

THE ORIGIN OF THE EARTH

Data from recent exploration of the solar system and telescopic observations of accretion discs around other stars make a model of Earth's origin more quantitative.

Thomas J. Ahrens

The question of the origin of the blue planet pictured in figure 1 is related to other questions about our beginnings. These include the origin of the universe, the evolution of galaxies and stars, the origin of life and the ascent of humankind. In the late 1700s both Pierre-Simon Laplace and Immanuel Kant suggested that Earth and the other planets in the solar system had condensed from a flattened nebular disk surrounding the Sun. Since these astute hypotheses were suggested, a series of well-known physical scientists including James Jeans, Gerald Kuiper and Harold Urey have developed a now widely accepted theory of the accretion of the Earth and planets. Their theory, which I describe below, was based on telescopic observations of the solar system, theoretical calculations and the study of meteorites. Now referred to as the Schmidt theory (after Otto Yu. Schmidt of the Institute of the Earth, Moscow), it explains the formation of the planets as resulting from the accretion of already solid bodies.

A competing hypothesis concerning the origin of the planets and Earth came from the theory of giant gaseous protoplanets, which was studied extensively in the 1960s. In contrast to the giant gaseous protoplanet hypothesis, however, the Schmidt theory is concordant with the differences between the inner and outer major planets. It provides some basis for understanding the similarity of major chemical ratios, isotopic ratios and relative noble gas patterns among the objects in the solar system.

The origin of the Earth was the subject of a unique interdisciplinary conference held on 23–26 January 1950 in Rancho Santa Fe, a suburb of San Diego, and organized by the National Academy of Sciences. That meeting brought together a remarkable group of physicists, chemists, geologists and scientists from other disciplines. (See figure 2.) Even though the conference took place prior to exploration of the solar system with spacecraft and the return to Earth of samples collected from the Moon, specialists today would have few objections to the main conclusions that came out of that meeting. These were:

- ▷ The Earth accreted from objects that were both depleted of volatile compounds and fractionated (chemically separated) relative to the composition of the Sun and that were probably cool before they impacted the nascent Earth. Because the Earth was not uniformly raised to fully devolatilizing high temperatures, it retained a fraction of the abundances of volatiles such as water, methane, ammonia and the noble gases (He, Ne, Ar, Kr and Xe) observed in primitive meteorites and in the Sun.

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Earth as seen by the Apollo 17 astronauts on their way to the Moon in December 1972. The origin of this water-covered planet is not obvious from its appearance, because its surface has changed drastically since it formed: Its oxygen-rich atmosphere has been attributed to life—photosynthesis in plants. Its plates, on which the continents ride, are constantly in motion as its interior convects like a viscous fluid. We have little understanding as to why its ice caps have at times disappeared, as well as grown and ebbed over 30% of its surface. Only primitive models exist for the dynamo that powers its 0.5-gauss surface magnetic field. The magnetic field has also reversed, probably thousands of times, during the planet's 4.5-billion-year history. **Figure 1**

▷ Upon accreting, Earth experienced considerable melting. Melting also occurred later in the planet's history. The melting was inferred from the then recently discovered Mohorovičić discontinuity—the globally defined seismic discontinuity between the differentiated crust and the presumably more primitive mantle.

▷ Most of Earth's crustal rocks are much younger than the oldest known rock radiometric age. At the time of the Rancho Santa Fe meeting,¹ the oldest crustal rocks known were 2.4 billion years old.² However, since that time, small quantities of mineral grains 4.2 billion years old, approaching the age of the Earth (4.5 billion years³), have been discovered.

Development of accretion scenarios

Starting well before the time of the Rancho Santa Fe meeting, and following the meeting as well, many scientists suggested that instability within interstellar molecular clouds led to gravitational collapse of a slowly rotating cloud core, producing an early Sun with a corotating solar nebula of gas and dust rather than a double or multiple star. In the most accepted theory of solar disk evolution, the disk evolves through a series of stages of planetary growth to produce the present solar system. Figure 3

shows Boris J. Levin's 1972 sketch⁴ of this process. Adherents of this view included Schmidt and Victor Safronov, both at the Institute of the Earth in Moscow, and Donald Lynden-Bell and Fred Hoyle, both at Cambridge University.⁵

