An Ancient Universe:
How Astronomers Know the Vast Scale of Cosmic Time

No. 56 - Fourth Quarter 2001

by Andrew Fraknoi *(Foothill College)*, George Greenstein *(Amherst College)*, Bruce Partridge *(Haverford College)* and John Percy *(University of Toronto)*

A Special Edition of
"The Universe in the Classroom"
A Newsletter on Teaching Astronomy in Grades 3-12

Published by the
American Astronomical Society
and the
Astronomical Society of the Pacific

INTRODUCTION:

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.

Many good books and articles have been published for teachers on the scientific basis of evolutionary ideas in biology. But rather little is available to help teachers explain to their students how we know that the galaxies, stars, and planets are really old. In this special edition of *The Universe in the Classroom*, 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 you can do with your students, 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 what happened *before* the universe as we know it existed. 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.

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 <u>evolution</u> – 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 issued a formal statement on behalf of the astronomical community in 2000. The Society, which is the main body of professional astronomers in the U.S., includes 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

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.

We live in a wonderful universe. It has inspired artists and poets through the ages, from ancient Greece to today’s *Star Trek* 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 universe is there for all to see on any clear night, and it is all around us.

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 of stars we call the Milky Way galaxy. A number 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 waves of information to us at the fastest possible signal speed, the speed of light. This is an amazing 300,000 kilometers per second (or 670 million miles per hour 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 km, 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 it 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.

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, they have also found ways of establishing the scale of cosmic time. These measurements show that the universe had its beginnings in a very dense, hot state we call “the Big Bang” about 10 to 15 billion years ago. The Sun and the Earth formed from the “raw material” gas and dust in the Milky Way galaxy some 4.5 to 5 billion years ago. The earliest evidence we have for living things on Earth goes back to about 3.5 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 in our activity listing below.

THE PROCESS OF SCIENCE: HOW DO WE KNOW?

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 your 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 nature 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, but 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 mile-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. 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 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 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. Astronomers have been making such measurements since the first decade of the 20th century.

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 entire universe of galaxies seems to be moving away.

Astronomers soon realized that they could use this information to measure how long ago the expansion began. To see how we do this, imagine for a minute that you are attending a year-end lunch with your fellow teachers. At the end of the lunch, all the teachers get into their cars and drive away from the lunch in different directions.

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 lunch broke up. Still, you have all the information you need to figure out when all the teachers 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 teachers, must have left at 3 pm. (To check you might call a number of other teachers 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 time will be the same.)

In the same way, we can find out roughly when the galaxies began their expansion by dividing their distances by their speeds. We find the age of the expanding universe to be between 10 and 15 billion years.

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 fuse together and produce helium nuclei – and energy. This is the same process that occurs in the hydrogen bomb on Earth. We can determine how long a star can shine by this process as follows: we know how much energy comes from fusing each atom of hydrogen, 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 it 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, 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 have found such a giant star, we know that it has used up all its 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 certain stars. When we apply this method to the oldest stars we can find, we obtain ages of 10 - 15 billion years.

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.

Light travels at 299,792.458 kilometers per second (300,000 km/sec is a convenient approximation). During the last century, this number has been measured with exquisite accuracy, and found to be constant. But even at the extraordinary speed of 300,000 kilometers per second (186,000 miles per second), 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.

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 km 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; the spacecraft cannot be controlled remotely from Earth because the communication time would be too long. This is why the spacecraft's instructions must be carried in its on-board computer.

The galaxies, however, 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 distant galaxies, we find that their stars are still being born from the loose gas from which the galaxies formed. When we study even more distant galaxies, we see them as they were 10 billion or more years ago. In these long-ago galaxies, we find that the stars are just beginning to form.

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 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 really far away – and thus long ago. And, indeed, they have greater proportions of hydrogen and helium. The other chemical elements 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 a galaxy very close to ours. Astronomers actually observed some of the newly-formed elements emerging in this explosion.)

Some *isotopes* (forms of the element with different numbers of neutrons in the nucleus) of these elements are *radioactive*; they change into other isotopes at a rate that can be measured accurately in the laboratory. As time goes on, less and less of the original or “parent” isotope is left and more and more of the product or “daughter” isotope can be found all around it. By comparing the amount of the parent isotope to that of the daughter isotope, astronomers can determine how long it has been since the radioactive parent isotope formed. In this way, astronomers have determined that, although some radioactive isotopes (such as the ones produced by the 1987 supernova) are recently formed, the oldest radioactive isotopes in the universe are 10-20 billion years old.

The same radioactive dating technique allows us to measure the ages of the oldest rocks on Earth, on the Moon, 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. That strengthens astronomers' view that the universe, the galaxies, and the stars are truly ancient, and not recent creations. There are other less direct ways of estimating the ages of these objects, and the age of the solar system, and they too are in agreement.

