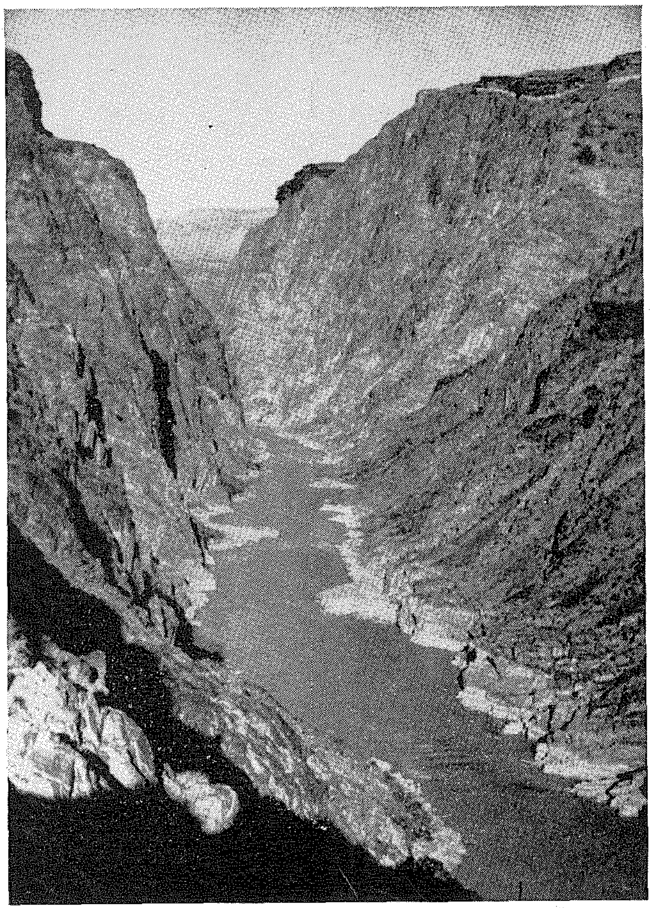
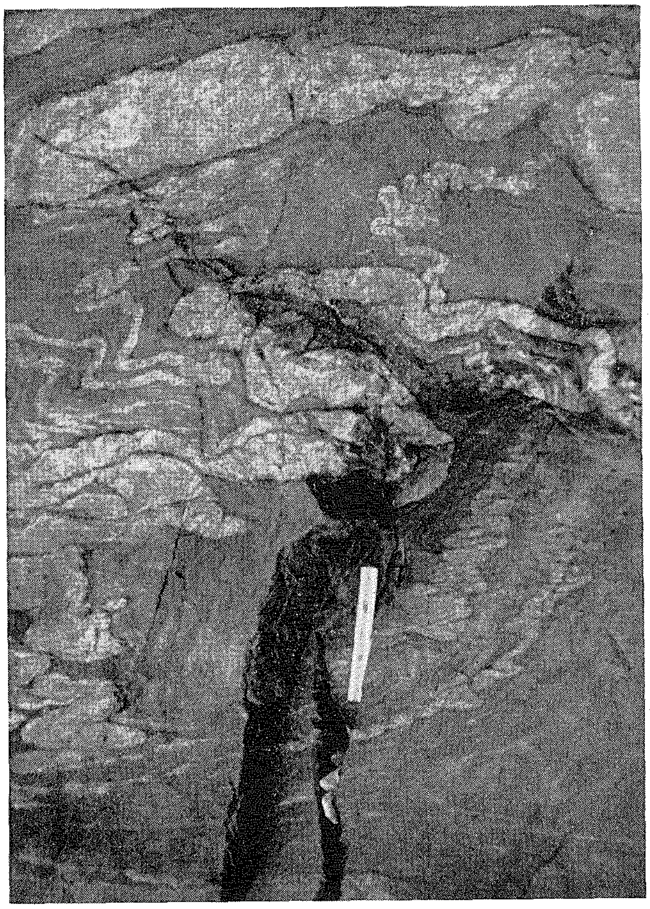


Ancient rocks like these in the granite gorges of the Grand Canyon help geologists date the age of the earth.



The geological ages have been dated by gauging the amount of radioactive decay in the oldest exposed rocks.

