S. schools. Based on their personal beliefs, they find fault not only with biological evolution, but also with modern astronomical ideas about the age, expansion, and evolution of the universe. They have been actively pressing their case in the political, media, and educational arenas, and their loud arguments sometimes drown out other perspectives, including science.

As a consequence, there has been much concern, in both the educational and scientific communities, about attempts to abolish the teaching of evolution in our schools. Astronomers share this concern because the term *evolution* – which just means change with time – is an underlying theme in all of science. Not only is evolution a unifying concept in biology but it also describes the way in which the planets, stars, galaxies, and universe change over long periods of time.

Evidence from a host of astronomical observations, which we will discuss below, strongly supports the great age of these objects, as well as the fact that they change significantly over the billions of years of cosmic history. Students should be given the chance to learn about these changes and what they mean for the development of life on Earth.

Concerned by the tendency to de-emphasize the teaching of evolution, the President and Council of the American Astronomical Society, the main organization of professional astronomers in the United States of America, issued a formal statement on behalf of the astronomical community in 2000. The Society's members include men and women from a wide range of ethnic, cultural, and religious backgrounds. The statement reads in part:

> *"Research...has produced clear, compelling and widely accepted evidence that astronomical objects and systems evolve. That is, their properties change with time, often over very long time scales. Specifically, the scientific evidence clearly indicates that the Universe is 10 to 15 billion years old, and began in a hot, dense state we call the Big Bang.*
>
> *Given the ample evidence that change over time is a crucial property of planets, including our own, of stars, of galaxies and of the Universe as a whole, it is important for the nation's school children to learn about the great age of, and changes in, astronomical systems, as well as their present properties. . . .*
>
> *Children whose education is denied the benefits of this expansion of our understanding of the world around us are being deprived of part of their intellectual heritage. They may also be at a competitive disadvantage in a world where scientific and technological literacy is becoming more and more important economically and culturally.*
>
> *Sincerely,*
> *President Robert D. Gehrz*
> *On behalf of The American Astronomical Society"*

Let's take a look at the scientific discoveries that lie behind the Society's statement.

The Universe: An Overview

Telescopes on Earth: These two domes house the twin Keck Telescopes perched high above the clouds on Mauna Kea (an extinct volcano) on the Big Island of Hawaii. Each dome contains a telescope with many mirror segments, which combine to give a light collecting area of 10 meters (about 10 yards) across. With such telescopes, astronomers can detect the light of very distant (and thus faint) objects. (Courtesy of William Keck Observatory and Caltech)

Astronomy is increasingly recommended as an integral part of the school science curriculum. The study of astronomy is deeply rooted in culture and philosophy. It harnesses our curiosity, imagination, and a sense of shared exploration and discovery, and it is also an area of great interest to people of all ages—especially children. With new and better telescopes on the ground and in space, astronomy is one of the most exciting and rapidly-growing sciences today.

And what we learn from our instruments is that we live in a wonderful universe. No wonder astronomy has inspired artists and poets through the ages, from ancient Greece to today's television series. Astronomy, the study of the universe, reveals a cosmos that is vast, varied, and beautiful. The sky is our window on this universe. The sky and its contents are there for all to see on any clear night.

When astronomers talk about the universe, they mean everything that is accessible to our observations. The universe includes all that we can survey or experiment on, from the moon that orbits our own planet out to the most distant islands of stars in the vastness of space. Since we cannot visit most of the universe, we rely on the information it can send to us. Fortunately, we receive an enormous amount of cosmic information all the time, coded into the waves of light and other forms of energy that come to us from objects at all distances. The main task of astronomy is to decode that information and assemble a coherent picture of the cosmos.

Locally, our planet is one of nine that orbits the pleasantly energetic star we call the Sun. The solar system (Sun's system) also includes dozens of moons and countless pieces of rocky and icy debris left over from when the system formed. Astronomers now have many samples of these other worlds to analyze, including the rocks the astronauts brought back from the Moon, the meteorites (chunks of rock) that fall from space, including a few that were blasted off Mars long ago, and the cosmic dust we can catch high in the atmosphere.

The Sun is one of hundreds of billions of stars that make up a magnificent grouping (or island) of stars we call the Milky Way galaxy. Over a hundred of these stars are now known to have planets, just the way the Sun does. Some stars show evidence of being much older than the Sun, and some are just gathering together from the raw material of the galaxy.

One of the nicest things about the universe is that it sends its information to us at the fastest possible signal speed, the speed of light. This is an amazing 300,000 kilometers per second (or 186,000 miles per second, in units your student may be more familiar with). The other stars are so far away, however, that even at this speed, light from the next nearest star takes 4.3 years to reach us. And it takes light over 100,000 years to cross the Milky Way galaxy. (The distance light travels in one year, about 9.5 trillion kilometers, is called a *light-year* and is a useful unit of measurement for astronomy. We can then say that the nearest star is 4.3 light-years away.)

Despite these distances, the stars are so bright that we receive enough light (and other radiation) from them to learn a great deal about how they work and how long ago some of them formed.

Beyond the Milky Way lies the realm of the other galaxies. Our largest telescopes reveal billions of other galaxies (collections of billions of stars) in every direction we look. The Milky Way shares its cosmic neighborhood with several dozen other galaxies, but only one that is bigger than we are. That one, the great galaxy in the constellation of Andromeda, is 2.4 million light-years away. The light we see from the Andromeda Galaxy tonight left it 2.4 million years ago, when our species was just beginning to establish a fragile foothold on the surface of planet Earth. Some galaxies are so far away that their light takes over ten billion years to reach us.

Night Sky: The dome of the 4-meter Blanco Telescope at the Cerro Tololo Interamerican Observatory in Chile is seen silhouetted against the Magellanic Clouds, two nearby galaxies (seen as fuzzy star groups at left) and the inner regions of our own Milky Way Galaxy (stretching upwards toward the right). Taken by Roger Smith with a very sensitive electronic detector, the picture is also interesting because the only source of illumination is starlight. (Courtesy Roger Smith/NOAO/AURA/NSF)

As we shall see below, astronomers do not quote such mind-boggling distances or times idly. During the 20th century, they developed techniques for measuring the distances to stars and galaxies and establishing the vast scale of the universe in which we find ourselves.

In similar ways, astronomers have also found ways of establishing the scale of cosmic time. These measurements show that the universe had its beginnings about 14 billion years ago in a very dense, hot state we call "the Big Bang". The Sun and the Earth formed from the "raw material" gas and dust in the Milky Way galaxy some 4.5 to 4.6 billion years ago. The earliest evidence we have for living things on Earth goes back to about 3.7 billion years ago.

On this scale, everything with which we are normally concerned is recent indeed. Here is an interesting thought experiment. Suppose we were to compress the entire history of the universe from the Big Bang to today into one calendar year. On that scale, the dinosaurs would have flourished a mere few days ago, and the life-span of a person would be compressed to a tenth of a second. (To see this worked out in more detail, see the "cosmic calendar" activity whose web link is listed in the "For Further Exploration" section at the end.)

The Process of Science: How Do We Know?