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 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 go from last week (for rocks that just congealed from lava flows in Hawaii) to more than 4 billion years ago.

If you and your students 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, a chunk about 10 km 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 layers of rock from 65 million years ago, when the fossil record shows this "great dying", they find higher traces of elements that are rare on Earth, but more common in these rocks from space. The huge mass of debris from the impact was carried by our planet's winds all over the Earth and is now part of the rocks from that time.

Robotic spacecraft orbiting 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 are clear 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 life-time 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 is.) We can see red giant stars in "mid-life crisis", bloated by changes deep within. And 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. We note (because some stars explode) that new generations of stars include some of the materials produced by previous generations and that 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 which 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, whereas 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 more spread-out 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.

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, 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 our students, whatever their cultural background or religious belief. Sharing the sense of belonging to the universe with our 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 how large our minds." Knowing that we are part of a vast, evolving universe, billions of years old, is part of the birthright of every thinking being on planet Earth.

Acknowledgements: We thank Nalini Chandra (University of Toronto), Douglas Hayhoe (Toronto District School Board), and Eugenie Scott (National Centre for Science Education) for their helpful comments.

Appendix One:
Creationism Versus Evolution: An Astronomical Perspective
A Resource Guide for Teachers

The list below offers two kinds of resources: First, some examples of readings that explain how scientists determine the antiquity of the solar system, the stars, and the universe as a whole. And second, guides to creationist claims and the responses scientists make to them.

1. The Age and Evolution of the Cosmos and its Contents

a. 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 at: www.astrosociety.org/education/resources/educsites.html

b. The Age and Evolution of the Solar System

Dalrymple, G. Brent *The Age of the Earth*. 1991, Stanford U. Press. A discussion of how we measure the ages of objects in our 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.

Wood, John "The Origin of the Solar System" in Beatty, J., et al., eds. *The New Solar System,* 4th ed. 1999, Sky Publishing/Cambridge U. Press.

c. 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.

Davies, Paul "Everyone's Guide to Cosmology" in *Sky & Telescope,* March 1991, p. 250.

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.

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

d. 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.

2. Responding to Creationist Claims

The literature examining this controversy is enormous; the list below is merely a representative sampling.

Books

Berra, T. *Evolution and the Myth of Creationism: A Basic Guide to the Facts in the Evolution Debate.* 1990, Stanford U. Press.

Futuyma, D. *Science on Trial: The Case for Evolution.* 1983, Pantheon. A leading evolutionary biologist explains the case for evolution that the creationists seek to deny.

Godfrey, L., ed. *Scientists Confront Creationism.* 1982, Norton. A useful collection of articles.

Kitcher, P. *Abusing Science: The Case Against Creationism.* 1982, MIT Press. A philosopher takes a critical look at the claims against evolution and illuminates the issues involved.

McGowan, C. *In the Beginning: A Scientist Shows Why the Creationists are Wrong.* 1984, Prometheus Books. A Canadian zoologist examines and refutes creationist arguments.

National Academy of Science. *Teaching about Evolution and the Nature of Science.* 1998, National Academy Press. A guide for teachers.

Ruse, M., ed. *But Is It Science?* 1996, Prometheus. A collection of articles about the creationism/evolution controversy, by scientists, philosophers, etc.

Strahler, A. *Science and Earth History: The Evolution / Creation Controversy*. 1987, Prometheus Books. A discussion from the geologist’s point of view, with lots of information about dating the Earth’s rocks.

Tuomey, C. *God's Own Scientists: Creationists in a Secular World.* 1994, Rutgers U. Press. An anthropologist examines the culture of creationism as if he were looking at far-away tribe.

Wilson, D., ed. *Did the Devil Make Darwin Do It? Modern Perspectives on the Creation-Evolution Controversy.* 1983, Iowa State U. Press. Interesting collection of essays, by historians, scientists, and educators, laying out the history of the controversy and the perspectives of the sciences.

Gould, Stephen *Rocks of Ages: Science and Religion in the Fullness of Life.* 1999, Library of Contemporary Thought. A well-known scientist and popularizer looks at the relationship between science and religion.

Articles

Abell, G. “The Ages of the Earth and the Universe” in Godfrey, Laurie, ed. *Scientists Confront Creationism.* 1983, Norton.

Asimov, I. “The Threat of Creationism” in the *New York Times Magazine*, June 14, 1981, p. 90.

Bobrowsky, M. “Teaching Evolutionary Processes to Skeptical Students” in *The Physics Teacher,* Dec. 2000, vol. 38, p. 565. Includes an astronomer’s responses to creationist arguments.

