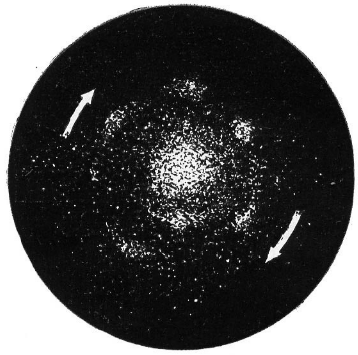
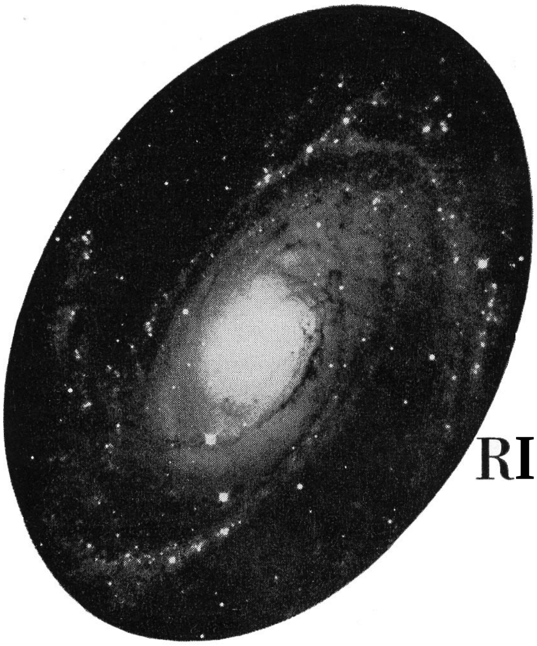


Kant—1755

Laplace—1796



THE ORIGIN OF THE EARTH

by ***Thornton Page***

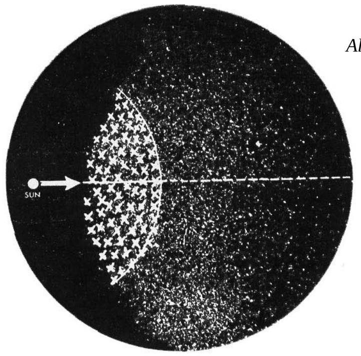
Pouring the evidence of many kinds of science into a single pot to answer this question, the author, an astrophysicist, finds that one is pushed successively from speculating on the origin of the earth to speculating on the origin of the solar system, the origin of stars, of nebulae, of galaxies, of the universe—on to the beginning of time.

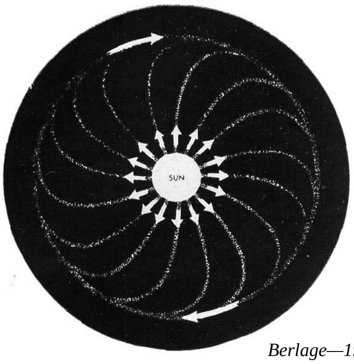
With all the spectacular success of recent scientific research, it is perhaps refreshing to examine a field so characterized by failure as this one. Although many speculations have been described as "theories," there exists today no real theory of the origin of the earth in the sense of a complete logical structure linking together the vast quantity of pertinent observations collected during the last century.

The most obvious approach to the problem is to study the visible surface of the earth for clues to its origin. This has been done in detail by geologists, geodesists, geophysicists, and geochemists, but it is perhaps not surprising that what they find has more to do with the earth than with its origin. It has been the astronomer, studying the relation of the earth to its surroundings, and the physicist, studying the behavior of matter, who have made the greatest progress in the study of the earth's origin.

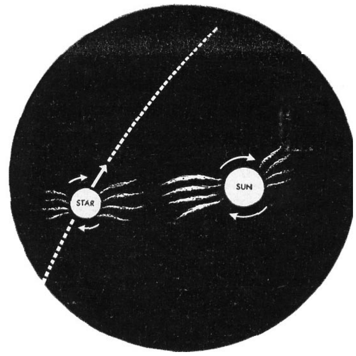
Early speculation on the subject was simple and direct because there were fewer observations to explain. The assumption of a divine creation of things as they are was generally accepted until the end of the 16th century. Then the revolution in scientific thinking, started by Galileo, turned men from assumptions of a catastrophic origin to a belief in natural development, understandable in terms of what can be seen and measured today. As the astronomical picture became clearer, it appeared that the earth is a relatively small, nearly spherical body moving around the sun together with the other planets, all under the influence of the sun's gravitational attraction. It was soon recognized as scarcely due to chance that all the known planets and their satellites are moving and rotating in the same direction, their orbits nearly circular, and in nearly the same plane. Therefore, in 1755, the great Ger-

Alfvén—1942





Berlage—1930

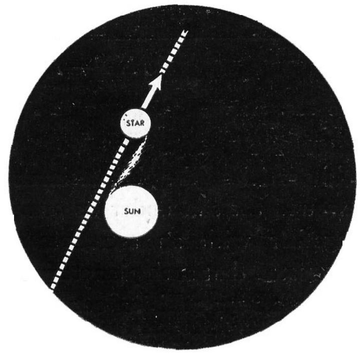


Chamberlin-Moulton—1900

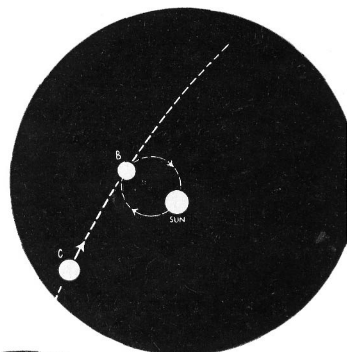
man philosopher-scientist, Immanuel Kant, speculated that the planets and the sun were formed from a single large rotating gaseous cloud, or nebula, which had condensed into smaller rotating parts, these further condensing into rotating planets with their satellites, all moving in the same direction round the nucleus of the nebula which became the sun. Kant's hypothesis explained nearly all of the available observational data within the framework of physics as it was developed at the time.

Later on, about 1800, the French mathematician, Laplace, independently proposed a modified form of the Kant hypothesis which, even though it was not given much weight by its author, soon became widely accepted as the concept upon which much of geology was founded. Laplace went further than Kant in explaining how the primordial nebula condensed into planets. He assumed that in the beginning the nebula was hot and spinning slowly, that the gas contracted as it cooled and therefore increased its spin in accordance with the law of conservation of angular momentum. As the spin increased, he reasoned, rings of gas would be thrown off by centrifugal action and each ring would condense into a planet. It is now recognized that no such condensation of hot gas at the rim of a spinning nebula would take place, but Laplace's speculation was important in that he introduced two new factors: the idea that the earth condensed from hot gases, and the consideration of angular momentum in the solar system.