The Andromeda Galaxy: The closest large galaxy to us is called the Andromeda Galaxy, for the constellation in which it is found. It is a large spiral-shaped collection of stars about 2.2 million lightyears from us–in other words, light takes more than 2 million years to reach us from this galactic neighbor. The area of the sky covered in this image is more than five times the area of the full moon. (Courtesy of T.A. Rector and B.A. Wolpa, National Optical Astronomy Observatories/AURA/NSF)

The nature of the universe, its age, its birth and life story, have been deduced through the process of science. This process has many aspects and stages. In the case of astronomy, it usually starts with making careful observations and measurements — something students can begin to do through inspection of astronomical images, and observation of the real sky. Together with our knowledge of the laws of physics, developed in laboratories here on Earth, these observations provide the basis for our understanding of the universe. From continuing observations, astronomers develop models and theories to explain how things work in the realms of the planets, stars, and galaxies.

In science, we test our ideas by making further observations and doing experiments. All suggestions (hypotheses) must ultimately be confirmed by testing them against the evidence of the real world. As much as possible, we must leave our prejudices and preferences outside the laboratory or observatory door. When the experiments and observations have spoken, we must accept their results gracefully.

When scientists measured the age of the universe (as we will describe in a moment), they did not hope or wish for it to have a particular age, and try to make their results come out according to those wishes. Instead, they did the best they could to understand the evidence nature provides and then reported what their observations had told them.

The Ancient Universe

With all this in mind, let's now look at what our observations and experiments have revealed about the age of the universe and its contents. We examine each thread of evidence separately, starting with the entire universe and coming "down to Earth." We will see that they fit together very nicely to reflect the ages we discussed above.

a) The Age of the Expanding Universe

Astronomers can estimate the distance of each galaxy of a certain type from its apparent size or brightness. The smaller and fainter a galaxy appears compared to similar galaxies, the farther away it must be. We experience the same effect here on Earth – the farther away a car, the closer together and fainter its headlights appear. In addition, there are other ways of measuring the distances to galaxies, using special stars that act like distance-markers.

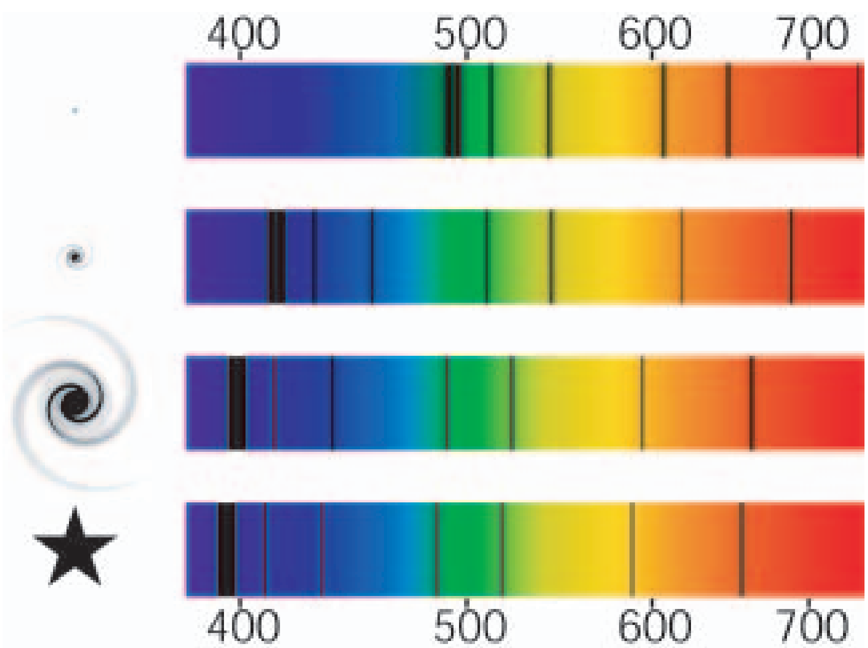
Astronomers can also determine the speed a galaxy is moving by breaking up its light into its component colors, rainbow-fashion. We call the light spread out like this a "spectrum" and it is something whose properties astronomers are very good at measuring. Each element leaves a unique pattern in the spectrum of light, allowing us to tell what objects in the universe are composed of by studying these patterns. But the spectrum also provides a "bonus" for those who study the patterns carefully.

Christian Doppler showed in 1842 that when a source of light is moving away from us, the motion stretches the waves, slightly changing the colors we see in the spectrum. This *Doppler Effect*, which applies to all kinds of waves, also explains why the sound of a police siren that is approaching us seems to have a higher pitch, and one that is moving away from us seems to have a lower pitch. When the source of waves moves away from us, the waves are slightly stretched, when it moves toward us, they are slightly compressed. Doppler radar uses waves that bounce off your moving car and tell the police whether you are speeding or not.

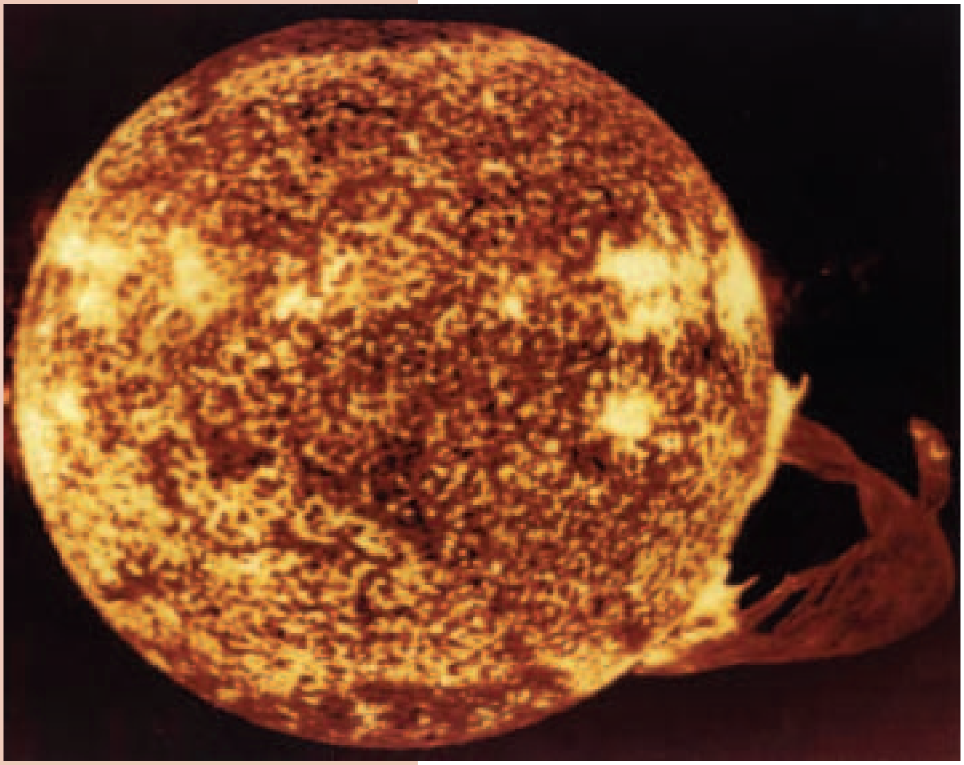
When we measure light from distant galaxies we find that their waves are always *stretched,* indicating that the galaxies are moving away from us. By measuring the stretching, we can determine the galaxies' speeds, in the same way as police using Doppler radar. Astronomers have been making such measurements of galaxies since the first decade of the 20th century. We should add that in terms of the modern theory of gravity, the recession of galaxies is caused by the expansion of space itself rather than any activity on the part of the galaxies. The expansion of space carries galaxies away from us and it also stretches the waves of light that galaxies emit to redder wavelengths.