The competing giant gaseous protoplanet theory of planetary formation has been investigated by researchers such as Gerald Kuiper of the University of Arizona⁶ and A. G. W. Cameron of Harvard University.⁷ In the giant gaseous protoplanet theory, protoplanets, like stars, formed directly through the collapse due to gravitational instability of the gas and dust in the solar nebula. Hence all planets started out with solar-like compositions. This theory would require the inner, rock- and metal-rich terrestrial planets to have lost massive quantities of hydrogen and helium, as well as less volatile, yet depleted elements, including nitrogen, carbon, potassium and the heavier noble gases. The outermost major planets Uranus and Neptune would also have to have undergone preferential element loss. Modeling calculations by David Stevenson at Caltech indicate that such separations do not occur easily once such massive objects form.⁸

Returning to the more accepted theory, depicted in figure 3, two mechanisms have been hypothesized to transform the rotating disk of dust and gas from micron-sized condensates



Conference on the origin of the Earth on 23–26 January 1950 in Rancho Santa Fe, California, gathered participants including Edward Teller (1), Beno Gutenberg (2), Harold C. Urey (3), Norman L. Bowen (4), Louis B. Slichter (5), Wendell Mitchell Latimer (6), William W. Rubey (7), Harrison Brown (8), Fred L. Whipple (9), Oliver Wulf (10), James Gilluly (11), William George McMillan (12), Perry Byerly (13), Howard P. Robertson (14), Carl Eckart (15), Linus Pauling (16), David Griggs (17), Adolph Knopf (18), Patrick Hurley (19), John Verhoogen (20), Roger Revelle (21), Maurice Ewing (22) and Edward Goldberg (23). **Figure 2**

to planetesimals 1–10 km in diameter, as sketched in figure 3a. These are nongravitational cohesion (essentially sticking) by grains and gravitational instability. Three-dimensional modeling of the growth of planetesimals by Safronov⁹ and later by George Wetherill¹⁰ and others in the United States demonstrated that once kilometer-sized planetesimals form, gravitational forces cause impacts among them, as figure 3b indicates. Glen Stewart and William Kaula of the University of California, Los Angeles, first demonstrated that in a Keplerian rotating reference frame, the largest of the planetesimals, which have a random mass distribution, have lower encounter velocities and hence grow at a faster rate than the smaller planetesimals.

Figure 4 shows the results of one of the many numerical simulations of accretion of the inner, terrestrial planets of the solar system. The time scale for the accretion of a single Moon-sized object is only 1.3×10^5 years in this calculation. After that time rapid and violent impact accretion occurs, followed by a regime that Wetherill calls runaway accretion. During runaway accretion planetesimals are swept up within zones defining approximately the present orbits of the terrestrial planets. The runaway phase leads to approximately Moon-sized bodies whose orbits are separated by about 0.01 astronomical units. (An AU is a distance equal to the average radius of Earth's orbit.) These then gravitationally scatter and

develop crossing orbits (the Safronov mechanism), leading to progressively larger bodies and eventually to the small number of terrestrial planets.

During the final stages of accretion, the last massive non-normal impacts left an imprint we can still see. In the expected geometry of the rotating planets all the axes of rotation would be exactly perpendicular to the planes of orbit, or approximately the ecliptic plane. Instead the inclinations of the rotation axes of the planets with respect to their orbital planes vary from 0° for Mercury to 98° for Uranus. Earth's inclination, which also varies as a result of gravitational perturbations, is now 23°.

Calculations by Cameron and his collaborators also suggest an origin for the Moon: The impact of a Mars-sized planetesimal with the Earth ejected sufficient quantities of devolatilized material for the Moon to form by accretion.¹¹

Although the rock and metal cores of the outer planets—Jupiter, Saturn, Uranus and Neptune—are believed to have had origins similar to those of the inner, terrestrial planets, they also accreted varying amounts of ices from the comet-like planetesimals then present in the outer solar system. Jupiter and Saturn also appear to have directly accreted large quantities of gas from the solar nebula. Jupiter's composition is believed to be close to that of primordial solar material, except for an enhancement of about a factor of ten in rock- and ice-forming elements. The fusion

reactions that power the Sun have presumably enriched the solar core with helium, but there is no fusion in the giant planets. It is believed that during planet formation the proto-Sun derived its luminosity mostly from gravitational energy and only to a small extent from deuterium burning.