Dutch, S. “A Critique of Creationist Cosmology” in *Journal of Geological Education*, 1982, vol. 30, p. 27.

Larson, E. & Witham, L. "Scientists and Religion in America” in *Scientific American*, Sept. 1999, p. 88. Deals with the range of scientists' religious views, and contains some useful insights on the issue of evolution.

Scott, E. "Antievolution and Creationism in the U.S." *Annual Reviews of Anthropology,* 1997, vol. 26, p. 263. A leading pro-evolution educator summarizes the issues.

Rusk, J. “Answers to Creationism” in *The Planetarian (Journal of the International Planetarium Society)*, Sep. 1988, vol. 17, No. 3.

Magazines that Follow the Controversy

Reports of the National Center for Science Education, P.O. Box 9477, Berkeley, CA 94709. The center works to oppose the efforts of creationists and to assist educators who want to present the evolutionary perspective.

Skeptical Inquirer Magazine, CSICOP, P.O. Box 703, Amherst, NY 14226. The official magazine of the Committee for the Scientific Investigation of Claims of the Paranormal, the leading skeptical group in the world; it seeks to educate teachers and the public about fantastic claims and how to test them.

A Few Helpful Websites:

National Center for Science Education [www.ncseweb.org/] is the key organization working to oppose the efforts of creationists and to assist educators who want to present the evolutionary perspective. The site is full of excellent information and links.

Science and Creationism [bob.nap.edu/html/creationism/] is a short booklet from the National Academy of Sciences, with a fine summary of the scientific perspective on evolution.

Teaching about Evolution and the Nature of Science [bob.nap.edu/html/evolution98/ OR www.nap.edu/books/0309063647/html/index.html] is a short book from the National Academy with hints and resources for teachers.

Talk.Origins Archive [www.talkorigins.org] contains articles, essays, and discussion about all aspects of the creation/evolution controversy.

Questions and Answers about Creationism/Evolution: [www2.uic.edu/~vuletic/cefec.html] A nicely organized summary of creationist arguments and scientific responses.

Voyages through Time [www.seti.org/education/vtt-bg.html] is a curriculum for a one-year high school integrated science course centered on the unifying theme of evolution, being developed by the SETI Institute and others.

A Few Resources on Science and Religion:

The American Scientific Affiliation (http://www.asa3.org) is an organization of professional scientists who are Christians. This group has written a handbook for teachers: "Teaching Science in a Climate of Controversy" (http://www.asa3.org/ASA/resources.html), which includes activities for students, and teaching strategies. It emphasizes the remaining open questions in biological and cosmic evolution, as well as the solid evidence for the parts that we do understand.

There is also a web site and email list of professional astronomers who are Christians: http://www.calvin.edu/~dhaarsma/chr-astro.html. Many religions other than Christian, of course, may be represented among your students. The web site www.geocities.com/fourtyres contains a thoughtful article, by science teacher Dr. Douglas Hayhoe, about some possible relationships between science and religion.

Appendix Two:
Activities for Teaching about the Age of the Universe and Its Contents

Below are a few activities that you can do with your students to show them how science works and how we have come to know about the age and evolution of the universe.

At the beginning of any discussion of the age and origin of the universe, it is helpful to have the students, working in small groups, discuss and write down their views on questions such as (a) How do you think the Universe began? (b) Where did you get this understanding? (c) Of the answers which your classmates gave for question (a), which do you think is the most correct? Why? This activity can be repeated at the end of the topic.

**** Cosmic Calendar:*** www.astrosociety.org/education/astro/act2/cosmic.html
Students learn to scale the history of the universe since the Big Bang to a one-year calendar, noting where significant events (such as the formation of the Earth or the rise of humans) would fall in that year.

**** Toilet Paper Geologic Time Scale:*** www.nthelp.com/eer/HOAtimetp.html
This activity uses a roll of toilet paper to measure out the 4.6-billion year time span since the Earth formed to scale. Includes a list of major events in biology and geology over that span.

**** Exploring Mars: Old, Relatively:*** cass.jsc.nasa.gov/expmars/activities/oldrel.html
Students examine an image of part of the Mariner Valley complex on Mars with craters and landslides, to see which features formed in what order. (A similar activity using an image with outflow channels and craters is found at: cass.jsc.nasa.gov/expmars/channels.html)

**** Hubble Deep Field Academy:*** amazing-space.stsci.edu/hdf-top-level.html
Students work with real images from the "Hubble Deep Field" – a long exposure view of the most distant galaxies – as they learn about galaxy classification and estimating galaxy distances. (Good use of real data!) Some of the "too-cute" web features may discourage older students, but hard-copy versions are available and can be down-loaded.