In the 1920's astronomer Edwin Hubble made the remarkable discovery that the speeds at which galaxies are moving away from us are not random, but have a pattern to them. The farther away a galaxy is, the faster it is moving away. This pattern is now called "the expanding universe", since the same behavior of receding galaxies is seen in every direction in the sky. We are confined to view the stretching of space from the Milky Way galaxy, but the same pattern would be observed by someone on a different galaxy. All the galaxies are stretching away from all the other galaxies. Thus we cannot conclude from Hubble's work that we are at the center of the expansion or that we have any special place in the universe.

Astronomers soon realized that they could use measurements of the stretching of light to measure how long ago the expansion began. To see how we do this, imagine for a minute that you are attending a banquet with lots of other people. At the end of the event, all the participants get into their cars and drive away from the banquet in different directions.



Redshift Figure: These spectra show the dark absorption lines first seen by Fraunhofer. These lines can be used to identify the chemical elements in stars, but they also can tell us the speed with which stars and galaxies move away from us. The pictures from bottom to top show a galactic star, a nearby galaxy, a medium distance galaxy and a distant galaxy and their spectra. The pictures on the left are negatives so the brightest parts of the galaxies are black. Notice how the pattern of absorption lines shifts to the red (longer wavelength) as the galaxies get fainter. The number above and below the spectra are the measured wavelengths in nanometers. (Courtesy of Edward L. Wright, Astronomy Department, University of California – Los Angeles)



The Sun: Our star, the Sun, is a powerhouse of nuclear energy, shining via a process called nuclear fusion. Deep in its core, smaller atomic nuclei are smashed together into larger ones, releasing energy each step of the way. Ultimately, some of that energy emerges from the Sun's outer layers. This image, taken in 1973, from Skylab, the early US space station, shows an enormous eruption (flare) on the Sun's surface. (Courtesy of NASA)

Say your home is 120 miles from the lunch site, and you drive home at 60 miles per hour. When you get home at 5 pm, you realize you forgot to look at your watch to see when the banquet broke up. Still, you soon realize that you have all the information you need to figure out when everyone started "expanding" away from the lunch. Since you traveled 120 miles at 60 mph, the trip took you 2 hours. Thus you can calculate that you, and all the other participants, must have left at 3 pm. (To check, you might call a number of other banquet attendees and ask them to do the same calculation for their trip home. They may have traveled a different distance, at a different speed, but the departure time will be the same.)

In the same way, we can find out roughly when the galaxies began their expansion by measuring how far away they are and how fast they are moving. The simplest way to estimate the age of the universe from galaxy motions is to divide galaxy distances by their speeds. However, this calculation omits the fact that the universal expansion used to be faster than it is now, but has slowed due to the gravity of galaxies tugging on each other. When the effect of gravity and another small effect which actually speeds up the expansion rate are included, the universe is estimated to be 12 to 14 billion years old.

b) The Age of the Oldest Stars

The Sun and other stars shine by converting superheated hydrogen in their centers into helium in a process called *thermonuclear fusion*. Under the intense heat and pressure in a star's core, hydrogen nuclei (the centers of hydrogen atoms) fuse together and produce helium nuclei – and energy. This is the same process that occurs in a hydrogen bomb on Earth. We can determine how long a star can shine by this process in the following way.

We know from experiments in nuclear physics just how much energy comes from fusing each atom of hydrogen. We also know the amount of hot hydrogen in the star's core, and how fast the star is using its energy. We can therefore calculate how long the star will last before it runs out of fuel. The answer for the Sun is about 10 billion years for its total lifetime. We know from measurements of the age of the solar system – see below – that the Sun is now about 4.5 billion years old. So our star is about halfway through its life.

Other stars may have different lifetimes. Stars smaller (less massive) than the Sun have longer lives because they fuse their hydrogen fuel so much more slowly. Similarly, a sub-compact car may have a smaller gas tank than a large SUV (sport utility vehicle) but it may be able to drive much longer on a full tank of gas, because it uses its fuel much more slowly.

When a star has used up the available hydrogen fuel in its center, it expands and becomes a "red giant". Once we find such a giant star, we know that it has used up all its central hydrogen. If we can estimate its initial mass, and hence its initial power, we can estimate its lifetime, and we therefore know its age. This is equivalent to saying that, if we see a car that has just run out of gas, and if we know its horsepower, fuel efficiency, and fuel capacity, we can figure out how long it had been driving since the last fill-up before it ran out of gas.

In this way, we can measure the ages of a large number of stars. When we apply this method to the oldest stars we can find, we obtain ages of 10 - 15 billion years.

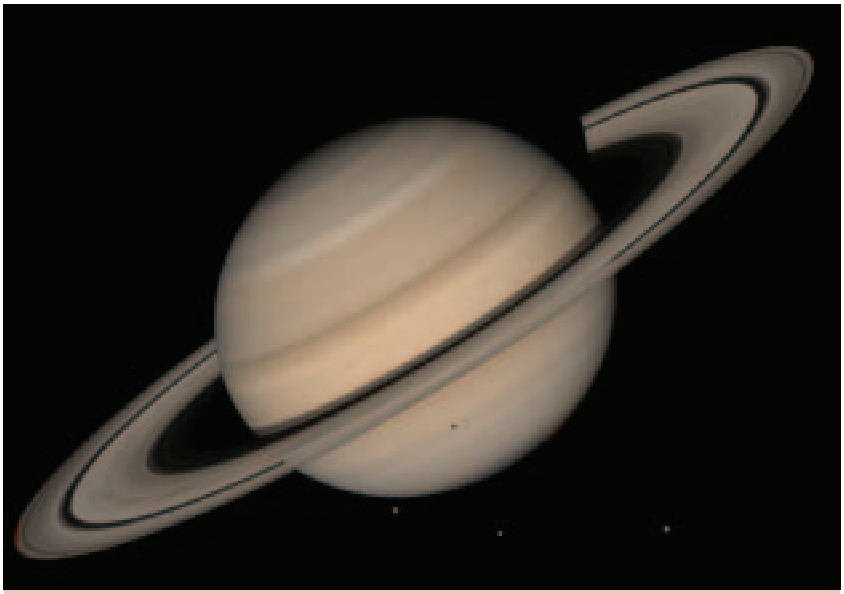
An example of the "time machine effect" in everyday life is to listen for the slower sound of thunder which accompanies a lightning flash; if the thunder follows the lightning by 10 seconds, then it is about 3 kilometers away; if the thunder and the lightning are simultaneous– the storm must be right on top of us! Another example: for spacecraft exploring the outer solar system, it takes many hours for their radio signals (which travel at the speed of light) to reach the Earth; quick changes by the spacecraft cannot be controlled remotely from Earth because the communication time would be too long. This is why many of the spacecraft's instructions must be carried in its on-board computer.

The galaxies are so distant that their light may take billions of years to reach us. So when we look deeply into space we are looking into the past, across vast gulfs of time. When we study other galaxies, we find that their stars are still being born from the loose gas from which the galaxies formed. When we study more distant, and therefore younger, galaxies, we see larger numbers of stars being born. This is consistent with the idea that gas converts into stars as time passes.