Other planetary systems

According to contemporary thought, stars evolved from the gravitational collapse of the cores of giant molecular clouds, producing single or multiple, corotating star systems. Stars that evolved along the main sequence of development are powered by fusion reactions within their interiors, which convert some of their initial ^1H budget into ^4He . The evolution takes about 10^{10} years for a star equal in mass to the Sun. If these ideas about stellar evolution are valid, at any given time a finite population of proto-Sun-like objects, possibly with accretion discs like those sketched in figure 3, should be telescopically observable.

In December 1984, to the delight of origin-of-the-Earth theorists, such a possible planetary system in the making was imaged in visible light by Bradford Smith of the University of Arizona and Richard Terrile of the Jet Propulsion Laboratory.¹² (See figure 5.) This accretion disk, which surrounds the star β Pictoris, is believed to be more than 10^8 years old and so may already contain planets. The dust that appears in the image may be analogous to the material that existed at the outer edge of our solar system from which many of the comets accreted. In the solar system, the region containing that material has been named the Kuiper belt. A series of other stars associated with much younger (10^6 year old) solar-system-like accretion discs have been imaged in the infrared and at millimeter wavelengths. (See the article by Anneila Sargent and Steven Beckwith in *PHYSICS TODAY*,

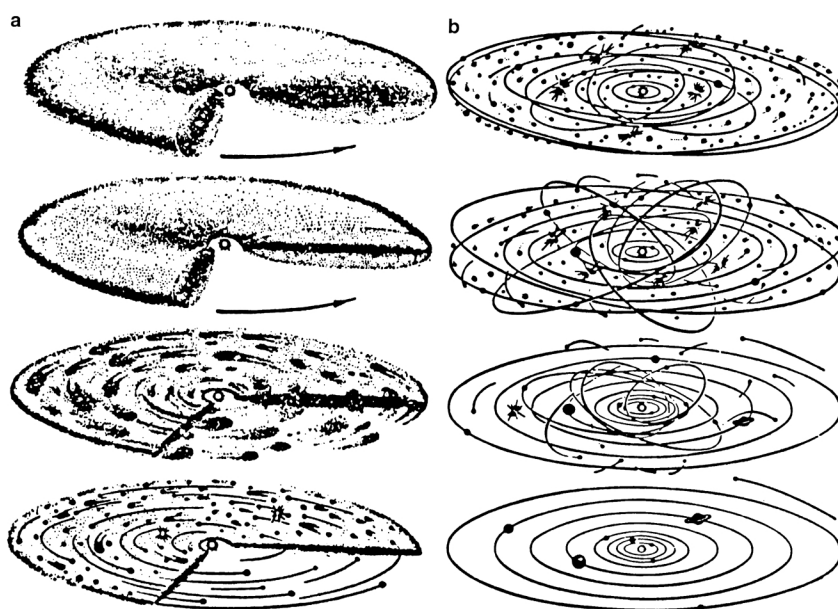
April 1993, page 22.) Recent optical observations have found protoplanetary disks in the Orion nebula. (See the news story on page 20.)

