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R. Grant Athay

Our Majestic Sun

It is New Year’s morning. The sun has not yet risen at our winter home in the Sonoran Desert of Arizona. The air is clear and cold, and I eagerly await the warmth of the morning sun. As I wait, I resolve to share my knowledge of the sun—that marvelous source of light and energy introduced by the simple words, “And God said, Let there be lights in the firmament of the heaven to divide the day from the night; and let them be for signs, and for seasons, and for days, and years: and let them be for lights in the firmament of the heaven to give light upon the earth: and it was so.” While conveying the message that God is the creator of heaven and earth, this brief, poetic account makes no attempt to emphasize the enormity and grandeur of that creation.

The sun’s enormity and grandeur are of great interest to me—solar research has been the central focus of my career as an astrophysicist. Beginning some forty years ago at an observatory located in the high mountains of Colorado where I daily focused a carefully designed and precisely crafted telescope on the rising sun, my pursuit of the sun has taken many turns. It has taken me to other mountain observatories in New Mexico, Arizona, California, Hawaii, the High Pyrenees, and the Swiss, German, and Japanese Alps. At other extremes, it has taken me to the deserts of Africa and to remote islands in the Atlantic and Pacific Oceans. Recently these observation sites have been supplemented by powerful extraterrestrial observatories placed in orbit by rockets or carried aboard the space shuttle. In using the unique data collected from these remote observatories, I have worked with the world’s most powerful computers as well as the most recent scientific theories. Hundreds of colleagues in the U.S. and in foreign lands have shared and aided in these efforts. Some of my colleagues have flown as astronauts, and others have endured the intense cold on the high plains of Antarctica in order to carry out delicate observations of the sun without interruption night and day for several days. Still others have built large facilities in deep mine caverns for detecting neutrinos, the most elusive of all solar radiations, emitted from the very core of the sun and able to travel almost unimpeded through both the sun and the earth.

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Hardly a day has gone by during these past forty years that I have not puzzled over the unsolved mysteries of the sun. While waiting for the sunrise and reflecting over the past years, I am still filled with awe by the beauty and majesty of this heavenly object. I am awed that this star of dwarfish proportions, compared to other stars, so effectively delivers light and heat to a small planet ninety-three million miles away. I am awed by the complexities associated with that delivery. The energy in the sun's rays that I will soon enjoy started its journey several million years ago from the extremely hot, dense core of the sun. At that time the energy was mainly in the form of x-rays gradually diffusing toward the sun's surface. In their outward diffusion the x-rays gradually softened, and by the time they reached the surface, they had been converted into the warm, gentle rays of light and heat so familiar to us. By current estimates this slow, tortuous journey from the center of the sun took about fifteen million years. Yet scarcely more than eight minutes is required for the journey from the sun's surface to the earth.

We have learned a great deal about the sun, and we continue to learn at an accelerated pace; several volumes are required to document and explain this knowledge. Yet, much of what we observe about the sun still defies comprehension and gives rise to some sense of defeat. Many of the mysteries have only grown deeper and more baffling as we have learned more about them. In most respects the sun remains our teacher, and we are subdued by the knowledge that none of us fully comprehends the sun's complexity. Nevertheless, in trying to understand the sun we have learned much about the universe in which we live.

The sun is one of our most valuable laboratories for studying the basic physical processes of the universe, as well as those of our own world. The sun displays a panorama of phenomena that cannot be duplicated on earth. On special days it is violently active and on other days relatively calm. Even at its calmest moments, however, it is restless and seething. By unraveling its mysteries, we enhance our knowledge of our environment.

It is a tribute to modern man that we have learned so much about the universe. Most of what we now know has been learned in the technological boom of the last few decades. Centuries of earlier work was limited by a lack of knowledge of atomic and nuclear physics and of the basic laws of thermodynamics. On the planet earth we live in a protected, subdued environment. In interpreting the universe around us, we have been forced to open our minds to circumstances far beyond anything we have experienced. In addition, we have had to use every tool of modern science and technology and to invent new tools when the need arose. Thus, when we consider the achievement and potential of modern astronomy, we have much to be proud of. Pride for these achievements turns to humility, however, when we realize what prophets of old learned without the benefits of modern science and technology. Through faith in God and a desire to understand his creations, they advanced their knowledge of the universe far beyond the secular knowledge of their day.