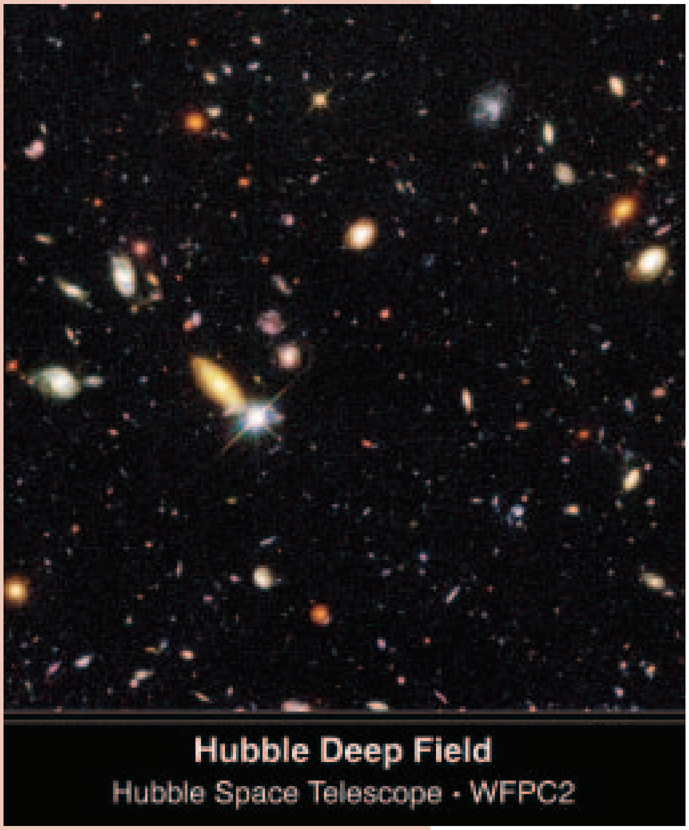
c) The Age of Light from the Most Distant Galaxies: The "Time Machine" Effect

Astronomers can measure the distances to other galaxies from their apparent size or brightness, and in many other ways. These distances are so great that billions of years are required for their light to reach us. Thus we are actually seeing these galaxies not as they are today, but as they were billions of years ago.

As we saw in the Overview section, light travels at 300,000 kilometers per second. During the last century, this number has been measured with exquisite accuracy, and found to be constant. But even at this extraordinary speed, light takes considerable time to reach us from distant objects. Light from the Sun, for instance, takes eight minutes to reach us, so that we see the Sun as it was eight minutes ago. Similarly, we see the stars in the nighttime sky as they were decades, centuries and even thousands of years ago.



Saturn and Some of Its Moons: This beautiful image of the planet Saturn was taken in August 1981 by the Voyager 2 spacecraft when it was 21 million kilometers from the planet. Saturn is one of the giant outer planets in our solar system, made mostly of liquid and gas. It has the most dramatic ring system among the four large planets that are surrounded by such swarms of small icy and dusty pieces. Three of Saturn's icy moons (Tethys, Dione, and Rhea) are visible as small dots of light at the bottom of the picture. The shadow of Tethys can be seen under Saturn's rings. (Courtesy of the Jet Propulsion Laboratory/NASA)



The Hubble Deep Field: In December 1995, the Hubble Space Telescope, high above the Earth, focused on a tiny spot of dark sky for over 150 consecutive orbits. The result was the deepest view into space we had ever had up to that time. Here we see about ¼ of that "deep field" and it shows galaxies (and only galaxies) at many different distances. The farthest among these galaxies is estimated to be so far away, its light has taken over 10 billion years to reach us. (Courtesy Robert Williams, the Hubble Deep Field Team, and NASA)

We also find that more distant galaxies often look like they are interacting or merging. This bears out a basic prediction of gravity theory in an expanding universe, that large galaxies are steadily assembled from smaller pieces. In both cases, there is evidence of evolution—the universe was not the same billions of years ago as it is now. We will return to this idea in the next main section.

The "Hubble Deep Field" is a 10-day time exposure made by the Hubble Space Telescope. Almost every object in this image is a distant galaxy, seen as it was in the remote past – at times up to 10 billion years ago. It is from images such as this that we can unravel the history of the universe and determine its age.

d) The Age of the Chemical Elements

Just after the Big Bang, the universe was made almost entirely of the simplest elements: hydrogen and helium. We have confirmed this by looking at galaxies that are really far away– and thus as they were long ago. These have greater proportions of hydrogen and helium than nearby galaxies (which we are seeing as they are in the present time). The chemical elements that are more complex than hydrogen and helium were formed later — some in nuclear reactions in the cores of stars, others when the most massive stars ended their lives in gargantuan explosions that astronomers call a *supernova*. (A spectacular supernova was observed in 1987 in the Large Magellanic Cloud, one of the closest galaxies to ours.* Astronomers actually observed some of the newly-formed elements emerging in this explosion.)

This idea, that it takes the enormous heat in the center of a star or in the explosion of a star to transform one element into a more complicated one is one of the great discoveries of modern astronomy and physics. All the atoms in the Earth and in us that are more complex than hydrogen or helium were "cooked up" inside earlier generations of stars. We can also use this notion to measure the age of some of the elements.

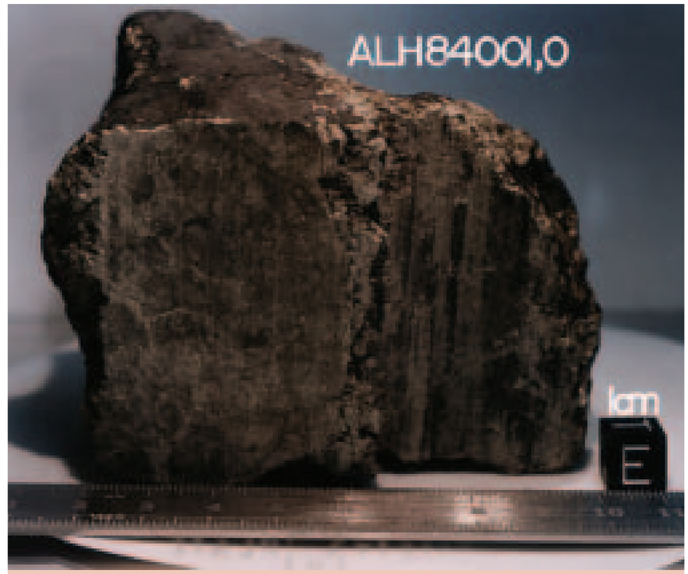
Some types of atoms are *radioactive*; they *decay* or change into other types of atoms at a rate that can be measured accurately in the laboratory. As time goes on, less and less of the original or "parent" atom is left and more and more of the product or "daughter" atom can be found all around it. By comparing the amount of the parent to that of the daughter, astronomers can determine how long it has been since the radioactive parent atom formed. In this way, astronomers have determined that, although some radioactive atoms (such as the ones produced by the 1987 supernova) are recently formed, the oldest radioactive atoms in the universe were formed 10-20 billion years ago. This age agrees with the age of the oldest stars.

*See the figure on page 16.