Solar system as chemical reservoir

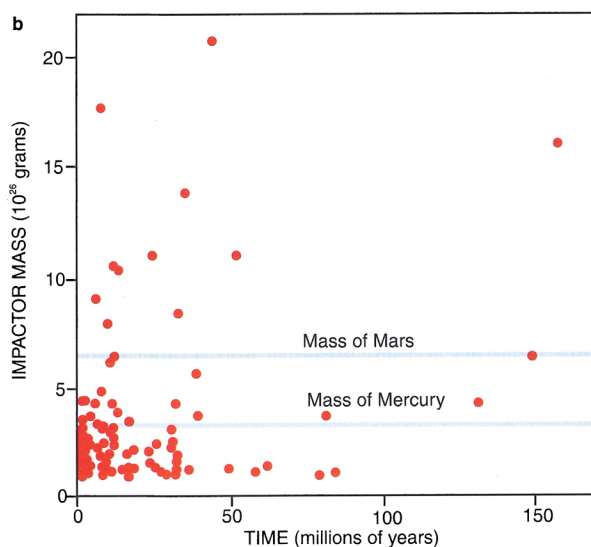
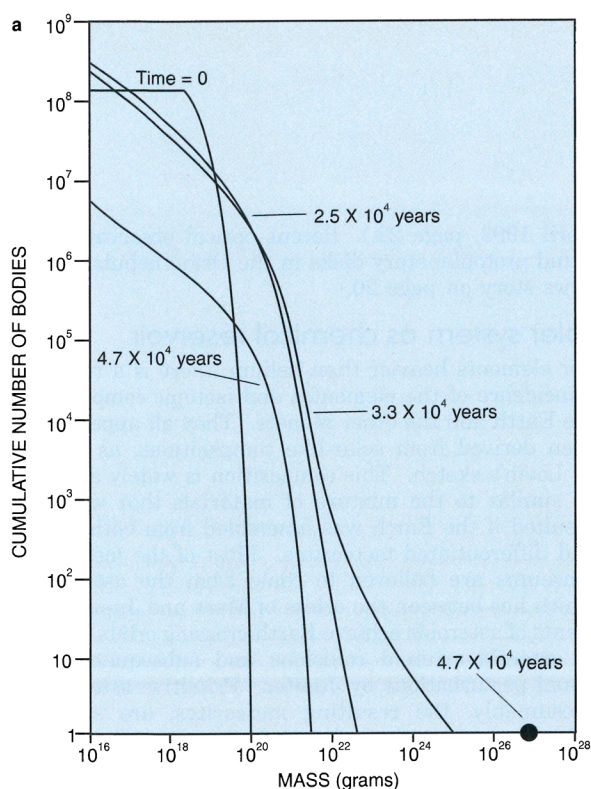
For elements heavier than helium, there is a remarkable coincidence of the elemental and isotopic compositions of the Earth and the other planets. They all appear to have been derived from solar-like compositions, as suggested by Levin's sketch. This composition is widely accepted to be similar to the mixture of materials that would have resulted if the Earth was assembled from both primitive and differentiated meteorites. Most of the meteorites in museums are believed to come from the asteroid belt, which lies between the orbits of Mars and Jupiter. Fragments of asteroids achieve Earth-crossing orbits as a result of asteroid-asteroid collisions and subsequent gravitational perturbations by Jupiter. Primitive asteroids and, presumably, the resulting meteorites, are samples of primitive objects that after their formation from the pre-solar nebula are believed to have never again been heated to above about 150°C (for example, by heat released from short-lived radioactive isotopes). Differentiated meteorites come from asteroids that underwent a degree of processing such that they contain primarily silicate (stony) and iron-nickel components.

A bulk chemical composition model for the Earth can be derived by assuming formation from a mixture of several classes of meteorites and is in accord with the following:

▷ The sampled composition of the Earth's atmosphere, crust and upper mantle and the inferred core compositions. Estimates of core compositions come from comparison of seismologically derived elastic-velocity and density profile measurements with data on the properties of candidate core minerals at high pressure and temperature.



Solar system evolution via the Safronov-Wetherill-Kaula scenario. **a:** Formation of asteroid-sized intermediate bodies from the dust component of the solar nebula. **b:** Runaway accretion leading to intermediate-sized bodies is followed by impact accretion of those bodies into planets. Accretion of gas by giant planets is not shown. The initially flat system of intermediate bodies thickens as a result of gravitational perturbations. (From ref. 4.) **Figure 3**



Size distributions of planetesimals and impactors obtained from simulations. **a:** Evolution of the size distribution of a swarm of planetesimals distributed between 0.99 and 1.01 astronomical units from the Sun. The simulation included fragmentation, a reduction of gravitational perturbations of runaway bodies, and the three-body gravitational enhancement in accretion cross sections for low-velocity bodies. Note the rapid, runaway growth of the largest bodies, with the most massive planetary embryo becoming detached from the remainder of the swarm. **b:** Distribution in size and time of giant impacts for ten simulations of the final accumulations of runaway embryos, under the same assumptions used for the simulation shown in **a**. On average, each simulation is associated with one impact on "Earth" of an object more massive than the present mass of Mars and about two impacts of objects intermediate in mass between those of present-day Mercury and Mars. (Courtesy of George Wetherill, Carnegie Institution of Washington.) **Figure 4**

which can make up as much as 10% by mass of primitive meteorites. These meteorites contain similar quantities of carbon and a wide range of hydrocarbons, including several dozen amino acids. The average D/H ratio in the meteorites is 1/30 000, which is almost precisely the same as that in ocean water. Because D/H ratios found in the universe vary considerably, the ocean's isotopic composition of hydrogen, along with the isotopic compositions of a large number of nonradiogenic elements in the Earth, strongly supports the meteorite mixture model for the chemical composition of planetesimals.