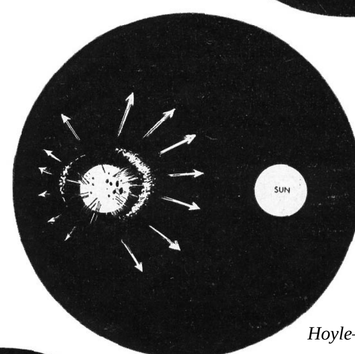
Not until 1895 was the Laplace hypothesis seriously challenged. By that date geology had come into its own as a science, and T. C. Chamberlin, an American geologist, considered the geological evidence incompatible with the concept of a hot gaseous sphere cooling to become the present earth. Instead, he proposed the planetesimal hypothesis, in which the earth and other planets were built by



Jeans-Jeffreys—1917

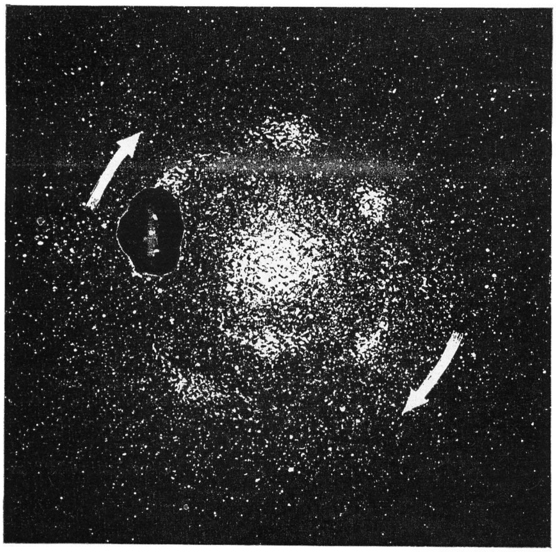


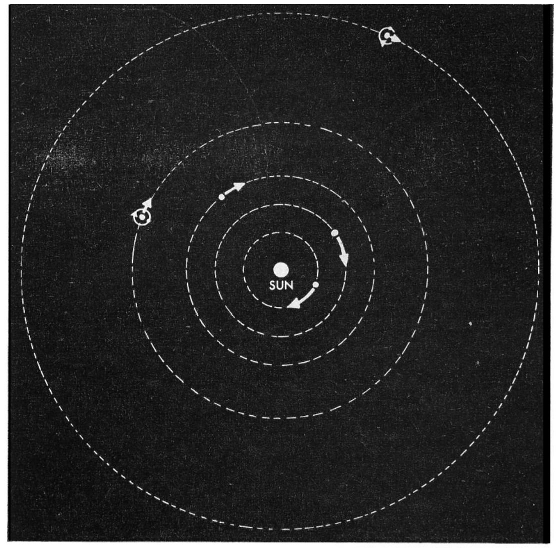
Lyttleton—1936



Hoyle—1944

Weizsäcker—1945





KANT—1755

Clotting mass of gas and dust in rotation.

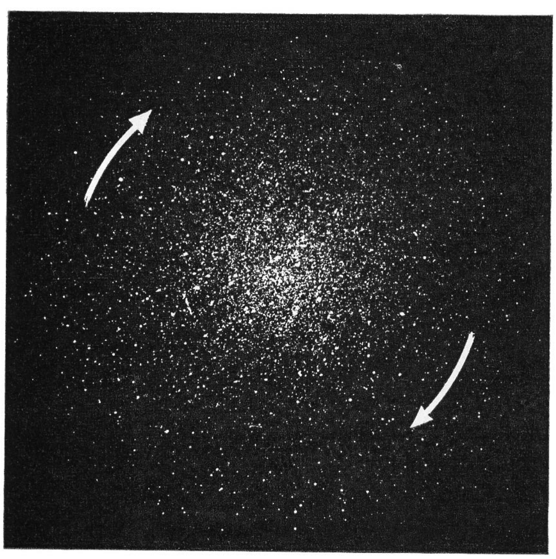
Clots grow by accretion to form planets and satellites. Remainder of nebula contracts to form sun.

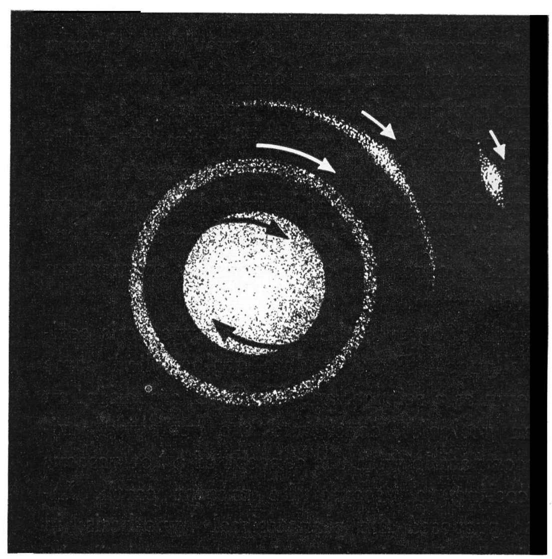
accretion of cold particles (the planetesimals) which were moving around the sun under its gravitational attraction. Together with an astronomer, F. R. Moulton, he suggested that such planetesimals might have resulted from a near-collision between another star and our sun. The planetesimal hypothesis introduced two new concepts: that the earth was built by accretion of cold solid material, and that another star was involved in forming the solar system. The near-collision presumably being a rare event, this represented a return, in part, to the old concept of a catastrophic origin.

During the last fifty years, most of the thinking on this problem has been divided between the two widely divergent hypotheses of Laplace and Chamberlin. Did the earth start hotter or colder than at present? Has it condensed and contracted, or grown by accretion? Was its origin a commonplace occurrence in a nebula (many of which can be seen in the sky), or due to a highly unusual near-collision between stars? Whatever drawbacks these incomplete speculations may have had, they have provided definite concepts on the basis of which further research has been and yet remains to be done.

The Record in the Rocks

In geology it is assumed that we can explain past developments on the basis of processes taking place today, and this assumption has been remarkably successful in tracing geological history to form a consistent pattern. The surface features of the earth

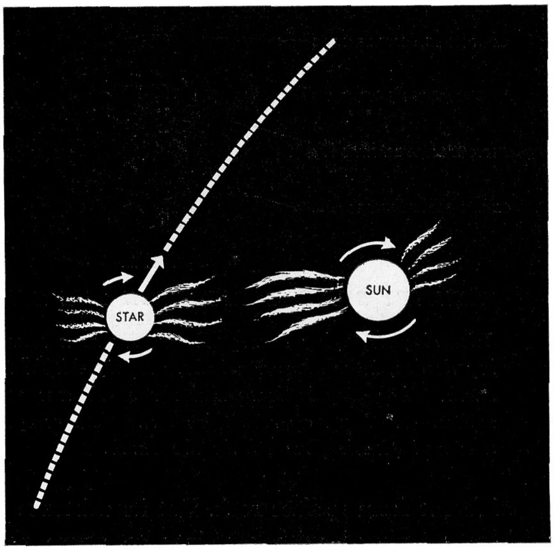


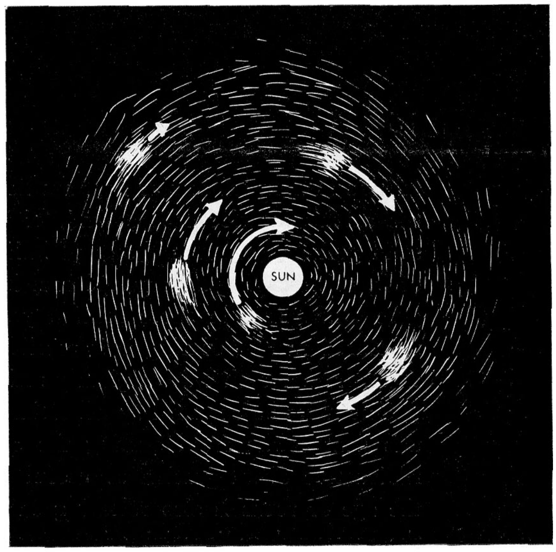


LAPILICE — 1796

Rotating nebula (hot gas).