The same radioactive dating technique allows us to measure the ages of the oldest rocks on Earth, on the Moon (from which astronauts brought back rocks), and in *meteorites,* chunks of rock from space that land on Earth. Such dating experiments have shown that the age of the solar system (the Sun and its planets) is about 4.5 billion years, as we mentioned above. The universe is a lot older than our little neighborhood. More recently, the same technique has even been used to confirm the ages of stars.

The key thing to notice is that all of the independent estimates of the age of the universe are in remarkable agreement – our best estimate being about 14 billion years, give or take a 10 percent measurement uncertainty. All this strengthens astronomers' view that the universe, the galaxies, and the stars are truly ancient and not recent creations.

Scientists always try to test their ideas in more than one way, if possible. That is why the agreement of different techniques is so important. Age estimates for the universe based on radioactive atoms observed in old stars, models of the lifetimes of stars, and the expansion history since the big bang all give the same answer. This web of evidence means that the assertion of a very old universe is not subject to possible problems or limitations of any single technique.



A Martian Meteorite: Millions of years ago, an enormous impact (a large chunk of rock or ice hitting Mars) blasted parts of the red planet's crust out into space. After a long time, some of these pieces of Mars landed on Earth. This Martian rock was found in Antarctica in 1984. We know it came from Mars, because scientist have found pockets of air inside, and this air is exactly like Mars' atmosphere and not like Earth's. Such chunks from space (called meteorites) allow astronomers to study the chemical makeup of other parts of the solar system. (Courtesy NASA Johnson Space Flight Center)

The Changing Universe: Evolution Happens!

Scientific observations have not only revealed that the universe is very old, they have also shown that it changes over time, or – to use the word that has stirred so much controversy – that it "evolves". These cosmic changes are often very difficult to observe, because they happen so slowly. We have been studying the sky with powerful telescopes for only about a century, but astronomical changes can take millions to billions of years. We must therefore combine observations of many different objects out there and use our deductive powers to uncover evidence of cosmic evolution. Luckily, nature has left a wide range of clues about evolution for us – at every scale of the universe – which we can uncover with some good astronomical detective work.

a) Changes in the Solar System

Because we have explored our solar system (with people landing on the Moon, and robot spacecraft landing on or flying by most of the planets), we have a lot of information about the history of our neighbor worlds. It is clear that all the planets have undergone profound changes with time and have a common origin in the great swirling cloud that made the Sun some 5 billion years ago.

We can calculate when the materials of the Earth's crust congealed from molten lava to hard rock (the geological, not the musical kind). As we discussed above, we can look at radioactive elements in the rock, and see how much of the radioactive parent and how much of the stable daughter elements are there. Our laboratory work shows that the process of radioactivity

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The Earth from Space: This image of our planet was taken in August 1992 by the GOES-7 satellite. You can see Hurricane Andrew near North America. (Courtesy of F. Hasler, et al, the National Oceanic and Atmospheric Administration, and NASA) is not affected by temperature, pressure, or other outside factors, and proceeds at a rate set only by the little natural clocks built into the nucleus of the atom. Since many rocks have more than one radioactive element, they actually have several nuclear clocks running at the same time. These can be compared to check our results. Individual rocks on Earth have measured ages that range from last week (for rocks that just congealed from lava flows in Hawaii) to more than 4 billion years ago.

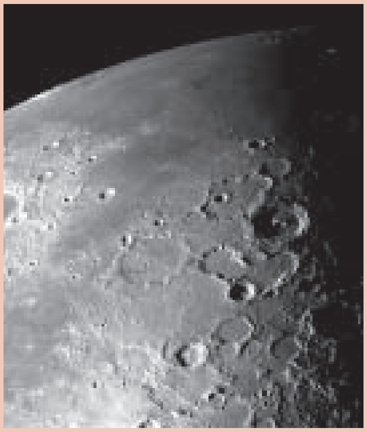
If you take a good look at a world map, you can see that the continents "fit into" one another like pieces of a jigsaw puzzle. The coastline of Africa, for instance, neatly fits into that of South America. This is because these continents used to be joined, but have been drifting apart. Far back in the past, the very face of our world was different. Today, scientists can actually measure the rate at which the continents are moving – a few centimeters per year – and estimate how long it has taken them to move apart to their present positions.

Impact craters on the Earth, Moon, and other worlds are formed by the bombardment of chunks of rock and ice from space. By studying these craters, we can learn how common these impacts have been. The Moon is a good place to do this, because its craters have not been eroded away, as they have on the active Earth. The Moon turns out to contain many old craters, and fewer young ones. So we conclude that the solar system experienced many more impacts in the distant past than today.

At the beginning, there were many more chunks of rock and ice around, but as our system has evolved, many of those chunks have either hit the planets and moons or have been flung out of the system by the influence of a large planet's gravity. By the way, we can observe the impacts of smaller chunks with the Earth today, and observe "near misses" by larger objects. In this way, we can determine the current *rate* of impacts. This provides another measure of the great age of the surfaces of the Moon and the solid planets.

We're grateful that the number of impacts has been decreasing, since large impacts can have devastating effects on the Earth. There is strong evidence that 65 million years ago, such a chunk about 10 kilometers across hit what is now Mexico. The resulting explosion raised so much dust and smoke that the entire Earth experienced a long dark period. The lack of sunlight and warmth killed off much vegetation, and many animals, perhaps including the dinosaurs. When geologists dig in 65 million years old rock layers, when the fossil record shows a "great dying", they find higher traces of elements that are rare on Earth but more common in rocks from space. The huge mass of particles from the impact was carried by our planet's winds all over the Earth and is now part of the rocks from that time.

By killing off large number of living species, such giant impacts can re-direct the course of biological evolution on our planet. Geologists have uncovered drastic sea level changes and episodes of volcanism that may also have profoundly affected the history of life on Earth. New species can thrive in environments created by drastic change, as our ancestors, the small mammals, began to do 65 million years ago.

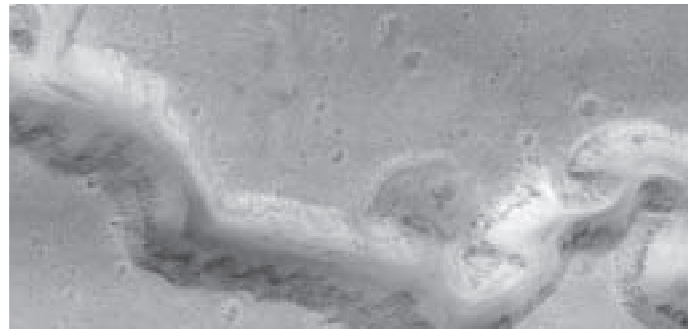


Top - Artist's Conception of an Asteroid Impact: Artist Don Davis paints a view of what a large asteroid might look like as it hits the Earth. Just such an asteroid is thought to have hit the Earth 65 million years ago, destroying more than half of all living species on our planet. (Courtesy of NASA Ames Research Center)

Bottom - The Cratered Face of the Moon: On its way to Jupiter, the Galileo spacecraft captured this view of the north polar region of the Moon in 1992. You can see craters of all sizes, each made when a chunk of rock (or occasionally, ice) hit the Moon and exploded from the violence of the impact. (Courtesy of Jet Propulsion Laboratory/NASA)

The primary evidence of Earth's biological history comes from fossils—the hard parts of formerly living creatures turned into stone by geological processes. The radioactive atoms in some fossils can be used to measure their ages directly. The fossil record is not complete, but there is clear evidence that organisms have generally evolved from simple to more complex over the past few billion years. Evolution of species is like a roadmap of the Earth's history.