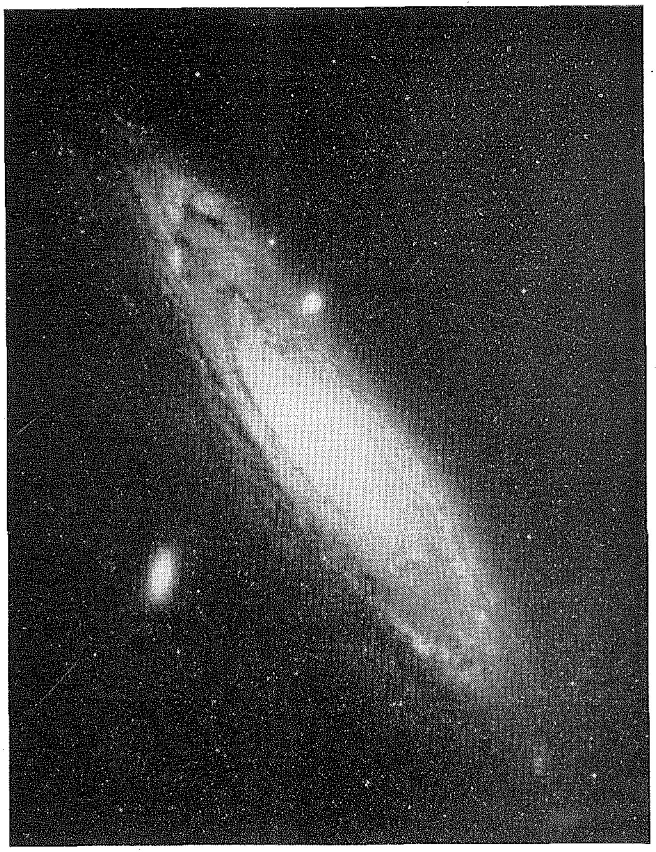
The Age of the Universe

Three branches of science tackle the problem and come up with the same answer

by Jesse L. Greenstein

HOW old is your copy of *Engineering and Science?* Obviously it was, in one sense, created when its pages were bound—in another sense, when the paper was made—in another, when the tree which furnished the wood pulp began to grow. But before all that, the tree grew out of the earth and the air, and the true age of everything on the earth is the same as that of the earth itself. Is that far enough back to look? Are the individual atoms of matter enormously older than the earth, sun and stars? Our question keeps traveling backwards in time, and we may doubt whether an answer exists for the question, "how old" is anything.

For the astronomer there are several ways of tackling the problem. The most attractive is to appeal to the authority of other sciences—geology and nuclear physics, which date the earth and meteorites. The evolution of life on earth, we know, took a long time, but the fundamental long-term time scale of geology comes from nuclear physics, and goes back before the beginning of life on earth. Spontaneous radioactive decay, unaffected by temperature and pressure, provides a dependable clock which, we hope, always ticks at the same rate. The radioactive elements uranium (either U^{238} or U^{235}) and thorium are naturally unstable. Their nuclei lose



Studies of spiral nebulae like the great Andromeda, right, furnish some evidence as to the age of the universe. A relatively short lifetime exists for the spiral arms of these typical stellar systems. Such galaxies make one turn in about 0.1 billion years. The arms, which are regions of higher density of stars and interstellar gas and dust, are young and impermanent features.

mass and turn into various stable isotopes of lead, with the emission of alpha particles which become stable helium atoms. If matter were extremely old, all naturally radioactive atoms would have disappeared from the universe. The existence of any naturally radioactive material immediately suggests that matter is either relatively young, or that the heavy radioactive substances are being continuously formed.

No evidence for the latter process exists—certainly not in the relatively undisturbed minerals at or near the earth's surface. The rates of decay are slow. The half-life (the time within which half of the original mass of an element disintegrates) is 4 to 6 billion years for U^{238}, 0.7 billion years for U^{235} and 14 billion years for thorium. Nowadays the number of atoms of U^{235} is about 1/139th that of U^{238}. But since U^{235} disappears relatively fast, as we go backwards in time, there must have been relatively more U^{235} as compared with U^{238}. Six billion years ago, for example, there would have been an equal amount of each isotope in uranium. From a rough consideration of the nuclear physical properties of the elements it seems very improbable that U^{235} was ever more abundant than U^{238}—and so it appears that uranium on earth is less than 5 billion years old.