Consider the following verses from the vision of Moses: "And worlds without number have I created . . . For behold, there are many worlds that have passed away . . . And there are many that now stand, and innumerable are they unto man . . . The heavens, they are many, and they cannot be numbered unto man . . . And as one earth shall pass away, and the heavens thereof, even so shall another come, and there is no end to my works" (Moses 1:33, 35, 37, 38). To interpret the meaning in these phrases, we must first define earths, worlds, and heavens. A common definition of worlds refers to human activities together with their environment. Similarly, in the Book of Moses, the term earths appears to refer to planets occupied by humans. This usage is consistent with the primary theme of the Book of Moses, which is man's relationship to God: "For behold, this is my work and my glory—to bring to pass the immortality and eternal life of man" (Moses 1:39). Thus, we shall define worlds and earths as being synonymous. The term heavens clearly refers to the stars, star systems, and other objects in those portions of the universe in proximity to an earth or world. For those of us on earth, heavens refers mainly to our own galaxy and more specifically to the stars and planets in our own neighborhood of the galaxy. Lastly, we shall interpret passing away as a form of death, or at least changes of such proportions that a previous state ceases to exist.

With these definitions, the phrases quoted from Moses state several important facts. Planets and stars have finite lifetimes; they are born and they die. Many have already died and new ones have replaced them. Creation, therefore, is an ongoing process. Our earth and sun were not the first planet and star. They had ancestors, and when they die, they will have offspring. In the scenario revealed to Moses, humankind's temporary occupancy of earth represents but a single family living in one generation of a family tree consisting of innumerable other civilizations on other earths which have their own stars and heavens. Earlier generations have "passed away" and new ones have yet to emerge.

Moses' portrayal of a living, evolving universe in which all things have rhythmic life cycles is in perfect harmony with modern astronomy and astrophysics. What Moses learned through revelation, we have had to learn through observations and the gradual discovery of the physical laws that describe the behavior of matter in the universe—an effort that has involved thousands of scientists and engineers.

Oases in the Universe

During the early nineteenth century, the scientific world believed that the sun, the moon, and all the planets of the solar system were inhabited. Little was known about the nature of stars or the possibility of other planetary systems resembling our own, although the universe was looked upon as friendly and nourishing to life. We have since learned that life, as we experience it, could survive without external support in relatively few places in the universe. Other planets in the solar system either lack air and water or they have noxious atmospheres and impossibly severe climates. The sun is gaseous throughout with no solid surfaces and is far too hot for earth life to exist. Thus in this solar system, the planet earth is unique as an abode for man.

When we look among other stars for possible earths, we find that most are unsuitable. For another earth, we would need a single star to provide heat and light as well as a constant gravitational field in which to orbit. Most stars occur in clusters ranging from pairs to swarms numbering tens of thousands. None of these is a good candidate. In the complex and constantly varying gravitational environment of star clusters, there are no stable orbits where planets can survive for long periods of time by orbiting a single star. Nevertheless, among the twenty billion stars of our galaxy we still expect to find millions of possibilities for earth-like planets sprinkled throughout the galaxy and separated from each other by an average distance of several tens of light-years.

Even when we find isolated stars with steady gravitational fields, conditions are not necessarily suited for life. We are accustomed to thinking of our sun's steadiness and dependability and its beneficial supply of heat and light. However, the sun is also unsteady, undependable, and hostile to life. In fact, we survive in the solar system only because earth acts as an oasis which protects us from the lethal radiation that appears to be a natural property of most stars.

For reasons not fully understood, the sun reaches a minimum temperature just outside its visual surface. From that minimum of about 4,500 degrees centigrade, the temperature of the gas around the sun climbs rapidly to a million-plus degrees centigrade. This hot gas surrounds the sun in a tenuous corona which influences the entire solar system. The corona emits x-rays, faintly at times and brilliantly at others. It also emits energetic particles that, like subatomic bullets, spray the earth and other planets. Like the x-rays, these particles are sometimes weak and sometimes intense but are always deadly to life.

Most of these particles are stopped in the earth's upper atmosphere. Very few reach the surface and fewer hit a human being. However, each particle that enters our bodies may kill cells in our tissues and organs and convert some to cancerous cells. Our bodies can tolerate some particle bombardment, but they cannot tolerate large, uncontrolled doses. As the radiation dosage increases, the rate at which cells die or become cancerous increases, leading, if safe limits are exceeded, to radiation sickness and death.