Accretion core and protoatmosphere

The atmospheres of Venus, Earth and Mars have similar noble gas abundance ratios. However, the fraction of noble gases in the atmospheres of Venus, Earth and Mars decreases in the order listed, and their atmospheres are all greatly depleted in noble gas content with respect to primitive meteorites.

Laboratory experiments indicate that as Earth grew from an object several kilometers in size to lunar size, most of the volatile elements and compounds from the accreting planetesimals remained in the protocore of the growing planet. I call this stage of Earth formation the primitive accretion core. Thus during the early phase of accretion, the Earth took up H_2O , CH_4 , CO , CN , hydrocarbons and noble gases present in the initial planetesimals. Encounter velocities, and hence impact velocities, ranged from a few meters per second to 2 km/sec, corresponding approximately to the escape velocity from the growing proto-Earth. If the H_2 -rich solar nebula gases had dissipated during this period, there would be only a minor terrestrial atmosphere, and the conditions on Earth's surface would be oxidizing such that metallic iron would react with water at low temperatures. I designate this type of accretion mode A (figure 6).

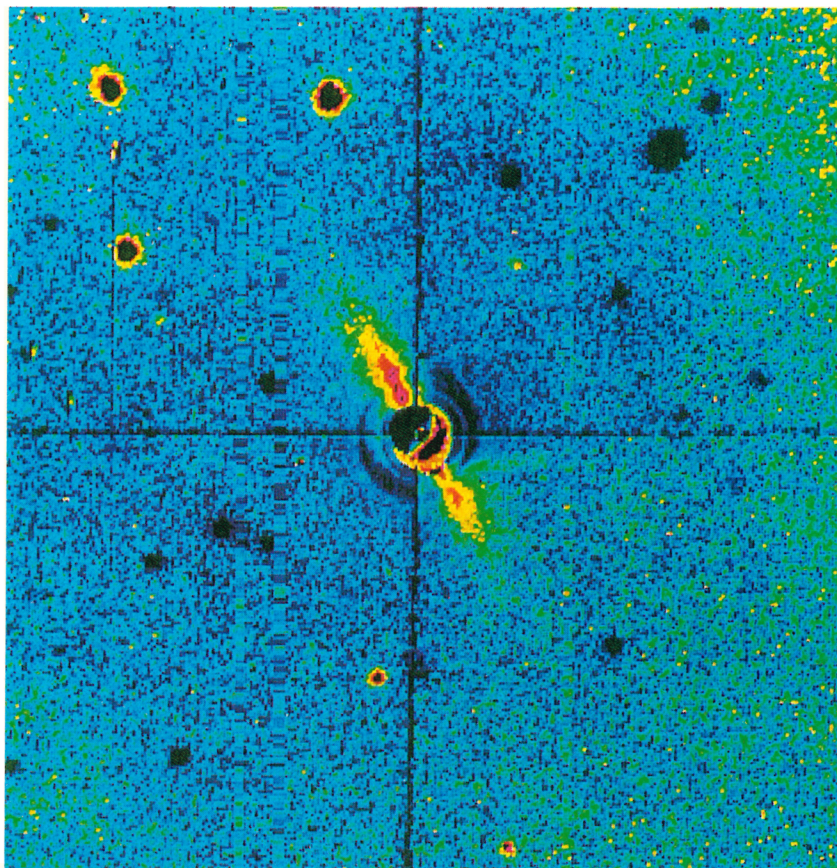
Experiments by James Tyburczy, Manfred Lange and myself demonstrate that impact velocities greater than about 2 km/sec induce sufficient entropy to devolatilize minerals. Thus as Earth grew to greater than lunar size (on the order of 1700-km radius), a primordial protoatmosphere largely composed of H_2O and CO_2 began to form (figure 6). Theoretical modeling by Yutaka Abe and Takafumi Matsui of the University of Tokyo using our experimental data demonstrated that this primordial atmosphere would have profoundly affected the thermal

▷ The composition of the Sun, as deduced from spectroscopic data, solar wind observations by spacecraft, and particles implanted in the surfaces of meteorites and of lunar samples returned to Earth.

▷ The ratio of elements and isotopes produced at the beginning of the universe by the Big Bang, as calculated from nuclear band structure theory. Subsequent nuclear reactions of the initial elements within precursor stars led to the elemental and isotopic abundances in our solar system.