A similar argument is obtained from a consideration of the ratio of the numbers of atoms of lead isotopes to those of the uranium isotopes. If all the lead in uranium-bearing rocks at the surface of the earth has been produced by radioactive disintegration, the present number of lead atoms would be the same as the numbers of uranium and thorium atoms which have disappeared. Comparing this number of disintegrated atoms with those still existing gives the maximum age of the mineral (maximum, since some lead may have been initially present). Again a lifetime of less than 5 to 7 billion years is indicated.

If we could be certain that our rock had never been subjected to heating, pressure or weathering, we could use the actual amount of helium in the rock, as compared with the amount of uranium, to provide more definite age estimates. However, these tend to be less certain—and often give minimum ages—since helium, chemically uncombined, leaks out of rocks easily.

Very elaborate work by geophysicists such as Arthur Holmes, employing all possible radioactive decay processes, has dated the geological ages, and by sampling the geologically oldest exposed rocks leads to the remarkable fact that few or no well-established ages exceed four billion years. The maximum frequency of age determinations for samples from the oldest minerals is at 3.35 billion years. Only a tenth as many samples can be dated back 3.9 billion years. Perhaps further exploration will reveal older materials on or in the earth, but we may take the 3.35 billion year figure as an indication of how long ago the crustal rocks were formed. And we may guess, from the very existence of the unstable isotopes of uranium, U^{235}, that the age of uranium itself is less than 5 billion years. (Of course one should not take these numbers too seriously, but 1.5 billion years might be enough time to form the galaxies, the interstellar gas and dust, the stars, and incidentally—and accidentally—the earth.)

Meteorites are our only contact with non-terrestrial matter. They are interplanetary fragments large enough to survive impact and heating in the atmosphere; they have been analyzed chemically and by the newer methods of nuclear chemistry. While their mineralogical properties differ from those of rocks, it is now apparent that they are a sample of matter which in the large has the same atomic species, in the same abundance ratio, as does the earth. For years they provided a strangely discrepant age for their atoms. Many meteorites averaged 7 billion years (twice as old as the earth) because they contained relatively large amounts of helium, which was considered the end product of a long cycle of naturally radioactive disintegrations.

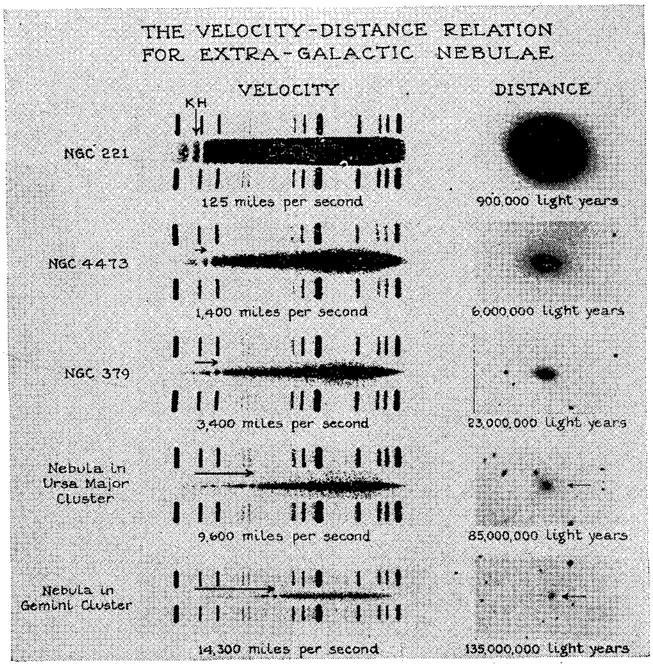
Recently it was pointed out that cosmic rays—a useful source of high-energy nuclear disintegrations in the laboratory—have had enough time to crack many atoms in a meteorite. In such high-energy nuclear collisions, artificially radioactive elements are produced from almost any common stable nucleus—and helium is a common end product of artificially induced radioactivities. Thus the meteorites contain helium produced by cosmic-ray bombardment, and the helium/lead ratio cannot give a correct age. Naturally radioactive potassium, K^{40}, (half-life 1.4 billion years) is found in meteorites together with ordinary K^{39}. We could get a maximum age from the mere existence of K^{40}, but more important is the observation that the ratio K^{40}/K^{39} is the same in meteorites as in terrestrial rocks, within an accuracy of three per cent. This means that the time elapsed since the formation of meteoritic calcium is the same as that since the formation of terrestrial calcium, within about 60 million years. This is an unexpectedly precise agreement and indicates that our search for a beginning may have real meaning.