Cooling nebula shrinks, spins faster, and is expected to leave rings of gas to condense into planets. Whole remainder forms sun.





CHAMBERLIN-MOULTON—1900

A passing star narrowly misses the sun. Huge eruptions are expected to occur on both as they pass.

The sun is left with a vast number of planetesimals which condensed from the erupted gases and slowly coagulate to form planets. The intruding star should also have planets forming.

can be explained as the expected result of erosion, of glacier action, of volcanism, and of movements of the crust itself, all of which are observed in action now. This reasoning might be expected to lead, step by step, to the origin of the earth.

The sequence of events in earth history is best summarized by the geologic column, a schematic pile of all the rock strata which have been classified, in the order of their formation. After fitting together rocks from all over the world, there are left only four major gaps in the record, when erosion in practically all parts of the earth now above sea level must have eliminated the rock deposits of millions of years. With these four exceptions, the geologic column, fitted together from the results of a century of world-wide geologic prospecting, gives almost as complete and consistent a picture of earth history as if the entries had been made in a diary. It lacks only the number of pears intervening between the various geologic eras.

The dates were supplied when the absolute ages of rocks were estimated from their radioactivity, first in 1905 by Boltwood, an English geophysicist. He measured the relative amounts of lead and helium in uranium deposits. The uranium ore crystallized when the molten magma solidified, and the radioactive uranium has since been disintegrating at a constant but very slow rate to form lead and helium which, in favorable cases, have both remained sealed in the igneous rock with the uranium. The process of radioactive decay has been thoroughly studied in the laboratory by many physicists, including the Curies and Rutherford (who suggested Boltwood's research), and the rate of disintegration accurately measured.

Dating various igneous rocks in the geologic column showed first how very long was the record; the oldest igneous rocks yet dated crystallized about three billion years ago. Moreover, there are even older sedimentary rocks through which the molten magma had pushed to form these oldest known igneous rocks; hence the earth must have had surface conditions about three billion years ago not radically different from those today. There must have been water and an atmosphere operating to erode rocks and form sand and mud beds. Fossils in somewhat younger rocks indicate that early forms of life existed at least one billion years ago when conditions must have been very like those today.

But the geologic column fails to yield the one feature which might provide conclusive evidence on the earth's origin. No rocks yet examined have the appearance of an original crust; they are all either old sediments or solidified magma which pushed up through sediments.

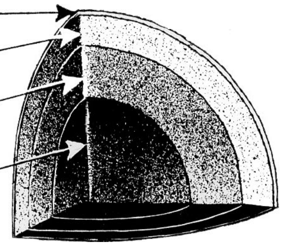
Temperature as a Clue

Trying another tack, we might expect that the earth's thermal history could be traced back to determine its temperature at birth. In deep mines and wells the temperature increases one degree Centigrade for each 125 feet below the surface. Knowing how rocks conduct heat, we find that ten million million calories of heat are flowing out from the earth's interior each second. If the earth were solid granite, all seven thousand billion billion tons of it, this escaping heat would cool it about one degree Centigrade in three million years. From this measured rate of cooling is it possible to determine whether the earth was originally molten?

One must be careful in such estimates; not all of this heat comes from cooling the earth, since the radioactive disintegration so useful in determining the age of rocks is also releasing energy. In fact if the measured radioactivity is constant with depth, the outer crust of the earth only twelve miles thick would provide all of the ten million million calories leaving the earth's interior. If the radioactive material goes deeper than twelve miles, the earth must, willy-nilly, be heating up! So the heat now leaving the earth does not give a clue to its original temperature, although it does point to another approach. Since it is highly improbable that the earth is heating up, the radioactive material probably is not distributed uniformly throughout the earth but is concentrated in surface layers.

Such a stratification within the earth might have a bearing on the original conditions. For instance, if the earth were once molten, we might expect heavier materials to sink to the center and lighter ones to come to the surface. A variety of measurements do prove that the earth is much more dense at the core than at the surface, and this central condensation was long used to support the concept of an originally molten globe. In fact the central core itself was generally believed still to be molten. But a few years ago, observations of faint earthquake waves which could only have passed through the core if it were solid, disputed the point.

It is now generally accepted that the earth's interior is stratified in three distinct layers on a central core which is four times as dense as the surface rocks, and although probably as solid throughout as surface rocks, it yields to plastic flow over long intervals of time. (The molten lava of volcanoes is only in local pools liquefied by a temporary release of pressure.) Recent work by geochemists shows that at least some of the stratification is due to chemical compaction, the tremendous pressures favoring the formation of heavier chemical compounds in the interior. There is no satisfactory explanation of the dense core — twice as dense as the densest materials known — which must be a material radically different from surface rock. But its existence can no longer be used with certainty to argue that the earth was once molten.



DENSITY STRATIFICATION IN THE EARTH

Seismologists, using earthquake waves as a sounding device, have discovered these layers within the earth. They may indicate that the earth was once molten — or they may result from chemical compaction and plastic flow within the earth.

Chemical Clues

Geochemical studies give a somewhat better clue to the earth's temperature at birth. Harrison Brown at Chicago has recently shown that all the elements which exist mainly in gaseous form — hydrogen, helium, neon, argon, krypton, xenon — occur in the earth, its seas and atmosphere to a very much smaller extent than expected from studies of the abundances of elements, both from theory and from observations of the sun and stars.

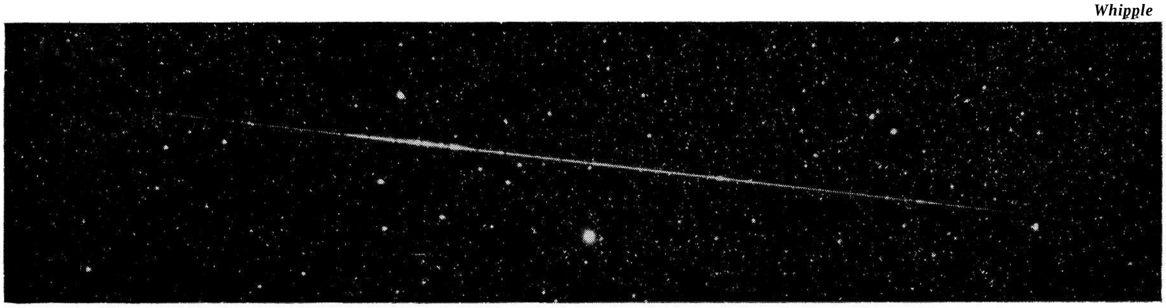
The low abundance of hydrogen and helium is easy to understand: at temperatures of five to six hundred degrees Centigrade they would escape from the gravitational attraction of the earth in a few hundred million years because of the high velocities and small masses of their molecules. But the heavier atoms, krypton and xenon, could have escaped in quantity only if the material of the earth were at one time in much smaller pieces, with correspondingly smaller gravitational attraction, or if the earth had for some time a temperature of ten to thirty thousand degrees Centigrade. Now this is hotter than most stars, and quite impossible for the earth to maintain, so we deduce that early in its history the material of the earth was in separate, small pieces. Since oxygen, nitrogen, and water vapor molecules are all lighter than krypton (and would therefore escape if krypton did), it appears that the earth's atmosphere and oceans must have been formed from the decomposition of heavier compounds after the earth achieved its present size.