Other planets evolve also. Robotic spacecraft orbiting and landing on Mars have found many dry river-beds there. But Mars is too cold today for water to exist in liquid form. Furthermore, the planet's atmosphere is so thin that any liquid water would rapidly evaporate away. Yet the river-beds and the geological formations our robotic rovers have explored in 2004 are evidence that in the distant past Mars had liquid water flowing on its surface. We conclude that Mars too has evolved. It was warmer and had a thicker atmosphere billions of years ago, but because of its lower gravity, has now lost much of its sheltering air.



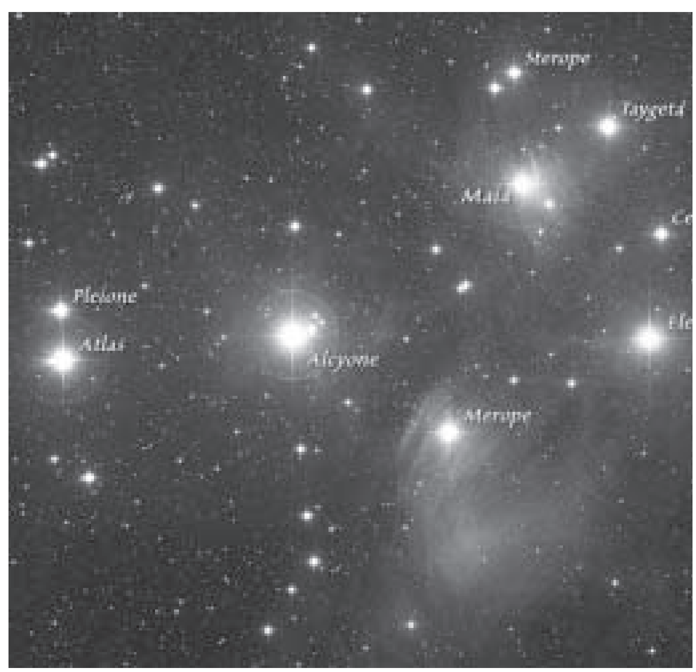
These and many other lines of evidence reveal that the planets of the solar system have changed over time. By studying these changes, we can gain insight into Earth's past and perhaps its future.

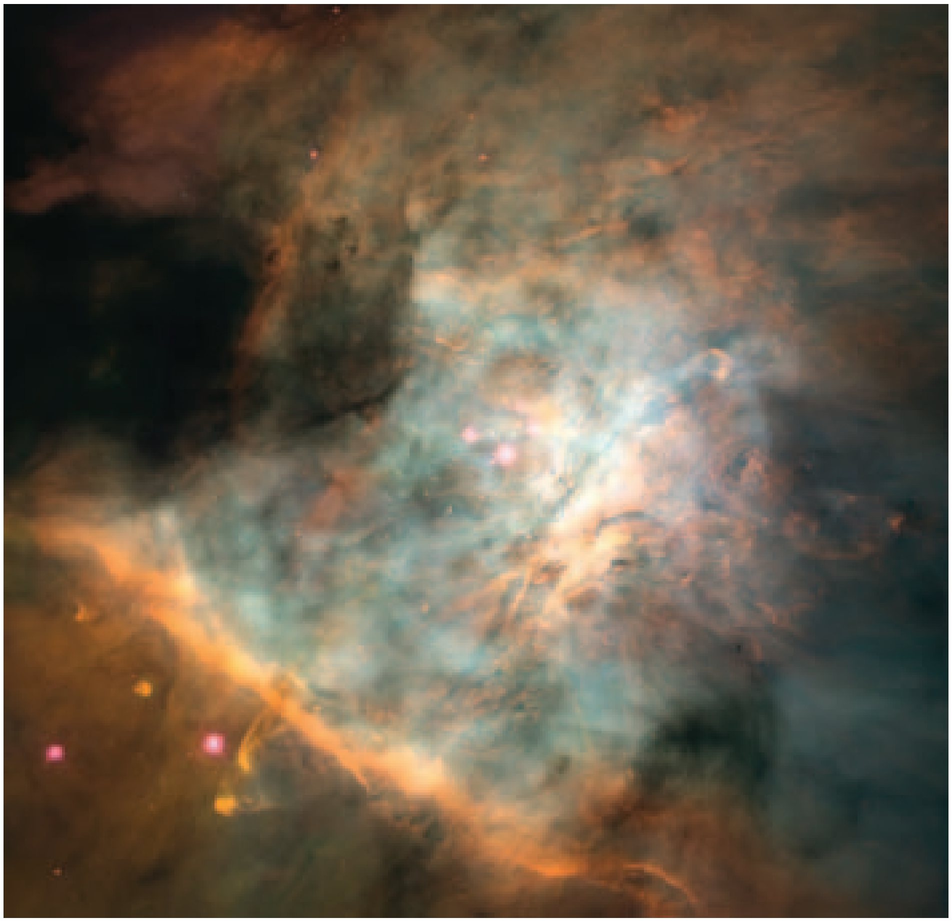
b) Changes in Stars

One of the great discoveries of modern science is that stars (like people) live only a measurable lifetime and then die. Although the lives of the stars are enormously longer than the span of a human life, we can learn about the life story of the stars by studying them at many different stages in their life cycle, from birth to death. As an analogy, imagine that a hypothetical race of aliens visited the Earth for an hour or two, and had to make observations to piece together the life cycle of humans. Studying one human being or even three or four in that short time would hardly give them much useful information.

The trick would be to examine as many humans of different types as possible and then deduce the different stages in our lives. For example, a few of them might visit a maternity ward, and see humans in a stage just before or after birth. They might even see a birth in progress. Others in the same hospital might witness the stages just before and after death. Some out on the street would observe people of various ages: young ones with their parents, old ones with their children, teenagers and adults in various groupings.

Similarly, astronomers (able to glimpse any given star for only a "moment" of its long existence) must examine many stars and hope to find some in each stage of its life. And we have been able to do exactly that – we have found young stars near the "maternity wards" of gas and dust where they are born. We can observe stars like our own Sun, which are in the stable "adult" stage of their lives. (A good number of such sun-like stars nearby are surrounded by one or more planets, just like the Sun.) We can see red giant stars in "mid-life crisis", bloated by changes deep within. Studying





stellar corpses called white dwarfs and neutron stars, we observe the after-effects of stellar death.

The slow processes of stellar life and death can be deduced from groupings of stars called *star clusters*, groups of stars which are born together and live out their lives as a group. A good example of such a group is the beautiful Pleiades cluster, which can be seen in the fall and winter sky. In such a cluster, different stars go through their lives at different paces, and we can find stars that started together, but are now in very different stages of their lives.

Changes in how stars live their lives can be observed *directly* in a special class of stars called "pulsating variable stars"; the North Star – Polaris – is one example. This star expands and contracts in rhythmic fashion, every 4 days. But as it slowly swells with age, it becomes larger, and the regular expansion and contraction take measurably longer.