Solar particle radiation is highly sporadic and, at times, exceeds safe limits to anyone exposed to its full intensity. It is a concern for astronauts and for aircraft crews flying high altitude polar routes where exposure to solar particle radiation is much enhanced.

Since our first penetration of space in the 1950s by rockets salvaged from World War II, we have flown x-ray cameras and particle detectors beyond the earth's protective shield. We now have firsthand knowledge of these lethal solar radiations and their variations. The x-rays and particles from the sun rise and fall in intensity with the sunspot cycle, which lasts roughly eleven years. Superimposed on this cyclic variation are short-lived flares of more intense radiation occurring most frequently near the peak of the sunspot cycle. From earth, we see the effects of the x-rays and particles as unusual displays of the Northern Lights, storms in the earth's magnetic field, and disruptions to shortwave radio communications. All these phenomena originate high above us in the earth's outer atmosphere.

Exactly why the sun has an active, hot corona, and how it accelerates energetic particles remains a mystery. However, the sun is not unique in this respect. X-ray cameras in space reveal that most stars have a hot corona surrounding them. Earth-based observatories detect cycles of activity on even very distant stars. These stellar activity cycles are similar in character to those of the sun, even to the occurrence of starspots and short-lived flares of more intense radiation. Therefore these stars probably produce energetic particles in addition to the x-rays that we observe. Indeed, these stars may produce many of the mysterious cosmic rays that continuously bombard the earth just as energetic particles from our sun stream out beyond the solar system to bombard other stars and their planets.

Although we do not understand the specifics of the processes by which stars produce hot coronas and accelerate energetic particles, we have identified the essential ingredients of these processes. Those ingredients are ions, rotation, and internal motion. All stars possess the first two and most possess the third. All stars are hot enough to free electrons from the more easily ionized elements, such as iron and other metals. Some rotate slowly, others rapidly, but all rotate. A majority, as is the sun, are stirred by restless convection. In combination, these three ingredients act as a giant dynamo that generates magnetic fields. These magnetic fields, in turn, are pushed and carried about by the restless, ionized gases of the star. This buffeting of the magnetic fields provides the means for heating stellar coronas and accelerating electrically charged particles to high energies. The high temperature of the sun ionizes solar elements and supplies abundant free electrons and positive ions. Thus stellar activity cycles with their x-rays and energetic particles are a natural consequence of the most basic properties of stars. The cycles of activity consist of dynamo cycles in which magnetic fields are generated and decay. The magnetic fields are a form of energy, and some of this energy reappears as the energy of the corona. Both on the sun and on other stars, starspots are at the loci of unusually strong magnetic field concentrations, and it is over these starspots that the coronas shine brightest and are the most active.

In our universe stars provide the energy essential to life but, at the same time, produce harsh radiation that destroys life. Our sun is no exception. Just as a desert oasis provides water along with foliage which protects one from the heat of the midday sun, the earth provides necessary nutrients along with a protective atmosphere and magnetic field without which none of us could survive. Again, we recognize that, just as the ingredients of life are natural to the sun and earth, the harmful radiations are equally natural. Life in the universe is precarious, and, for life to exist elsewhere would require planetary oases similar to earth orbiting isolated stars of modest or weak coronal activity.

Along with the discovery that our sun has an unfriendly side caused by its corona, we are learning much about the sun's interior.

Beneath the Sun's Surface

Compared to the earth, the sun is a giant. Its diameter of 870,000 miles is over 100 times that of earth, and its mass exceeds the earth's by 330,000 times. However, our sun belongs to a populous class of somewhat dwarfish stars. Some supergiant stars are a hundred times more massive, some nearly a thousand times larger in diameter, and some a hundred thousand times more luminous. At another extreme, there are stars much smaller in diameter than the earth but more massive than the sun.

Stars produce prodigious amounts of energy. Energy flows through the solar surface at the approximate rate of 8,000 horsepower per square foot. Even as far away as the earth, the energy in sunlight is over 1.5 horsepower per square yard. In more graphic terms, the sunlight falling on a full-size horse standing in a sunny field at midday carries more power than two horses working at a normal rate.