To summarize the best geological evidence: the earth is at least three billion years old and its surface conditions of temperature and atmosphere have not changed materially in one billion years and not radically in three billion years. Its stratified layers from density about three at the surface to density about thirteen at the center could result from plastic flow and chemical compaction whether or not the earth were originally molten. Finally, the earth lost most of its gases early in life, probably because it was at one time in pieces of too small mass to hold on to light gas molecules.

As the meteor flashed across the sky a spinning blade in front of the camera lens interrupted the exposure every 1/10 sec. From the length of the dashes the speed of the meteor can be determined.

PHOTOGRAPH OF A METEOR TRAIL

Whipple



Shooting Stars

An important bridge between geology and astronomy is provided by the meteors. Millions of these small chunks of rock and iron collide with the earth each day, most of them burning up high in the atmosphere. Some of the larger, slower-moving ones reach the ground; there the few collected are the only material from outside the earth available for detailed study. Are they a few remaining planetesimals—or are they visitors from outside the solar system?

Measures of meteor speeds by Whipple at Harvard have established that they are at least members of the solar system. If they came from outside they would be moving much faster than observed. Radioactivity measurements (as in dating rocks, but corrected for the effects of cosmic rays which form extra helium) show that the meteors are between two and three billion years old, in startling agreement with the earth's age. Their high iron and nickel content has supported the assumption that the earth's core is nickel-iron (so that earth and meteors would have the same over-all composition).

Furthermore, Harrison Brown's recent studies of the chemical compounds present in meteorites show that they were probably at one time under the high pressures and temperatures of a planet's interior. It would seem that, far from being planetesimals, the meteors are the remains of a fair-sized planet which was formed at the same time as the earth, and which broke up in some large-scale interplanetary collision at a later date.

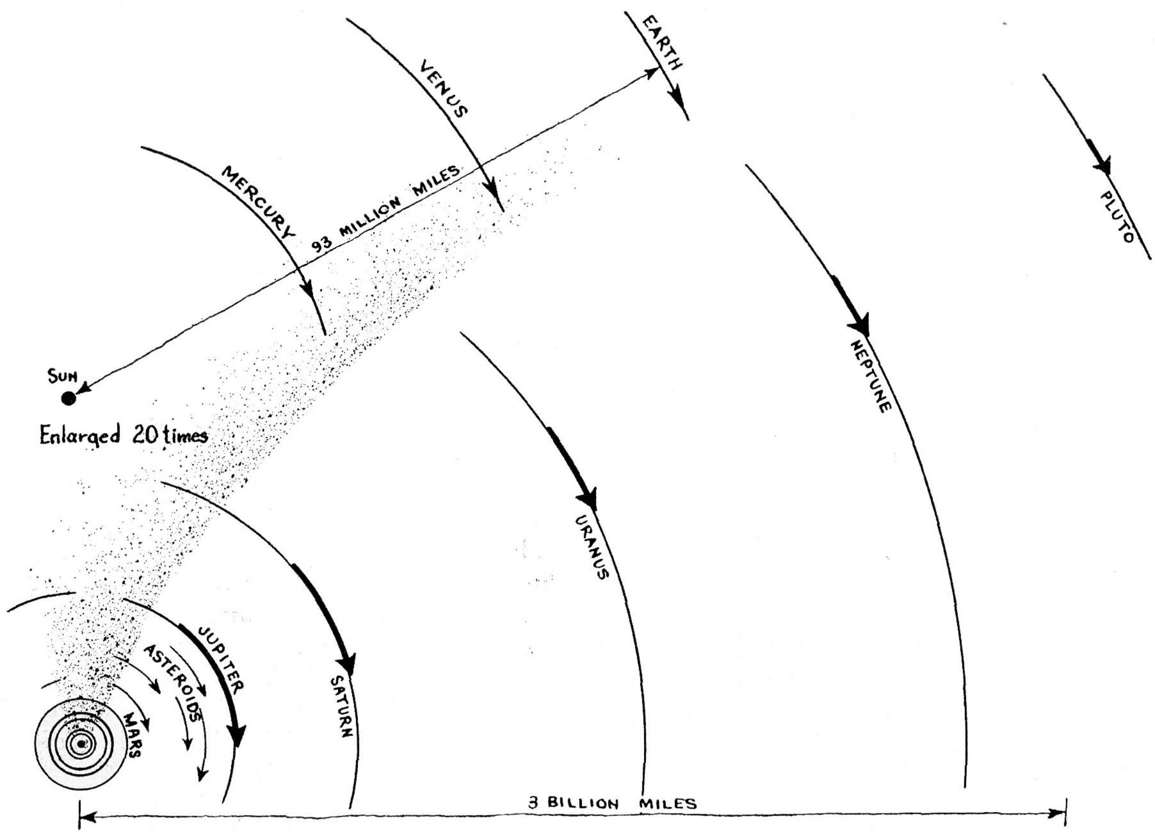
The Gamut of Speculation

The astronomer, in his approach to the problem of the earth's origin, started by recognizing a certain order and regularity among the planets, their satellites, and the smaller asteroids, all moving about the sun. The emphasis is shifted from the origin of the earth, as one of the planets, to the origin of the solar system as a whole. The latest trend goes even further in linking the origin of the solar system with the early history or origin of our galaxy of stars and even of the whole universe.

The solar system regularities noted by Kant clearly indicate that the planets had a common origin ; ever since Kant's time it has been the fond hope of cosmogonists to establish the exact nature of that origin from further studies of the over-all pattern of the solar system. The first clue of this sort to be noted was the spacing of the planets; they are not at irregular distances from the sun, but spaced approximately in geometric progression — that is, the distances can be calculated roughly from a formula called Bode's law after its discoverer. Since the planets continue to move in the same orbits year after year, this spacing must have been established during their formation.

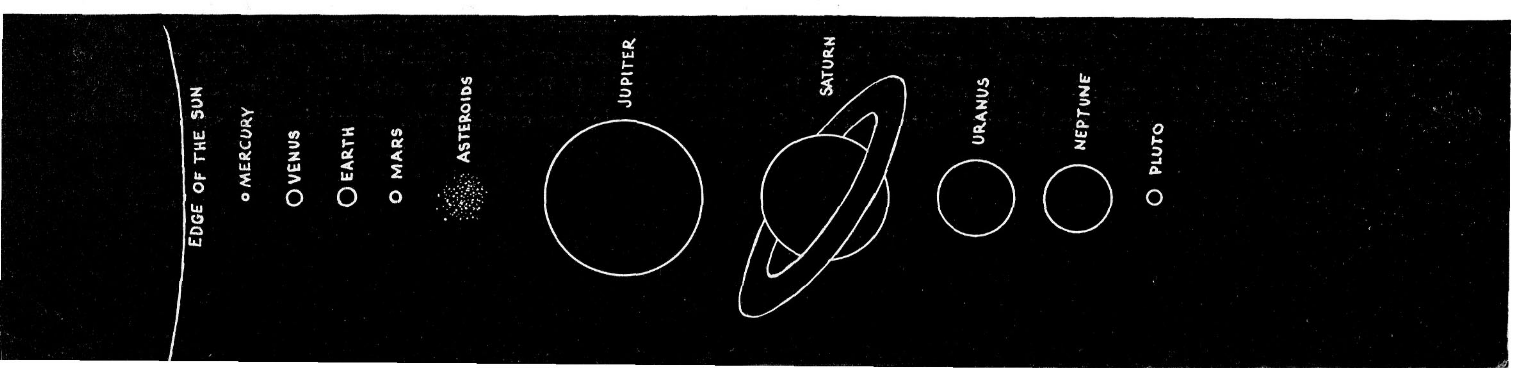
A second possible clue to the origin lies in the progression of planet sizes — from the smallest, Mercury, which is nearest the sun, increasing through Venus, Earth, and Mars to Jupiter, the largest, then decreasing through Saturn. Uranus and Neptune to Pluto, a small planet, and most distant from the sun.