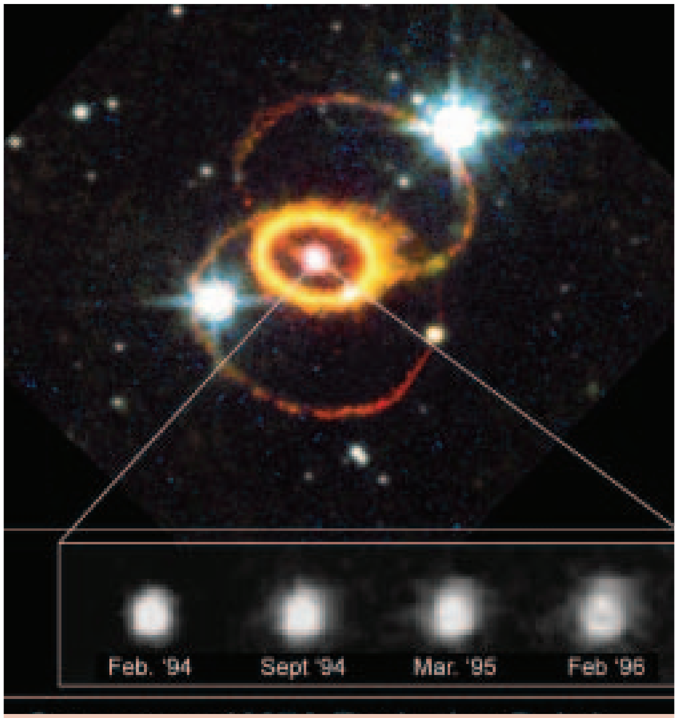
What do we learn from studying the stars in different stages (and by simulating their behavior and physics on high-speed computers)? We find that stars evolve from one form to another – from energetic youngsters, to stable adults, to bloated giants, and on to death and becoming a corpse.

Recall from our earlier discussion that, because some stars explode, new stars include some of the materials produced by previous generations of stars.

Facing page top - Old Riverbed on Mars: This spectacular image of part of a winding channel called Nanedi Valles was taken by the Mars Global Surveyor spacecraft in 1998. The channel is about 2.5 km across, and shows a variety of geologic features that strongly suggest the channel was carved by running water. (Courtesy of Malin Space Science Systems/JPL/NASA)

Facing page bottom - The Pleiades Star Cluster: Stars are often found in groups. This relatively nearby grouping is about 400 lightyears away, and contains several hundred stars. The brightest of them are visible to the naked eye or in binoculars, and are labeled here with their names from classical mythology. The stars look fuzzy because there is a cloud of dust moving among them and the dust reflects the stars' light. (Courtesy of the Space Telescope Science Institute Digital Sky Survey.)

Left - The Orion Nebula: This Hubble image shows part of a vast cloud of gas and dust from which new stars and new planets are forming. Located in the star pattern called Orion about 1500 lightyears away, this star forming region reveals how stars continue to be born whenever enough cosmic raw material can gather together. (Courtesy C. O'Dell & S. Wong (Rice University) & NASA)



Supernova 1987A: This Hubble Space Telescope image shows the remnant of a supernova – a star that blew itself to pieces. We first saw the light of the explosion on Earth in 1987, and this image was taken in 1994. The remnant of the explosion itself is the blob of stuff in the center; the rings are regions of material ejected by the star earlier in its death throes. They have been "lit up" by the energy of the explosion. The inset at the bottom shows the expansion of the exploded material in the center from 1994 through 1996. Seven to nine years after the star "formally exploded", the remnant is seen to expand at almost 10 million kilometers per hour. Supernovae are nature's way of making and recycling some of the heavier elements that make up the universe. (Courtesy of C. Pun & R. Kirshner, the Space Telescope Science Institute, and NASA)

Thus the number of more complex atoms in the universe is slowly growing. We have good evidence that our Sun (with its planets) was not among the first stars the universe produced, but formed later from materials enriched by the deaths of previous generations.

This is a key idea in astronomy – that the evolution of the stars gradually changes the make-up of the cosmos. The stars are not mere backdrops to our existence on Earth – creatures as complex as we are could not have evolved on Earth without the materials that earlier generations of stars contributed to the cosmic "element-pool." And the Sun itself will not last forever, but will someday die. In the process, it will eventually expand and make life on Earth impossible, quite independent of what we humans do.

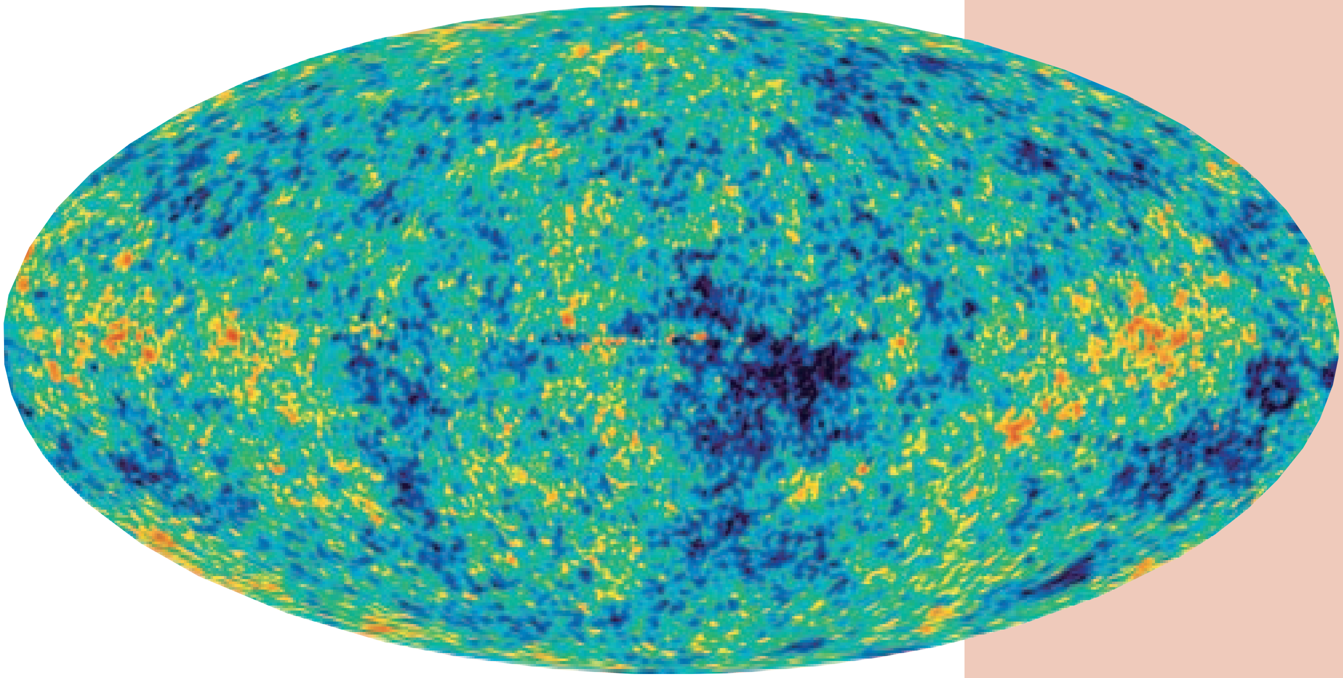
c) Changes in the Universe

As we have mentioned, light takes a good deal of time to reach us from the distant parts of the universe. Therefore, if we look far out, we are also looking far back in time. By examining light (and other radiation) coming from different epochs in cosmic history, we can learn about the evolution of the entire universe.