Attempts to explain such vast amounts of energy ended in frustration until the first half of this century when Albert Einstein discovered a formal equivalence between energy and mass. Others probed the nuclei of atoms and experimented with nuclear reactions until it became clear that nuclear energy provided a promising explanation for the sun's power. Other possibilities had been considered earlier, including energetic chemical reactions, such as explosives, and the power of the sun's gravitational energy. These more conventional sources can produce sufficient energy for short periods of time, but they have limited reserves. The shrinking size of a star under the force of gravity does provide the main source of energy during the formative, youthful stages of stars but cannot supply enough energy for stars the age of the sun. Nuclear energy, on the other hand, is enormously more efficient and easily provides sufficient fuel to power the sun for several billion years. Furthermore, the hot, dense interior of the sun provides just the proper environment to stimulate and nourish the nuclear reactions.

The chemical makeup of the sun and stars is determined by a spectral analysis of the light those stars emit. Each atom and molecule, regardless of whether it is in the laboratory or in a distant star, leaves its own unmistakable "fingerprint" in the light spectrum. Throughout the universe, stars are composed mainly of hydrogen with only traces of heavier elements. The next most abundant element is helium, followed by oxygen, nitrogen, and carbon. Metal atoms are less abundant still. In the sun, 90 percent of the sun's atoms are hydrogen, about 10 percent are helium and all others combined make up less than 0.1 percent. The most common nuclear reaction in the sun is the fusion of hydrogen to create helium, the same process used in hydrogen bombs. In this process, about 0.7 percent of the mass in the hydrogen nuclei is converted into energy in accordance with Einstein's famous equation. The remaining 99.3 percent forms the mass of helium nuclei. Even though only a small fraction of the hydrogen mass is converted to energy, this reaction alone can sustain the sun for a billion years at its present level of power by fusing only about one percent of the available hydrogen into helium. In reality, even less consumption of hydrogen is required because of other nuclear reactions that occur along with the hydrogen-helium reaction. We expect the sun to use up much more than one percent of its available fuel during its life-span. Thus, the sun should continue in its present state for several billion years.

Once we know the source of the sun's energy and its mass, radius, luminosity, and chemical composition, we can determine its internal structure. For the sun to remain in equilibrium, the energy produced by its internal nuclear reactions must equal the observed luminosity and must be carried to the surface at exactly the same rate that it is generated. Also, the pressure inside the sun must be high enough to support the weight of the overlying material. These factors—the rate of energy production, the rate of energy flow to the surface, and the pressure—are regulated by the temperature and density inside the sun. Therefore, the equilibrium requirements on the pressure and energy generation together with the observed size, chemical composition, mass, and luminosity enable us to determine the internal temperatures and densities.

At the center of our sun, the temperature rises to 20 million degrees centigrade (45 million degrees Fahrenheit), and the pressure rises to three billion tons per square inch. The enormous pressure compresses matter to a density about ten times that of solid lead even though it is made up mostly of hydrogen, the lightest of all elements. Because of the high temperature, however, even this very dense material is still a gas—each atom is free to race about at high speed among its very crowded neighbors. As a whole, the solar gas in the deep interior is still and moves only with the solar rotation.

Higher temperatures and densities accelerate nuclear reactions. As a result, most of the energy that escapes the solar surface is generated near the very center of the sun. During most of its journey to the surface, the energy diffuses slowly outwards in the form of radiation. But the hot solar gases are extremely opaque, allowing photons of radiation to travel only short distances before being absorbed and then reemitted. The reemission occurs in random directions, causing the photons to travel backwards nearly as often as forwards. Thus progress to the surface proceeds slowly.

For about the last quarter of the distance from the sun’s center to the surface, the gas becomes restless. A broad zone of convection sets in with hot, ascending columns separated by cool, descending plumes. This convection gives rise to a net upward flow of heat that is much more efficient than the slow diffusion of radiation, thereby decreasing the time required for the energy to reach the surface. Nonetheless, the journey from the sun’s center to the surface requires approximately 15 million years.

Even though we can model the interior structure of the sun to successfully produce its observed bulk properties, we continue to seek new means for testing the model. Two very different tests are currently in use. One involves elusive particles known as neutrinos that occur as by-products of the nuclear reactions. A second involves sound waves generated by the turbulent action of the convection zone.