Modern astronomy provides several ways of dating beginnings—in general less precise. One of the most convincing, however, is the argument based on the simple nuclear physics of the energy generation in stars. The stars have poured out enormous amounts of radiation. The sun, for example, has emitted two ergs per second per gram for at least a billion years, the probable age of life on the earth. This is equivalent to 500,000 billion horsepower. This much energy cannot be supplied by chemical processes, gravitational contraction, or natural radioactivity.

The only plausible energy source is the conversion of matter into radiation, and the most probable process is the Bethe cycle of captures of four successive hydrogen atoms by an original stable carbon nucleus, until an unstable oxygen nucleus is formed which disintegrates, yielding carbon and a helium atom. Now four hydrogen atoms weigh less than one helium atom by 0.0287 of the mass of a hydrogen atom. Thus 0.0072 (0.7 per cent) of the mass of each hydrogen atom has disappeared in the process—and from the famous Einstein equation $E = mc^2$, we have 10^{-5} ergs of radiation energy made available in the creation of one helium atom from four hydrogen atoms. This much energy would keep the sun shining 100 billion years at its present rate, if it were made completely of hydrogen. Since the sun is in fact about 90 per cent hydrogen, its future life is long indeed. If initially it had been all hydrogen, and had produced the helium now found, by the above process—and at the present rate—it would be 43 billion years old. Since we have no reason to suppose that primordial matter was completely hydrogen, we can be certain that the sun is less than 43 billion years old. (As with all speculative certainties, we must limit ourselves to the qualification, "unless a new energy source is found!")

The sun is a typical star, in mass and brightness. However, exceptional stars of very great brightness and mass exist. Such objects, while rare, provide a difficult problem. Spendthrift stars are known, with masses about ten times that of the sun, which are perhaps 10,000 times as luminous. They would convert their hydrogen into helium completely 1,000 times as fast as the sun—so they could not have shone for more than 0.1 billion years at their present rate. It is almost certain that these stars of high luminosity are either younger than the average star, or are being refueled with fresh hydrogen from interstellar space. The latter process may occur if a star passes through a sufficiently dense cloud of gas in space. But newness is an equally satisfactory conjecture. These bright stars are rare and are confined to regions of space in the galactic system where spiral arms and interstellar gas and dust exist. It seems quite possible that stars are still being born, and that the supply of giant bright stars is being replenished.

One strange (theoretical) consequence of the burning up of hydrogen in a normal star is that it cannot gradually lose its brightness as its hydrogen becomes exhausted. It must become brighter, even though its fuel is disappearing. The process then eventually becomes catastrophic—perhaps novae and white dwarfs are the end products of this hydrogen-exhaustion. But before the explosion, a hydrogen-poor star of the mass of the



Studies of extragalactic nebulae add further information on the age of the universe. These nebulae are found to be moving away from the earth; and the further away they are, the faster they appear to move. A linear relation between distance and speed is indicated in the picture at the left. Arrows above the nebular spectra (left) point to H and K lines of calcium, show the amounts these lines are displaced toward the red end of the spectra. Comparison spectra are of helium. Direct photographs (right) illustrate the decrease in size and brightness with increasing velocity, distance, and red-shift.

sun would have had to be considerably brighter than the sun. Thus, if some very old stars (say 20 billion years) existed in our part of space together with younger stars, we might well expect to find the older stars to be objects with the mass of the sun, but perhaps ten times as bright. Now observation indicates that there is a good mass-luminosity relation, and that there are no stars of the mass of the sun which are very much brighter. This provides a strong argument against many stars being much older than the earth. It does not exclude the recent formation of stars like the sun. In 3 billion years the sun cannot appreciably exhaust its energy supply, or change its brightness, and new sun-like stars would be unrecognizable.

Other methods of dating stars

Not all methods of dating stars or stellar systems are dependent on nuclear physics. Gravitational forces balance dissipatory forces in stellar systems. Dense clusters exist in which stars which were probably formed together some time in the distant past have moved nearly parallel through space. Members of such flights of stars are subject to near collisions with field stars, or to close approaches to each other, or to the tidal distortion of the massive center of our own galactic system. Depending on how great the cohesive mutual gravitational attraction of the group is, compared with the disruptive forces, the cluster will be stable or unstable. Loose swarms of stars are known which are disintegrating—dense ones which may be permanent for many billions of years. Actually most clusters in our part of the galactic system are probably relatively young, some perhaps only 0.1 billion years old. A similarly short lifetime exists for the spiral arms of typical stellar systems. These galaxies make one turn in about 0.1 billion years, and in very few spiral nebulae are more than three or four turns visible in the spiral pattern. The arms, which are regions of higher density of stars and interstellar gas and dust, are young and impermanent features. Presumably they dissipate into the general field of stars—perhaps to be replaced by new spiral structures.