The solid, liquid and gaseous Earth as depicted in figure 6 has the inferred mean composition shown in the table on page 44. Most of the water that was delivered to the early Earth is believed to be locked up in water-bearing minerals such as serpentine, $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$,

Disk of matter around the star β Pictoris, viewed edge-on and extending out over 400 AU on either side of the star. The picture was taken with a special coronagraph technique that blots out the light from the bright central star. The disk, discovered from Infrared Astronomical Satellite data in 1983, is believed to be the remnant of the accretion disk that formed in the star's protostellar nebula. (Courtesy of Bradford Smith, University of Arizona, and Richard Terrile, Jet Propulsion Laboratory.) **Figure 5**



regime of a growing Earth, inducing what I call a super greenhouse effect.

In the ordinary greenhouse effect, sunlight spectrally peaked at visible wavelengths shines through the transparent atmosphere and deposits energy onto the surface. The surface of the Earth reemits radiation spectrally peaked at about 10 microns, corresponding to a Planck radiation temperature of about 300 K. However, absorbance of the reradiated energy by the so-called greenhouse gases such as carbon dioxide, water and methane keeps Earth from radiating the solar flux away to space and hence warms the planet.

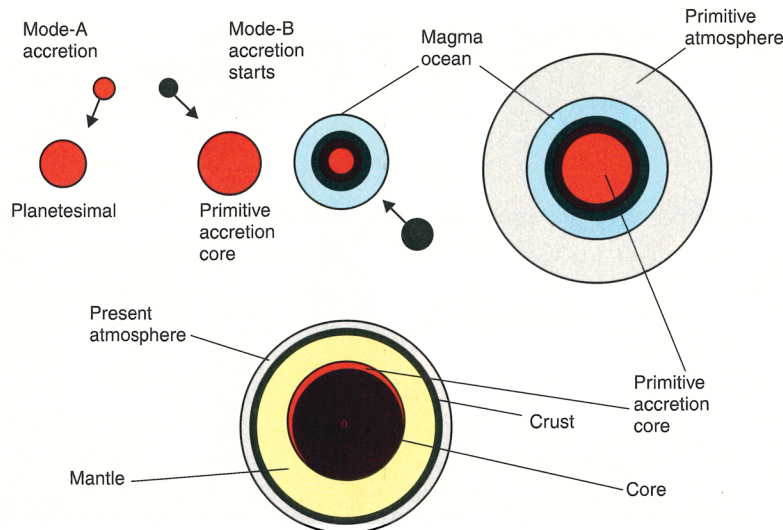
During Earth's accretion, the regular greenhouse effect continued to operate to some extent. In addition to sunlight, however, the impact of planetesimals on Earth's surface provided an energy flux that for brief periods greatly exceeded the solar flux. The gaseous atmosphere was also augmented by fine impact ejecta down to aerosol sizes. Both the greenhouse gases and the fine impact ejecta absorbed the energy flux from the strongly heated surface and attenuated the radiative energy loss to space. The result of this super greenhouse effect was melting of the surface rocks and possibly, depending on the rate of accretion, silicate vaporization when temperatures reached 1500–3000 K (figure 7 is a schematic representation). Such temperatures would have produced a global pool of molten material, termed a magma ocean. Planetesimals that contain both silicate and metallic iron minerals would have melted upon impact. As pointed out by Stevenson,¹³ the resulting molten blobs of metallic iron (probably largely alloyed with sulfur and nickel) would have easily coalesced and fallen inward through the molten silicate magma ocean to form a metallic core.

Because planetesimals contain carbon, accretion with

an overlying primitive protoatmosphere results in surface reducing conditions that I denote as mode-B accretion.¹⁴ Alfred E. Ringwood of the Australian National University first pointed out that these reducing conditions could have been so severe that Fe^{2+} -bearing silicates such as Fe_2SiO_4 were transformed to metallic Fe and Si, which might later have been incorporated into the growing Earth's core.¹⁵ Virtually all the volatile elements and compounds contained in the planetesimals at this later stage of accretion would have been vaporized on impact and hence reside in the atmosphere. It is likely that the abundances of gases dissolved in the magma ocean during mode-B accretion reflect the high temperature and pressure conditions at the base of the primordial atmosphere: The lighter noble gases (He and Ne) would have been more soluble in the magma ocean, while heavier gases (such as Xe) were excluded from the magma ocean and thus from the solid Earth that formed upon later cooling.