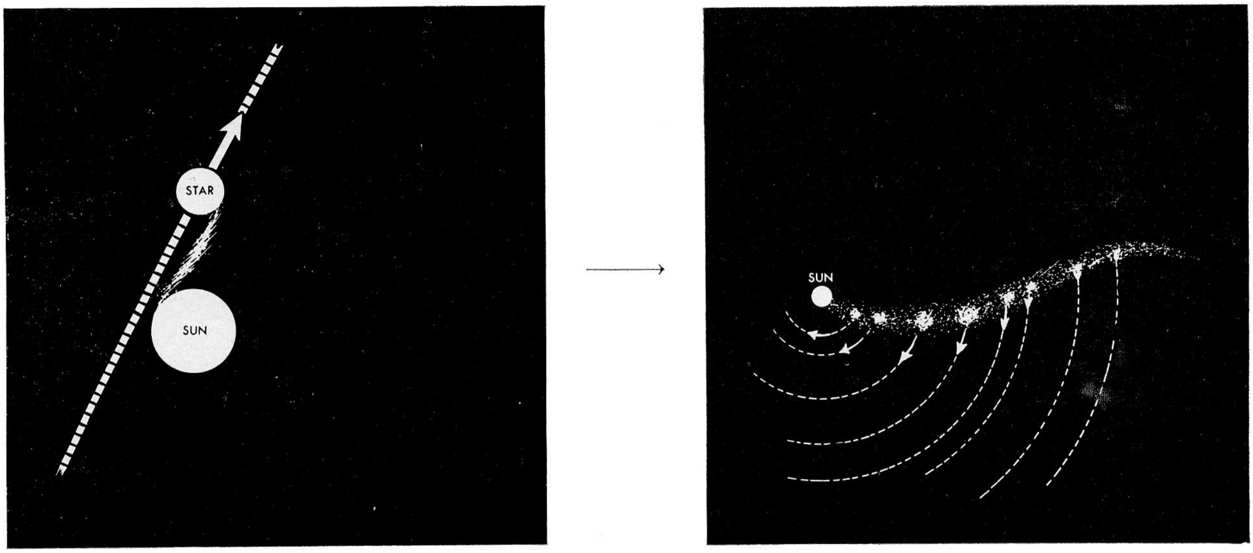
Further clues will be noted as we follow, now, the twentieth century history of speculation on the birth of the solar system, from Chamberlin to Weizsäcker and Whipple. Each of these theoreticians has started either from the Kant nebular hypothesis, or from the Chamberlin two-star hypothesis, and tried to show by more or less exact reasoning that the presently observed solar system would have resulted naturally. Chamberlin and Moulton in 1900 guessed that the close approach of another star to our sun would raise great eruptions on the sun, that hot solar material would condense into small planetesimals moving around the sun and that these planetesimals would later stick together to form the planets by accretion.



THE SOLAR SYSTEM

The diagram above, with an enlargement of the central portion, shows the general layout of the solar system. The scale is so large that the planets appear only as points, and the sun only shows as a 1/20-inch circle in the enlargement. A theory of the origin must explain the regularities apparent in the solar system. The scale of planet sizes is shown below.





JEANS-JEFFREYS—1917

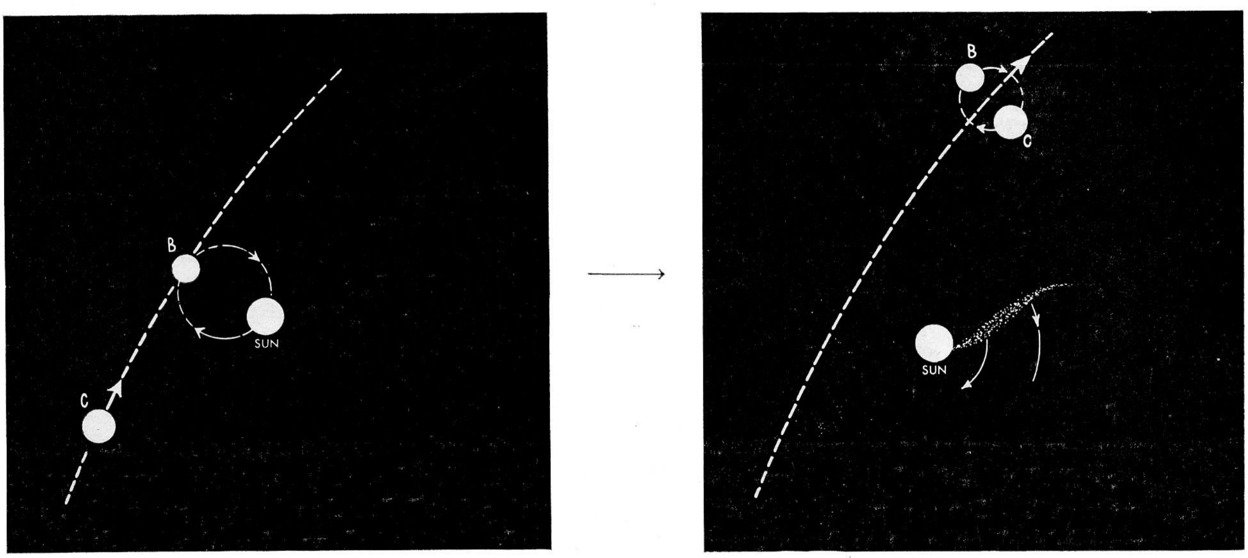
A passing star sideswipes the sun, tearing out a long filament of gaseous material.

The gas is expected to cool and condense into planets, the largest one in the middle and smaller ones at either end.

In 1917 the English astronomers Jeans and Jeffreys made more exact calculations and concluded that the eruptions would not have taken place; rather, the intruding star would have to sideswipe the sun, peeling off a long filament of solar material which would then condense into the planets. They pointed out that this filament would he thicker in the middle than at the ends, thereby accounting for the progression of planetary sizes.

The Jeans-Jeffreys hypothesis seemed satisfactory until 1930, when Nolke in Germany and Kussell at Princeton pointed out another clue: the angular momentum of the planets. Just as a spinning top would keep on spinning forever if there were no friction, so the planets must have maintained constant angular momentum in their orbits around the sun, since nothing analogous to friction is known in the solar system. If the planets were formed from material pulled out of the sun, this law of conservation of angular momentum requires that the original planetary material must have started moving around the sun with the same angular momentum the planets have today. Russell showed mathematically that a grazing collision with another star could not start the filament of planetary material off with anywhere near enough angular momentum.