**** The Expanding Universe:*** btc.montana.edu/ceres/html/uni1.html
An activity on Hubble's Law, which describes the expansion of the universe. Students measure the separation of dots on an expanding balloon and derive the relationship. Involves learning about cepheid variable stars and cosmic distance measurement.

**** Direct Hit at the K-T Boundary*** in *Exploring Meteorite Mysteries:*
spacelink.nasa.gov/Instructional.Materials/NASA.Educational.Products/Exploring.Meteorite.Mysteries/
Students search for evidence for an impact 65 million years ago that may have killed the dinosaurs (and as many as half of all species living on Earth) and study how such an impact might have affected global climate.

For more activities like this, see two collections of hands-on astronomy activities published by the non-profit Astronomical Society of the Pacific:

- *Universe at Your Fingertips* [www.astrosociety.org/education/astro/astropubs/universe.html]
- *More Universe at Your Fingertips* [www.astrosociety.org/education/astro/astropubs/moreuniverse.html]

You can call 1-800-335-2624 to order these books.

For a much longer list of good astronomy activities on the Web, see:
www.astrosociety.org/education/activities/astroacts.html

An Ancient Universe: Illustrations

An Ancient Universe: Illustrations

[to go at the beginning]
Figure 1: Galaxies. This Hubble Space Telescope image shows a selection of galaxies – great "islands" of billions of stars seen in every direction our telescopes can look. The area of sky seen here is very small – about the size of President Roosevelt's eye on a US dime, when the dime is held at arm's length. The galaxy that appears so large at the upper left is 300 million lightyears away – so far that light from it takes 300 million years to reach us. Some of the galaxies that look smaller are even further away. Everything on this image that is not a circular dot is in fact a galaxy of stars. (Courtesy of William Baum, the Space Telescope Science Institute, and NASA.)

SOURCE: http://oposite.stsci.edu/pubinfo/pr/1995/07.html

[page 3]
Figure 2: Telescopes. 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. These are currently the largest light-collecting telescopes in the world, although the European Southern Observatory is building a series of four giant telescopes in Chile which will have a larger collecting area when their light is combined. With such telescopes, astronomers can detect the light of very distant (and thus faint) objects. (Courtesy of William Keck Observatory and Caltech)

SOURCE:
http://www.astro.caltech.edu/mirror/keck/realpublic/gen_info/kiosk/pages/distantkecks.html

[page 3]
Figure 3: Saturn with Some 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)

SOURCE: http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA01364
[tilt so the picture is horizontal]

[page 3]
Figure 4: A Martian Meteorite. Millions of years ago, an enormous impact (a large chunk of rock or ice hitting Mars) blasted parts of the planet 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.)

SOURCE: http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA00289

[page 4]
Figure 5: 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)

SOURCE: http://www.noao.edu/image_gallery/html/im0685.html

[page 6]
Figure 6: 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. 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)

SOURCE: http://www.hawastsoc.org/solar/cap/sun/sun.htm

[page 7]
Figure 7: 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 _ 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)

SOURCE: http://oposite.stsci.edu/pubinfo/PR/96/01.html
[use the one called 96-01a: Hubble Deep Field Wide View]

[page 7]
Figure 8: 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. Even after 7 to 9 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)

SOURCE: http://oposite.stsci.edu/pubinfo/PR/97/03.html

[pages 8-9]
Figure 9: The Earth from Space. This image 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)

SOURCE: http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA01462

[Page 9]
Figure 10: 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)

SOURCE: http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA00126

[Page 9]
Figure 11: 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)

SOURCE: http://impact.arc.nasa.gov/

[using the buttons on the left side, go to “Multimedia Gallery” and then scroll down to the third image: “Nature Remodels the Coastline” – that’s the one]

[Page 9]
Figure 12: 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 it was carved by running water. (Courtesy of Malin Space Science Systems/JPL/NASA.)

SOURCE: http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA02094

[Page 10]
Figure 13: 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.)

SOURCE: http://heritage.stsci.edu/public/2000dec6/dsslabw.jpg

[Page 11-12]
Mapping the Cosmic Background Radiation. This map, made from data gathered by the COBE spacecraft, shows the intensity of the left-over radiation from a period not long after the Big Bang. Tiny variations (shown by the different colors) in the intensity of this radiation show where matter in the early universe was more densely or less densely concentrated. The denser regions most likely gave rise to the concentrations of matter (like great groups of galaxies) that we see in the universe today, over ten billion years later. (Courtesy COBE Science Working Group/NASA Goddard Space Flight Center.)

SOURCE: http://space.gsfc.nasa.gov/astro/cobe/cmb_fluctuations_big.gif