As their name implies, neutrinos are electrically neutral. They have little or no mass, at most a tiny fraction of the electron mass. They interact only slightly with the more common forms of matter, and almost all of them escape the sun without difficulty. For the same reason, however, they are very difficult to detect and not a great deal is known about their properties. But, we do know the rate at which nuclear reactions are occurring in our solar model, and, as a result, we can predict the rate of neutrino production. By measuring the neutrino flux, we have a direct test of the interior model.

The task of measuring solar neutrinos has been undertaken by physicists working thousands of feet underground in deep mines. By placing the neutrino detector in underground mines, they hope to shield the detector from other forms and sources of radiation that could influence neutrino detection. Their equipment includes large tanks containing thousands of tons of fluid in which a few neutrinos are detected each year. The neutrinos themselves are not detected directly, but in passing through the detector they produce intricate but detectable changes in the fluid. The rate at which these changes occur provides a measure of the neutrino flux.

Different nuclear reactions produce different species of neutrinos, but there is evidence that neutrinos can evolve into a different species in less time than it takes them to travel from sun to earth. Neutrino detectors generally detect only one type of neutrino, so observations need to be made with several different detectors. Although only one species of solar neutrino has been studied thus far, the results have created much excitement. The observed neutrino flux is less than half the amount predicted. Either the solar model is not quite correct or most of the neutrinos of the type detected have evolved into a different species and, in so doing, have escaped detection. We will not know the answer until we have a set of observations which includes the other species of neutrinos. When the answer does come, we will learn more about the solar interior or more about the fundamental nature of neutrinos themselves.

Whichever way the answer to the neutrino riddle turns out, we probably will not need to radically revise the interior model of the sun. The types of nuclear reactions that occur in the sun are extremely sensitive to temperature, so relatively small changes in temperature can substantially alter the flux of particular species of neutrinos. Also, other factors not accounted for in the models can alter the rates of particular reactions and their associated rates of neutrino production. As we fine-tune the model to agree with the measured neutrino fluxes, we may need to account for some of these secondary influences. Until we finally solve the neutrino problem, however, we will continue to be uneasy about just what goes on inside the sun.

The second means of studying the solar interior involves techniques similar to those used in terrestrial seismology. The convection of the gases and the intense flow of radiation in the sun produce a variety of wave modes including sound and gravity waves. Gravity waves propagate mainly horizontally, but sound waves travel in all directions. Those that go upward are reflected back by the hot solar atmosphere. As the reflected waves travel downward, the increasing density and temperature in the interior of the sun cause the waves to follow a curved path that eventually leads them back to the surface where they are again reflected by the hot atmosphere above. Thus, the sound waves are trapped within the outer mantle of the sun. The higher frequency waves are trapped in the layers nearest the surface, while the lower ones penetrate deep into the interior. As in an organ pipe, the trapped waves resonate at certain well-defined frequencies determined by the size of the enclosure and the speed of sound. The sun resonates especially to waves with periods about five minutes long. Hundreds of such resonances occur with measurable amplitudes that reveal the periodic fluctuations of the solar surface in both brightness and velocity.

Precise measurements of the frequencies at which the sun resonates provide information about how both the speed of sound and the rate of rotation vary with depth. Temperature determines the speed of sound, so measuring sound provides a measure of the interior temperature. Temperature measurements, in turn, serve as a check on the solar model. Studies of internal rotation are important for understanding such phenomena as the sun's dynamo action and the rate at which one layer mixes with another. Rotation studies are based on the fact that the rotation of the sun splits each resonance frequency into two closely spaced components whose separation is proportional to the speed of the rotating gas.

Precise measurement of the sun's resonance frequencies requires observations over long periods of time with as little interruption as possible. The days of midnight sun in summertime at the earth's poles have been used with moderate success, but improvements are needed. Solar physicists are currently building a network of six observing stations located at strategic longitudes around the globe and at sites noted for their sparse cloudiness. Identical instruments placed at each site will provide observations interrupted only by occasional periods of simultaneous cloudy weather at consecutive sites. Also, a joint U.S. and European satellite, currently in an advanced planning stage, will carry an instrument for measuring solar oscillation frequencies. The orbit will be such that the satellite will experience the long periods of uninterrupted sunlight ideal for the accurate measurement of frequencies.