Atmospheric blow-off

As accretion of the Earth continued, the planetesimals themselves accreted, and gradually some became very large. Thus as the Earth grew, hundreds of 10-km-radius objects, tens of 100-km objects and several Moon-to-Mars-sized objects, 1000 km in radius, impacted the Earth. Although all impacts of objects with radii greater than about 100 m would have caused some of the atmosphere to be ejected (as pointed out by Cameron), the larger of these objects substantially eroded portions of the underlying atmosphere by ejecting it at speeds greater than the escape velocity. Occasionally a very large impact, like the ones indicated in figure 7, ejected all or most of the protoatmosphere and drove the Earth back into mode-A (oxidizing) accretion. After such an event, which may



Stages of Earth accretion. The Earth starts accreting all material under mode-A (oxidizing) conditions. When the infall (escape) velocity exceeds about 2 km/sec, at approximately lunar size, planetesimals devolatilize upon impact, producing in succession a protoatmosphere, super greenhouse effect and magma ocean. Accretion under these, mode-B conditions, reduces iron, and possibly silicon, in silicate to a metallic form. **Figure 6**

have occurred more frequently toward the end of Earth accretion, the atmosphere built up again. Heinrich Wanke of the Max Planck Institute for Chemistry, in Mainz, Germany, has estimated that some 15% of the Earth accreted in mode A.

Minor impacts of asteroids and comets still occur on the Earth. To the surprise of many scientists who think of evolution as a gradual process, a particularly energetic event apparently occurred 65 million years ago, at the boundary between the Cretaceous (K) period and Tertiary (T) era: the impact of a 10-km-diameter asteroid or comet that apparently gave rise to drastic changes in Earth's biota. Fossil evidence indicates that life on the continents was dominated by reptiles until this K-T extinction bolide fell and temporarily drastically affected climate, resulting in the sudden extinction of some 90% of all the living families. This event ended the last geologic period of reptiles (K) and led to the present era of mammals (T) and eventually the ascent of humankind.

Although 4.5 billion years have passed since the Earth accreted, I believe the following physical and chemical

observations are evidence of the way the Earth originated:

- ▷ A flux of primordial gas is currently being expelled from Earth, largely along the midocean ridges. Some 4 atoms/cm²/sec of primordial ³He (which is not produced by radiative decay) is emanating worldwide on the average. It is likely that this gas streams from material deeply buried in the Earth, and probably in part from the primitive accretion core, although subduction into the mantle of deep seafloor sediments, which are rich in interplanetary dust particles, may also provide substantial quantities of noble gases.

- ▷ The mantle contains a distinct signature of excess so-called siderophile elements (Mn, V, Cr, P, W, Co, Ag, Ni, Sb, As, Ge, Mo, Au, Re and Ir). These were presumably added to the Earth and thoroughly homogenized in the upper mantle during mode-A accretion.

- ▷ The terrestrial atmosphere is likely to be derived from both solid Earth degassing and the effects of biological processes such as photosynthesis. The primitive atmosphere has long been blown away by big impacts during the latter stages of accretion. Hence the present terrestrial atmosphere may, in part, inherit a composition that reflects an early equilibrium of the protoatmosphere with gases dissolved in the magma ocean. Thus the Earth is depleted in noble gases such as Xe, which were less soluble in the molten silicate magma ocean.

- ▷ The 23° inclination of Earth's spin axis with respect to the plane of its orbit is believed to have been produced by a large oblique impact toward the end of Earth's accretion.

Unsolved problems

There are a host of unsolved problems regarding both the nature of Earth, especially the chemical composition of its interior, and the processes by which the planet evolved:

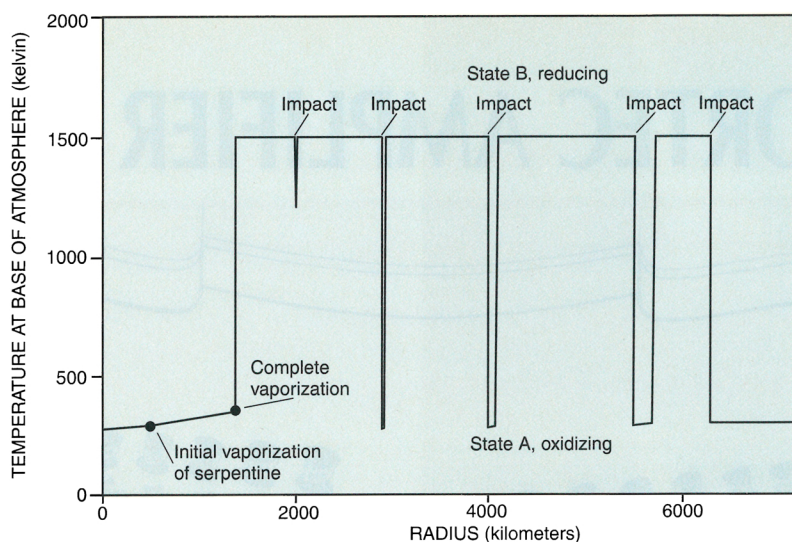
- ▷ A simple model of accretion such as that shown in figure 6 suggests that a primitive accretion core reservoir containing material rich in primordial ³He still resides in the Earth. Other models suggest that the planet is well differentiated, that the lower mantle no longer contains a reservoir of primordial material and that the volatiles that stream out in molten rock from the deep Earth (in the so-called mantle plumes such as the Hawaiian island chain) are actually recycled surface crustal material that has been subducted. Detailed study of rocks from mantle plumes may reveal the origin of ³He and other plume volatiles.

- ▷ The liquid outer core of the Earth is some 10% less dense than pure iron under the pressure and temperature

Bulk Earth composition

Compound or element	Percentage by mass
SiO ₂	31.14
MgO	25.03
Metallic Fe	24.74
Metallic Ni	4.25
FeO	3.44
H ₂ O	2.88
Na ₂ O	2.62
CaO	2.14
Al ₂ O ₃	1.94
Organic compounds	1.46
S	0.86
Cr ₂ O ₃	0.22
TiO ₂	0.19
NiO	0.18
MnO	0.12
P ₂ O ₅	0.05
K ₂ O	0.01

Total differs slightly from 100% because numbers are averages from various sources.



Two modes of accretion correspond to different surface temperatures over the evolution of Earth. A primitive core containing most of the initial complement of gases within planetesimals accretes until complete vaporization of these gases occurs upon impact. During the interval between initial and complete vaporization of serpentine, mode-A (oxidizing) accretion occurs. The loss of water and other infrared absorbing species to the atmosphere causes thermal blanketing and mode-B (reducing) accretion. Large impacts produce temporary loss of the protoatmosphere and temporary periods of mode-A accretion. Finally the rate of impact of planetesimals declines to the point where generation of the protoatmosphere and thermal blanketing does not occur and the magma ocean does not form again. The last mode-A stages of accretion may account for the excess of the siderophile elements in the upper mantle relative to the amounts expected for equilibrium with molten iron during mode-B accretion. (Adapted from ref. 14.) **Figure 7**

conditions of the core. The presence in the core of one or more geochemically plausible elements such as S, Si, O, C and even H has been proposed to produce this density deficit. A sulfur-rich core would imply that core material formed near the surface and sank rapidly in a molten magma ocean. As already mentioned, the presence of Si in the core would reflect mode-B conditions of Earth accretion. In contrast, an oxygen-containing iron core requires special conditions, since at low pressure, O is highly insoluble in liquid iron. Possibly there was mixing of liquid iron and mantle material at high pressures, and hence if the core is indeed lightened by oxygen, a very turbulent condition may have existed deep in the Earth during core formation or evolution. The presence of C or H in the liquid core of the Earth presents special problems, since in primitive meteorites these materials normally are carried in the highly volatile minerals and hence would be expected to have been volatilized into the atmosphere during impact accretion. A process that would incorporate substantial quantities of these elements into a liquid iron core has not yet been identified.

▷ The remarkably uniform enrichment of siderophile elements in upper mantle rocks (relative to what is expected for a silicate in equilibrium with liquid iron) has defied explanation by two- or even three-component mixing models like that sketched in figure 6.

Thus many of the problems and questions concerning the origin of Earth relate to models of the composition of the planet's interior. The issues are difficult, as we have samples only of the outer several hundred kilometers. We rely in the absence of samples on detailed study of Earth's interior using seismological and geodetic techniques, as

well as on high-pressure, high-temperature mineral physics and chemistry experiments.

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