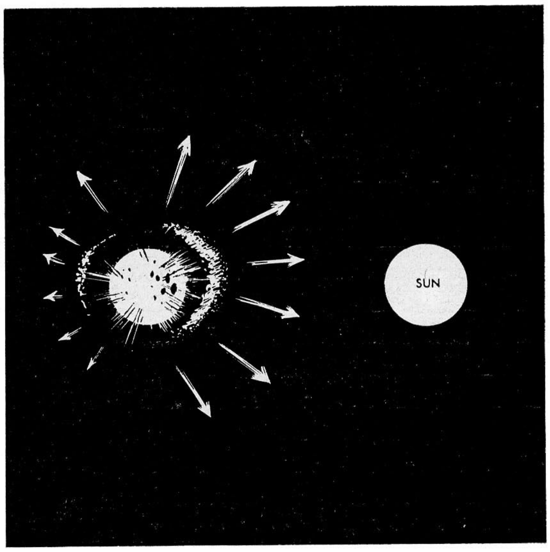
In an effort to patch things up, one of Russell's students, Lyttleton, analyzed mathematically the

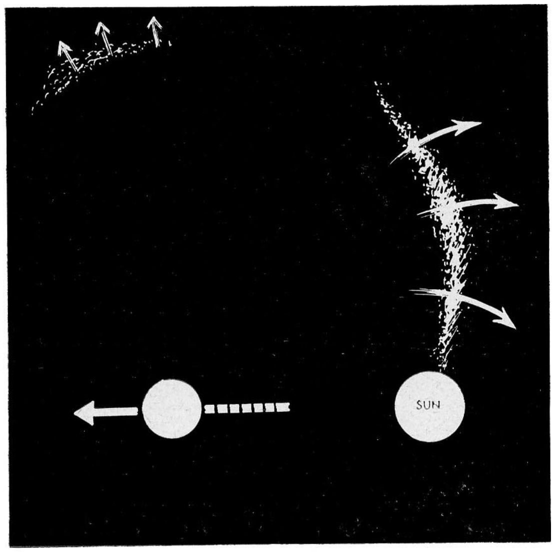


LYTTLETON—1936

If the sun originally had a close companion, B, spinning around it, a third star, C, might have sideswiped the companion. . . .

. . . carrying it away and leaving a filament of its gas moving around the sun, with lots of angular momentum.





HOYLE—1944

A star near the sun might have blown up, throwing off a large shell of material, possibly more in one direction than the others. Such nova explosions are observed frequently.

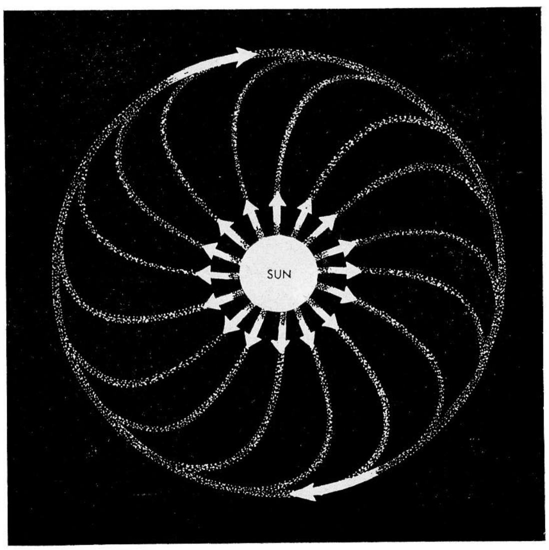
Part of the nova shell could be caught by the sun's gravitation, while the nova itself recoiled away from the one-sided explosion.

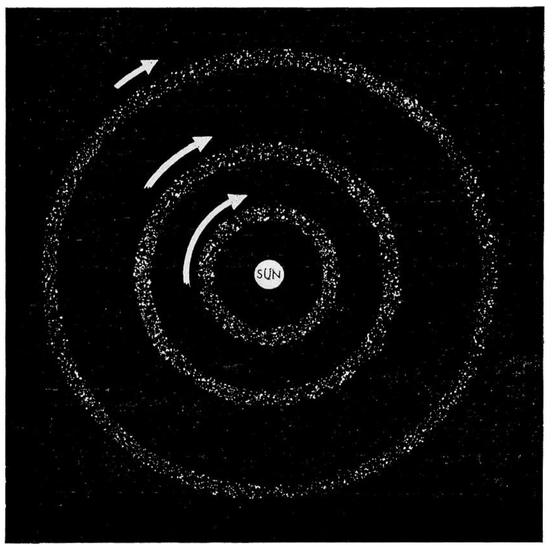
case of a collision between three stars, and found that it was just possible to produce a filament of material moving with sufficient angular momentum about one of them. An English astronomer, Hoyle, showed it was also possible if one of two close stars blew up, as a somewhat asymmetrical nova, propelling itself away and leaving some planetary material moving around the other star.

But these mathematical exercises and the whole sequence of speculations based on the two-star hypothesis were brought sharply to a close in 1939 when Spitzer, another of Russell's students, calculated that the material pulled out of the sun, or any other star, could not condense into planets or planetesimals anyway — it would expand with explosive violence to form a tenuous gaseous nebula!

Back to the Nebular Hypothesis

Long before Spitzer had showed that the two-star hypothesis would lead to a nebula, other scientists had been working away on the nebular hypothesis, trying to find some means by which material near the sun would form a group of planets all moving in the same direction in nearly circular orbits and in nearly the same plane. In 1914 a Norwegian physicist, Birkeland, calculated that electrically charged particles shot out of the sun would spiral out in the sun's magnetic field to definite circular orbits at distances depending on the ratio between the electric charge and the mass of the particles. This promising lead was followed further in 1930 by a Dutch meteorologist, Berlage, who as-

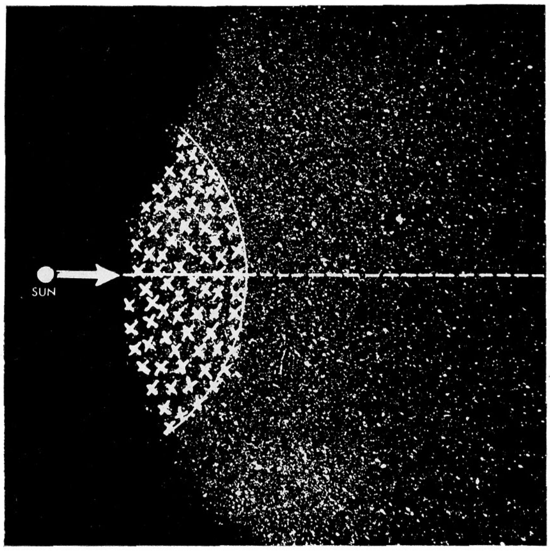


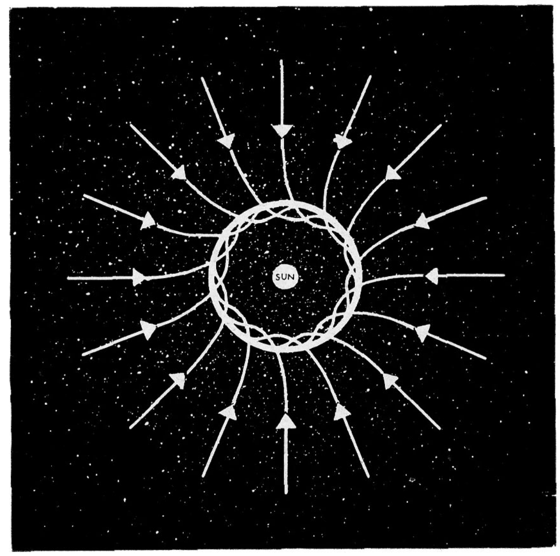


BERLAGE—1930

Electrically charged atoms and molecules shot out of the sun spiral in solar magnetic field.

Rings of gas result, each ring formed of atoms or molecules with the same ratio of charge to mass. Condensation into planets is uncertain.