For example, observations reveal that *quasars*, gigantic energetic events in the cores of galaxies, are more common at great distances than they are nearby. Thus we conclude that they were more common in the distant past than today. In a universe that is not evolving, we should see as many of these hyper-active galaxy cores in each period of cosmic history. But if we see more in the past, it implies that over time the quasars have become less common. The evidence shows that they are active when galaxies are young, but generally tend to fade out as they the galaxies get older. Our Milky Way galaxy seems to have a dead quasar at its center as do several other galaxies in our neighborhood.

In the same way, observations show that galaxies that are billions of light years away, and are therefore seen as they were billions of years ago, are forming stars at a much greater rate than nearby, older galaxies. Early in their lives, galaxies have more resources for forming new stars, but it gets harder to make new structures from the diminishing supply of raw material as the galaxies grow older. Again, we see that the galaxies themselves are evolving.

Perhaps the most spectacular discovery of all was a faint "hiss" of radio signals coming equally from all directions in the universe. This background hiss has a spectrum (a range of waves) that can only be produced by matter compressed to high density and heated to enormous temperatures. What could have filled the entire universe with such radiation? Our evidence shows that it is the faint remnant of the blazing inferno of the Big Bang, now cooled down by the expansion of the universe. This discovery provides direct evidence that, far back in the past, the universe was ultra-dense and ultra-hot, very different from the cold and much



WMAP Image of the "Seeds" of Galaxies: The first detailed, all-sky picture of the infant universe. The WMAP image reveals 13 billion + year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. Encoded in the patterns are the answers to many age-old questions, such as the age and geometry of the Universe. (Courtesy "NASA/WMAP Science Team")

more spreadout universe we see today. Many other lines of evidence also point to a hot beginning for the cosmos.

Today, astronomers are mapping this "background radio radiation" in detail to learn everything we can about how the universe evolved in those early days. Recently these maps have started to reveal the "seeds" of the structure we now see in the universe – denser regions of gas that subsequently gave birth to the great groups of galaxies we observe around us.

Again, it is clear that the universe has changed profoundly since its earliest days, going from a hot smoother state to the cooler "lumpier" appearance we see today.

Science and Religion

Humanity has always wondered about the nature, origin, and purpose of the universe, and these thoughts have been important parts of many religious traditions. Science and religion are not necessarily in conflict. Indeed, many scientists have strong religious beliefs. A survey of American scientists conducted in 1997 found that 40% believed in a personal God, the same number as was found in similar surveys conducted in 1914 and 1933 (See the article on "Scientists and Religion in America", in the Sept. 1999 issue of *Scientific American* magazine.) Many people from a variety of religious faiths accept the testimony of science, including evidence for the great age of the universe. Indeed, they may find that it deepens their understanding of creation and reinforces their faith.

The approach a person adopts for relating science and religion probably depends on his or her life experience and presuppositions. When talking with students or young people in general, we should avoid claiming that science and religion are necessarily opposed to each other. Students need not give up their faith to be scientists or to appreciate the scientific view of the universe.

Neither do they need to reject science to keep their faith. We should avoid giving simplistic answers to questions about the relationship between science and religion. Such questions are complex, and people of many faiths have found many different answers to them.

The awe and splendor of the universe have inspired artists and poets as much as they have scientists. Planets, stars, galaxies, and their histories remain a source of beauty and wonder for people of all ages and all beliefs. The illumination brought by science can enhance every form of spirituality – religious or humanistic. The awareness, understanding, and appreciation of the vast scales of space and time can enhance the life of all people, young or old and whatever their cultural background or religious belief.

Sharing a sense of belonging to the universe with students can be one of the most satisfying tasks of a teacher. None of us should feel insignificant or unimportant when we look at, or think about, the universe. To paraphrase the French scientist Henri Poincare: "…astronomy is useful because it shows how small our bodies, but how large our minds." Knowing that we are part of a vast, ever-evolving universe, billions of years old, is part of the birthright of every thinking being on planet Earth.

For Further Exploration

Below are a few representative readings on the science topics in this booklet. A more detailed reading and web-site list, with sources that also include responses to claims by those who doubt the age of the universe and its evolution, plus a list of relevant classroom activities, can be found at http://www.astrosociety.org/education/publications/tnl/56/

1. General Readings

The Oct. 1994 issue of *Scientific American* magazine was devoted to "Life in the Universe" and has articles on the evolution of the universe, the Earth, and life.

Zimmer, C. "How Old Is It?" in *National Geographic,* Sept. 2001, p. 78. An excellent, up-to-date, profusely-illustrated resource.

Any modern textbook in astronomy can give you a good introduction to how we measure ages and how we view cosmic evolution. A list of currently available textbooks (and their web sites) is kept on the Web at: www.astrosociety.org/education/resources/educsites.html

2. The Age and Evolution of the Solar System

Hartmann, William "Piecing Together Earth's Early History" in *Astronomy,* June 1989, p. 24.

Wood, John "Forging the Planets" in *Sky & Telescope,* Jan. 1999, p. 36.

Yulsman, T: "From Pebbles to Planets" in *Astronomy,* Feb. 1998, p. 56.

3. The Age and Evolution of the Universe

Chown, Marcus *The Magic Furnace: The Search for the Origin of Atoms.* 2001, Free Press/Simon & Schuster. Readable history of the discovery of atomic structure and how stars build up atoms over time.

Ferris, Timothy *The Whole Shebang.* 1997, Simon & Schuster. See especially Chapter 7 on "Cosmic Evolution."

Glanz, James "On Becoming the Material World" in *Astronomy,* Feb. 1998, p. 44. On how the elements were made in the universe.

Larson, R. & Bromm, V. "The First Stars in the Universe" in *Scientific American,* Dec. 2001, p. 64.

Roth, Joshua "Dating the Cosmos: A Progress Report" in *Sky & Telescope,* Oct. 1997, p. 42.

4. Measuring Cosmic Distances

Eicher, D. "Candles to Light the Night" in *Astronomy,* Sep. 1994, p. 33. On ways we use cosmic objects that have a standard brightness to measure distances.

Ferguson, Kitty *Measuring the Universe: Our Historic Quest to Chart the Horizons of Space and Time.*1999, Walker.

Reddy, F. "How Far are the Stars?" in *Astronomy,* June 1983, p. 6.

NOTE: More astronomy resources and web links for teachers on how best to convey the astronomical ideas in this booklet can be found on the education web sites of the two sponsoring organizations:

- The Astronomical Society of the Pacific at http://www.astrosociety.org/education.html
- The American Astronomical Society at http://www.aas.org/education.

The Cosmic Calendar Activity referred to in the Overview section can be found at:

http://www.astrosociety.org/education/astro/act2/cosmic.html

Cover image: PIA05988: Out of the Dust, A Planet is Born (Courtesy of NASA/JPL/Caltech)
Background image: PIA03153: Solar System Montage (Courtesy of NASA/JPL)

To order additional copies of this booklet, send email to aas@aas.org