Evidence from extragalactic nebulae

The study of the extragalactic nebulae, the most distant objects we can observe, was some years ago the source of striking evidence for a finite age of the universe and of the matter it contains. These nebulae are all found to be moving away from the earth—and the further away they are, the faster they appear to move. Within the observational accuracy, and with allowance for the individual motions of the nebulae, it seems probable that a linear relation exists between distance and speed. So far, a recession of 25,000 miles a second is the largest measured, and there is little reason to doubt that the 200-inch Hale reflector will nearly double that figure. A linear increase of speed with distance can be interpreted kinematically, and naively, as a pure expansion. If we simply reverse the direction in which time flows, and ask what the situation was at a zero epoch about 1.9 billion years ago, we would find all the nebulae concentrated together at the earth, with all their mass at one point.

This extraordinary situation might well be the kind of zero point of time that we had been searching for, indicated by ages of perhaps 3 to 5 billion years for atoms and stars, based on nuclear radioactivity, or on astronomical considerations. Unfortunately, the agreement is not too good—and is made worse by application of the theory of relativity. The late Professor Tolman's analysis of the observational results obtained at the Mount Wilson Observatory has suggested that the initial moment of time was only 1.2 billion years ago. While it is not impossible that the stars, and even the earth, are older than the nebulae, which are aggregates of stars, it seems highly improbable. For as we go backward in time toward the zero epoch, the space density of matter rises and becomes so enormously high that it seems unlikely that anything as delicate as the solar system would survive.

The earliest epochs, with high density of matter and radiation, seem to be ideal times to form stars and systems of stars. In fact, if we consider the very earliest few minutes, when all the matter of all the nebulae was concentrated to the density of nuclear matter, we have the only possible conditions for the formation of the chemical elements from "something simpler."

Not all relativistic cosmologies lead to such high densities, or to the short (1.2 billion year) time scale now apparently indicated by work on the expanding universe. It is possible that the 200-inch can supply new observational data which will more closely describe the early history of our universe. Cosmology is sufficiently complex at present, however, to make it unsafe to assert what the earliest stage of the expansion was like, or when it occurred. But if we may speculate a bit, we can use the present abundances of the different chemical elements and isotopes to describe conditions at the zero epoch, when the elements were born.

The relative abundance of the elements

One of the common goals of geophysics and astrophysics is the determination of the relative abundance of the elements. The earth proves to contain an undersupply of the light elements, presumably lost in the early days of its formation. The stars contain by weight about 70 per cent hydrogen, 28 per cent helium, 1.5 per cent oxygen, carbon, nitrogen, and 0.5 per cent heavy elements. But in spite of their stellar rarity the elements heavier than nitrogen in general seem to have the same abundance relative to each other in most stars, the sun, the earth and in meteorites.

This common constitution points to a common origin, and various theories have been developed to explain how the elements were formed in a very dense, hot cloud of neutrons, by successive nuclear collisions. The most elementary considerations give fantastic initial conditions. If nuclear collisions are to occur, and are to be able to build up by successive captures the elements with atomic mass 200, the initial density and average energy must be very high. The first attempt to explain the cooking up of a nuclear brew of simple particles in such a way as to give the present heavy-element abundance required a temperature of 8 billion degrees and a density of 200 tons per cubic inch.

More complicated recent treatments diverge somewhat in their picture of the initial moment. One pictures the heavy elements formed in the centers of primitive, massive, unstable stars which exploded and mixed these elements in with the original pure hydrogen gas. In another picture, enormous amounts of radiation were present, although the density of matter was relatively low initially. In still another, the density of matter was enormously high, up to a million tons per cubic inch. These speculations make a pleasant end to my subject—but they are not completely foolish. It is obvious that the zero epoch of our universe was an extraordinary moment—we can date it approximately 3 billion years ago—and we can be sure that whatever existed before was quite unlike anything we know now.