By such techniques, and perhaps others yet to be discovered, we will gradually come to understand the primary structure and phenomena of even the deepest layers of the sun. Whatever happens in the interior of the sun will influence the surface layers in an observable way; therefore, interpreting surface phenomena correctly discloses events in the interior.

The Generations of the Stars

The first step for understanding the universe is a reliable measurement of distances. The standard unit of distance in astronomy is the light-year, the distance light travels in one year through space. One light-year is approximately 6 trillion miles or 63,000 times the distance from sun to earth.

The distances to stars in our immediate neighborhood are measured by triangulation, the method used by surveyors to measure distances beyond the reach of their tapes. As a baseline for these measurements, we astronomers use the diameter of the earth's orbit, which is 16.6 light-minutes. By such measurements, we discover that the star nearest the sun is more than 4 light-years away and that some 100 stars inhabit space within 22 light-years from earth. The mean distance between these 100 stars is 7.6 light-years.

Triangulation gives reliable distances for tens of thousands of stars, which is a large enough sample to establish some of the basic properties of stars and determine how these properties are interrelated. Added evidence comes from studying compact clusters of stars which reside at such great distances from earth that all the stars in the cluster are effectively at the same distance. Cluster studies, added to those of the nearby stars, show that there are close relationships between a star's spectrum of colors and the star's absolute brightness. Absolute brightness depends on the star's total rate of energy radiation, and this remains the same regardless of the star's distance from earth. The apparent brightness of a star depends on its absolute brightness and its distance from us. As the distance increases, the apparent brightness decreases in a known way—doubling the distance decreases the apparent brightness to a quarter of its former value. Thus, by carefully measuring a star's spectrum, we can determine its absolute brightness, and if we then measure its apparent brightness, we can determine its distance. Similarly, the brightness of some stars pulsates, with periods ranging from fractions of days to weeks. Such stars exhibit a close relationship between the period of pulsation and absolute brightness; by measuring the period of pulsation and apparent brightness, we again have a reliable measure of a star's distance.

These techniques, plus others, work equally well on stars in distant galaxies. By using a combination of techniques, we have learned that our Milky Way Galaxy is in the form of a giant disk measuring some 150,000 light-years in width and 50,000 light-years in thickness. Our solar system is located approximately 27,000 light-years from the galactic center. Roughly 140,000 light-years from us are two other galaxies named the Magellanic Clouds which are visible to the naked eye from the southern hemisphere. Another dozen galaxies are within 1.6 million light-years of earth and complete a local cluster of galaxies. Beyond these are other clusters, many measuring in excess of 10 million light-years in width and containing hundreds of galaxies. On a still grander scale, we see in all directions galaxies and groups of galaxies arranged in patterns extending as far as our best telescopes can see, which is several billion light-years.

Since distance can be expressed as light-years, distance is equivalent to time. A star located 50,000 light-years from us is seen today as it was 50,000 years ago and a distant galaxy a billion light-years away is seen as it was a billion years ago. We, therefore, cannot escape the conclusion that the age of our universe extends billions of years back in time.

Modern science was not the first to posit such an ancient beginning for the universe: The universe's age was apparently known to the prophet Abraham. A quotation taken from the *Times and Seasons* states:

> Eternity, agreeably to the records found in the catacombs of Egypt, has been going on in this system (not this world) almost *two thousand five hundred and fifty five millions of years:* and to know at the same time, that deists, geologists and others are trying to prove that matter must have existed hundreds of thousands of years;—it almost tempts the flesh to fly to God, . . . and see and know as we are seen and known![1]

This quotation appeared in the same time period as Joseph Smith's translation of the Book of Abraham, which accounts for the reference to "records found in the catacombs of Egypt." In 1844, astronomers were just beginning to realize the vastness of our Milky Way Galaxy and what it implied in terms of ages. They knew little about the universe beyond our galaxy. Similarly, geologists were becoming aware that the earth, also, had a much longer history than they had previously supposed. Not until this century, however, did scientists begin to think in terms of billions of years.

What about our own star, the sun? How old is it? How much longer will it last? The answers to these questions come from diverse directions. Geologists set the age of the earth at approximately 4.5 billion years. Moon rocks gathered by astronauts and robotic lunar landings show the effects of exposure to solar particle radiation as it has accumulated over time. The total amount of dosage found in the moon rocks requires an exposure time of about 4.5 billion years at the current rate of solar particle radiation. We know that young stars are more active than old stars, and we infer that the sun radiated particles at a greater rate in its youth. Stellar youth is measured in millions of years rather than in billions, however, and even allowing for the increased activity of the youthful sun, the moon rocks still require a sun of the same age as the earth.