ALFVÉN—1942

The sun, rushing through space at twelve miles per second, passes through a gaseous nebula. Its presence creates electric charges on the atoms of gas.

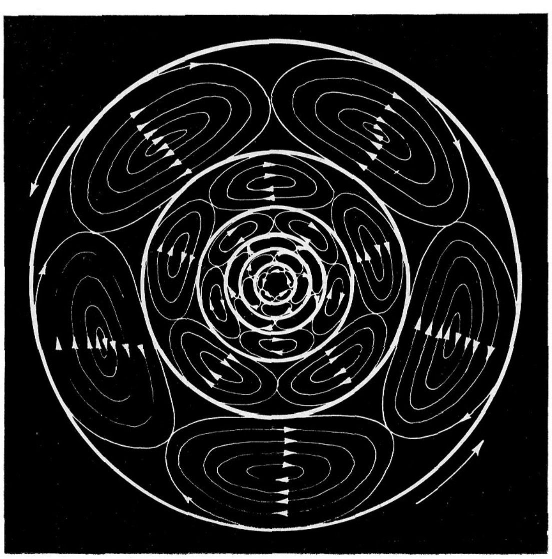
The charged atoms spiral inward to form rings of gas (only one is shown here) which might later condense into planets.

sumed the particles were charged atoms More recently, in 1942, the Swedish physicist, Alfvén, was able to predict by similar reasoning that rings of gas with sufficient angular momentum would be formed around the sun as the sun moved through a nebula, but both he and Berlage have avoided the embarrassing problem of how this gas could condense to form planets.

Lastly in the sequence of nebular speculations, a German physicist, Weizsäcker, has recently investigated in detail the motion of a large cloud of dust and gas in rotation about a massive central body like the sun. From this return to the ungarnished Kant hypothesis he was able to show that, while most of the gas would escape into outer space, the planets could be formed by the accretion of the dust particles over a period of a hundred million years —a short time compared to the age of the earth. The spacing of the planetary orbits Weizsäcker explains in this manner: The inner parts of the rotating nebula would be pulled around more rapidly by the sun's gravitational attraction than the outer parts. Like stirring a bowl of soup near the center, this would set up eddies, and at the boundaries of the eddies the dust would coagulate most rapidly. These boundaries, Weizsäcker calculated, would be spaced approximately in a geometric progression from the sun just as the planets are observed to be.

The Weizsäcker hypothesis accounts for more of the observational data than any of the previous speculations, but because it is so recent a number of its consequences have not been explored and some of the estimates may need revision.

One of the interesting consequences is that the formation of planets should be an extremely common occurrence. Possibly in the process of formation of every star the conditions would be correct to form planets. Thus we might expect billions, if not hundreds of billions of planets in our galaxy, the strong likelihood that life has developed on a million or more of these, the high probability that there are other civilizations of mankind, and even the possibility that men on other planets are writing articles on the origins of their solar systems!



WEIZSÄCKER—1945 ***Vortices formed in the equatorial plane of a nebula of gas and dust rotating about the sun, according to Weizsäcker. Accretion would take place along the heavy concentric circles, to form planets and satellite systems with direct rotation and revolution.***

The Origin of Stars

But where did the original gas and dust come from? How was it started in rotation? One reason the Weizsacker hypothesis has received so much attention is that a separate line of research on the origin of the stars has provided answers to these questions. The argument hinges on the energy necessary to keep the stars shining.

The closest star — our sun — is radiating energy at such a stupendous rate that no ordinary energy generator could keep it going for the three billion years we know it has been shining on the earth. However, it is now known that atomic energy provides the sun's light and heat by a process in which four atoms of hydrogen are converted into one atom of helium and the excess mass changed into radiant energy. The details of this process, which can only proceed at the high temperature and pressure of a star's interior, were established by Hans Bethe at Cornell in 1938. But there are many hot stars thousands of times brighter than the sun (if viewed from the same distance), and a simple calculation shows that they would use up all their atomic energy in a mere ten million years. Where did these hot bright stars come from if they can last only one three-hundredth as long as the earth has been in existence?

A possible answer was provided only last year (1947) by Lyman Spitzer at Yale, and Bart Bok at Harvard. Spitzer showed theoretically that diffuse gas and dust which is observed between the stars could, under some circumstances, be compressed by the pressure of radiation from all the other stars, to condense into a new star. Bok observed in the Milky Way certain small dark knots of such interstellar material, which may well be stars in the process of formation. Here is the process of growth by accretion on a much larger scale. This theory is well enough established that Whipple at Harvard has recently proposed that the planets coagulated in the manner postulated by Kant and by Weizsäcker during the formation of the sun itself.

Galaxies

As we are pushed further and further in explaining the origin of our planet, new sources of evidence come into the problem. The next evidence comes from a study of the large groups of stars called galaxies.

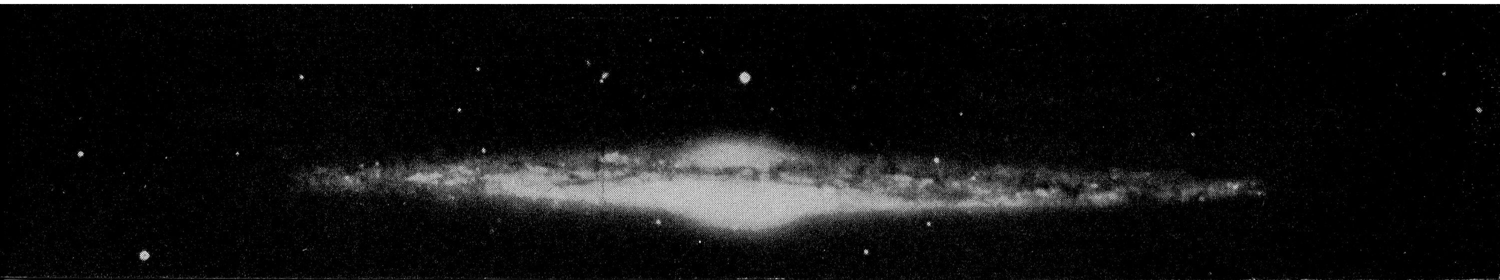
Passing from the solar system to the stars is no larger a jump — and no smaller — than from the earth to the solar system. Our galaxy includes all the visible stars and is a correspondingly large system, outside of which the telescope shows many other galaxies. These are believed to be very like our own galaxy—a disk-shaped conglomeration with a mass, determined from its rotation, of about two hundred billion star masses. There are about one hundred billion stars in a galaxy, the rest of the material being spread between the stars in the form of gas and dust.

The outside galaxies, often called "spiral nebulae," are being studied by Hubble at the Mount Wilson Observatory in California, and by other astronomers with large telescopes. As Hubble looks further and further out into space (by taking longer photographic exposures with larger and larger telescopes), he finds more and more spiral nebulae, apparently without limit. In 1925 Hubble and Humason found from the redness of their light that the more distant spirals are receding from us more rapidly than the closer ones, and that the speed of their retreat is in direct proportion to their distance from us. At first sight this appears to leave our galaxy (with our sun and earth) in a central and somewhat unpopular position, with the rest of the universe running away. Rut a little thought shows that our view of the universe is the same as the view from any one of the other galaxies; each would see the rest receding from him with velocities proportional to their distances from him.

Tracing the motions back in time (there is no evidence that the spirals are accelerating or decelerating) shows that all the spiral nebulae would have been near our galaxy between two and three billion

SPIRAL NEBULA

Mt. Wilson Observatory



Above, our view of some spiral nebular. The arrows indicate velocities. Note that spiral B, which is twice as far from us as spiral A, is receding twice as fast. C, three times as far, is receding three times as fast, and so on.

Below, spiral B, considering himself to be at rest. It is the principle of relativity that he has just as much right as we do to consider himself at rest. He gets the same view as we do; all the spirals are receding from B with velocity proportional to distance.

years ago. The coincidence of this with the age of the earth and the age of the meteorites is too marked to need further comment—the whole universe seems to have started with a bang about three billion years ago!

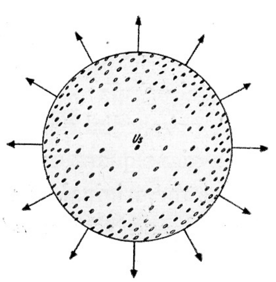
The Beginning of Time

This curious evidence that the spiral nebulae were all close to—if not entangled with—our galaxy three billion years ago, means that the formation of the solar system at that time probably took place under conditions somewhat different from those of today. To be sure of the reasoning, we must examine the conditions of three billion years ago more carefully; it was this re-examination which led, in 1945, to the most bizarre suggestion of all in this field already rich in speculation. It was put forward by the English biologist, J. B. S. Haldane, and is based on a new theory—or philosophy—of relativity proposed in 1932 by the English mathematician, E. A. Milne. First we shall speak of Milne and his brand of relativity.

To make the reasoning clear we must start with Einstein's earlier relativity theory which links space and time in such a way that if one observer is moving at constant velocity past another his measurements of distances and time intervals will differ from those of the first observer, although the relation of time and distance is such that they both observe the same laws of physics. Einstein formulated his relativity on the philosophy that it is simply impossible to tell which observer is "at rest." Complicated as it sounds, this scheme has been developed to form a logically complete theory in terms of mathematical transformations. Milne extended the established principles of relativity in his "cosmological principle," which is, in effect, an assumption that the view of the whole universe from one spiral nebula must be the same as the view from any other. Moreover, he has redefined distance measurements in terms of the travel time of light signals, as in radar ranging, thus reducing both time and distance measurements to readings of clocks, in principle.

Milne then raises the disturbing question: How are we sure that our clocks are reading constant intervals of time? In fact, the slowing down of the earth's rotation (which is normally our "master clock") has been .measured as one-thousandth of a second per century by comparison with the planets. and we have no philosophically sound assurance that the planets keep "perfect time."

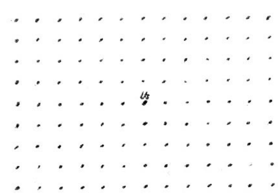
The cosmological principle leads mathematically to two kinds of time, one of which is speeding up relative to the other. Milne has shown that pendulum clocks, the earth, and the planets keep "dynamic" or clock time, while vibrating atoms and radioactive decay have constant period only in "kinematic" or atomic time. There is no philosophical reason for choosing one kind as the "correct"



MILNE'S PICTURE OF THE UNIVERSE

If all measurements are made in atomic time the universe, in Milne's theory, started expanding from a point three billion atomic years ago. As we see it now the spiral nebulae shown in the left diagram are all moving away from us and (if we could see far enough) would be much more numerous near the "edge." At this edge the velocity of recession is equal to the velocity of light, so we can never hope to see the edge itself.

On the other hand, if clock time is used for all our measurements, the universe is static and the spiral nebulae, as shown on the right, above, are uniformly distributed on to infinity. The more distant nebulae are redder because we see them as they were many years ago with "slow" atoms. The "edge" of this picture comes when this reddening gets so extreme that galaxies are no longer visible.



time; if we used a pendulum clock to time atoms we would find, after a very long interval, that the atoms are gradually speeding up in their vibration; if we used an atomic clock we would similarly find that the planets are slowing down in their orbits.

If this is correct — and no one has yet proved it otherwise — the age of the earth is three billion atomic years as determined from radioactive decay, but it is many more clock years, since in the past the clock year was shorter than the atomic year. (They are equal at present — by definition.)

The coincidence between the age of the earth and the time of recession of the spiral nebulae Milne explains as a result of the difference in these two kinds of time. Since the light we observe from a spiral one hundred million light years away left there one hundred million years ago, we are seeing the atoms there ticking off the units of atomic time in use one hundred million years ago. Compared to our present atoms, these early atoms ran slow; as a result the light they emitted is redder than the light emitted now by similar atoms on the earth.

From this effect and his cosmological principle, Milne calculates that in the past infinite number of clock years there were three billion atomic years. The origin of the earth, and the time when all the spirals were close to our galaxy, both of them three billion atomic years ago, therefore occurred at the beginning of time (since one could hardly expect more than infinite time on the clock scale).

Now for Haldane's suggestion, which he calls "A Quantum Theory of the Origin of the Solar System": It is based, as its name implies, on the well-established quantum theory of radiation, and on a mathematical result of Milne's theory: that the universe, as measured in atomic time, has expanded with the velocity of light, starting from a point of zero radius three billion atomic years ago.

Since the universe started from zero radius, Haldane was able to pick an early enough instant, just a fraction of a second after the start of atomic time, when the whole universe was but a fraction of an inch in diameter — much smaller than the wavelength of visible light — smaller, by far, than the wavelength of x-rays or gamma rays. (These fractions are too small to write out easily; the first requires seventy-two zeros after the decimal point, the second, sixty-two!) The wavelengths of radiation in existence in this small universe could scarcely have been bigger than the universe itself, Haldane reasoned, therefore the only radiation in existence was of these incredibly short wavelengths. But the basic principle of the quantum theory is that radiant energy comes only in packets, or "quanta," inversely proportional to the wavelength in size. So, at this early instant all radiation was in giant quanta of very small waves. And the energy of one of these giant quanta can easily be calculated as sufficient to knock one or more planets out of the sun. The even smaller waves at a somewhat earlier instant would have been in quanta with sufficient energy to tear apart stars, and even earlier, to tear apart the galaxies from some primordial globe of matter.

The details of this remarkable suggestion have been carried no further, but Haldane's investigation points up one important general fact: whether or not Milne's new relativity is accepted, conditions at the time of the origin of the solar system were probably considerably different from those today. If Milne's cosmology is accepted, the relationship between radiation and matter was most radically different. It may seem that this last and most fantastic speculation — which can neither be completely explained nor fully evaluated here — contradicts our former conclusion that the solar system was formed from a rotating nebula of gas and dust. However the condensation of the planets and the distribution of angular momentum (which have been so difficult to explain in all previous theories) may follow from further mathematical investigation of the first second of atomic time. In fact, if the details can be worked out rigorously, Haldane's suggestion may lead to confirmation of Milne's cosmology, which is as yet lacking.

In an echo of the introductory remarks it scarcely needs to be emphasized that we have no complete theory of the origin of the earth. The reader may be impressed with the diverse investigations involved and with the promise of the latest speculations; or he may notice the infinite regression implicit in any question of origins: if the planets were formed from dust or planetesimals, whence came the dust or planetesimals? if the dust and planetesimals came from a primordial nebula, whence came the primordial nebula? if the primordial nebula was formed by the absorption of a giant quantum by a fragment of matter, whence came the original matter and radiation in the universe? and so on, ***ad infinitum*** (clock time).