We also learn about stellar ages from their evolutionary patterns. Through spectral classification, we categorize young stars, middle-aged stars, old stars and the remains of dead stars. The sun is clearly in the middle-aged group. It is a normal star, albeit relatively inactive and somewhat dwarfish in size. In the life of a star, middle age begins after the formative phase of gravitational contraction has subsided and the nuclear fire has been ignited in the star's core, and middle age lasts an exceedingly long time. There is little, if any, reason for pronounced change as long as the nuclear fuel remains plentiful. As we noted in the preceding section, the sun has sufficient fuel to burn steadily for several billion years.

Stellar death rates provide a measure of the average life-span of stars. We can determine death rates because some classes of stars brighten spectacularly in their death throes and are readily identified even in distant galaxies. In a galaxy of 20 billion stars we expect to see only a few stars die each year if the average star lives a few billion years. On the other hand, if the average life-span were much shorter, many more stars would die each year. By observing stellar death rates, we infer that stars of the same mass and absolute brightness as the sun have a life-span of several billion years. Thus, available evidence points to an expected life-span for our sun of several billion years.

Exactly where the sun is in its life cycle is not so readily determined. Its level of activity suggests that the sun has been middle-aged for some time. Stellar aging is accompanied by a decreasing rate of rotation, or spindown. The sun is a slow rotator, again suggesting a respectable age.

What about our sun's ancestry? How many generations preceded it? Not too surprisingly, our galaxy is much older than the sun and approaches the age of the universe itself. Among star clusters within the galaxy, we find both young and old. The oldest group have ages of about 20 billion years. Star clusters in nearby galaxies indicate ages similar to those in the Milky Way Galaxy. Aside from determining the ages of star clusters, the primary means of measuring the age of the universe is through its expansion rate. Galaxies beyond ours are moving away from us. The more distant galaxies are receding at a higher velocity than those that are nearer. The expansion velocities are so regular and so universal that they suggest a common beginning to the expansion itself. The beginning of the expansion is ascertained by projecting the observed law of expansion backward in time until the universe becomes compact. This is the so-called Hubble time, currently evaluated at 17 billion years, which is compatible with the estimated ages of the older star clusters in our galaxy and in other nearby galaxies.

Both our galaxy and the universe are much older than the sun. Thus the sun was created in an already existing galaxy of stars. It is of a relatively recent generation, but not the most recent. There is other evidence that our galaxy is a birthing center for stars. Within the galaxy there is much tenuous matter distributed between the stars. Additionally, in regions of unusually dense interstellar clouds, we observe many very young stars. Most are in their youthful stages of high activity and rapid rotation. Some appear to be just emerging into an identity as a star. Numerous such birthing centers for stars are already known, and with the new infrared technology of recent years, more are being discovered.

Each new generation of stars forms from the ashes of earlier generations. Each generation consumes a little more of the plentiful supply of hydrogen in the universe, and, in so doing, creates more carbon, oxygen, silicon, calcium, iron, and all the elements with which we are familiar. Thus, a star's chemistry reveals its history and its ancestry. Early-generation stars have only traces of heavy elements. Recent generations are much richer in the heavy elements fused by earlier generations that have lived and died since the birth of the galaxy. The sun's chemical makeup suggests that it is of the fifth or sixth generation.

Conclusion

Once again an early morning hour finds me waiting for the rising sun's energy, energy that has been traveling over the previous millions of years. I wonder about earlier generations of stars whose demise created the elements of the earth, as well as those of the sun. The ashes of those same stars also supply the elements of which our bodies and all living things on earth are made. I am conscious that the warm gentle rays of the sun are vital to life, while the deadly x-rays and atomic bullets emanating from the sun's fiery corona would destroy life if we weren't protected on our earthly oasis. I marvel at all we have learned concerning the sun and the rest of the universe—all referred to in Genesis by the brief phrase "And God said let there be lights in the firmament of the heaven." But I yearn to know more, much more.

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1. *Times and Seasons* 4 (1 January 1844): 758.