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The Universe and Its Origin:
From Ancient Myth to Present Reality
and Fantasy

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THE ORIGIN OF THE SOLAR SYSTEM

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Abstract:

The Solar System comprises many different classes of bodies with astonishingly different chemical and physical properties. By what processes did these bodies arise from a largely homogeneous initial state? This review summarizes our theoretical attempts to solve this problem, and presents a brief and selective review of recent data on our planetary system as a means of testing the predictions of these theoretical constructs. Some crucial remaining uncertainties that hinder us in choosing between these theories are mentioned, and the prospects for early testing of these theories are discussed in light of present plans for planetary exploration in the United States, the Soviet Union, Europe, and Japan.

Astronomical Setting of Star Formation

A large body of astronomical observations suggests that the formation of stars and stellar systems begins in the gas- and dust-rich lanes in the spiral arms of our Galaxy. There the interstellar gas and dust clouds can attain densities so high that their gravitational potential energies exceed their internal thermal energies. When an interstellar cloud (compressed by an intercloud collision, a passing shock wave from a stellar explosion, or the radiation pressure of surrounding stars) becomes sufficiently dense to meet this criterion, its internal pressure ceases to be sufficient to prevent its collapse.

Collapsing interstellar clouds may commonly be formed with alarge amount of angular momentum. Their collapse can then cause spin-up to such high speeds that they fragment into dense cloudlets orbiting about a common center of mass. The original cloud may have a mass of several thousand Suns. After several generations of collapse and fragmentation, and after a time measured in hundreds of thousands of years, a hierarchy of structures will be found, ranging from individual prestellar nebulae with masses roughly comparable to that of the Sun, through small associations of only a few such nebulae, on up to clusters of hundreds to thousands of nebulae. Indeed, the spiral arms of our Galaxy today are full of such associations and clusters. The large majority of the stars in the spiral arms (outside the dense, gas- and dust-poor galactic core) are indeed found in association with other stars. Only 5 to 20% of the stars near the Sun are apparently single stars, devoid of stellar companions. The rest belong to double, triple, and even more complex multiple stellar systems. Since some stars are exceedingly faint, with luminosities ten thousand times smaller than that of the Sun, many of the stars that appear single to us may in fact be accompanied by one or more very faint companions.

The somewhat unusual status of the Sun as a single star does not necessarily mean that planetary systems like our own are infrequent. Many stellar systems are either very compact, with the stars much closer together than Mercury and the Sun, or very widely separated, with orbital periods of thousands of years or more. In such multiple systems there is a wide range of separation distances within which planetary orbits would be stable for billions of years. In many systems, two or three stars orbit so far apart that each star could have its own stable planetary system. The masses of the stars in multiple systems range from a few percent of the mass of the Sun (so-called "brown dwarfs", the smallest bodies with enough luminosity to be visible to us over interstellar distances) up to an upper limit that lies somewhere in the range from 60 to 200 solar masses. The luminosities of the stars vary as a very sensitive function of their mass, from about 0.0001 solar luminosity for the least massive to roughly 1,000,000 solar luminosities for the most massive. The Sun is brighter (more luminous) than about 95% of the stars. The most common type of star in the Galaxy is the red dwarf, a tiny, cool stellar type with less than a thousandth of the Sun's luminosity. The overwhelming majority of the mass in the spiral arms of the Galaxy is in the form of dark or faintly luminous matter, such as red dwarfs and interstellar matter. On the other hand, the minuscule portion of the total stellar mass that is found in very massive stars is responsible for virtually all of the luminosity of the Galaxy.

Two stable, hydrogen-fusing stars that differ by a factor of 100 in mass (say, 0.1 and 10 solar masses) will differ by a factor of several million in luminosity. Thus 10 solar masses of material distributed among 100 equal-mass small stars will contribute about 100,000 times less light that it would if collected in a single star. It requires little mathematics to deduce that the hydrogen fuel in the larger stars will be consumed in a very short time, whereas low-mass dwarf stars can survive for hundreds of billions of years, a time far longer than the 15 billion year present age of the Universe.

When low-mass stars exhaust their supply of fuel (in the distant future), they will subside gently into obscurity. But very massive stars have such powerful gravity that they can build up and hold immensely high temperatures and pressures in their interiors. In the deep interiors of low-mass stars, conditions are barely suitable for the slow fusion of hydrogen into helium. But at the extreme temperatures, pressures and densities encountered in the deep interiors of massive stars, a host of complex nuclear reactions can take place, leading to the synthesis of a wide range of chemical elements ranging from helium through carbon, nitrogen, and oxygen, then the rock-forming elements silicon, magnesium, and iron. The evolution of such a massive star constantly accelerates until, in a final incredibly violent paroxysm, the star explodes. A portion of the star, containing every known element up through the radioactive actinides, is ejected in a powerful shock wave traveling at a few percent of the speed of light. For a brief time, the blazing remanents of the exploding star shine brighter than an entire galaxy. The ejected shell of gas departs, leaving behind an immensely dense sphere of collapsed matter where the star once orbited.

A star with 30 solar masses will burn its fuel about 200,000 times as fast as the Sun. Instead of remaining a stable, well-behaved hydrogen-burning ("Main Sequence") star for 10,000 million years like the Sun, it will instead run through its entire lifetime in a mere 50,000 years. This means that in regions of star formation, where stars will appear over a time of hundreds of thousands of years, any very massive stars formed early in the collapse process will have run through their entire lifetimes and exploded while star formation is still taking place nearby. Indeed, the high luminosity of the star pushes against nearby gas and dust clouds and accelerates their collapse. The star's final cataclysmic supernova explosion not only helps squeeze the interstellar cloud material to high densities, but also fecundates it with freshly synthesized elements. The rock-forming elements are the raw material of terrestrial-type planets; the radioactive elements are the fuel that drives the melting, thermal evolution, outgassing and internal convection of the planets; and the carbon, nitrogen, oxygen and other light elements are the precursors of life.

Formation of Planetary Systems

Let us now consider a region within which star formation has been occurring for some time. Many stars, mostly tiny red dwarfs, have come into being. A small proportion of the new stars have masses similar to that of the Sun. Collapsing prestellar nebulae have shrunk to sizes comparable to the present size of the Solar System by radiating off their internal energy. Angular momentum has been shed by fragmentation episodes and by the shedding of mass from the outer edges of the collapsing nebulae. Each rotating nebula collapses rapidly toward its equatorial plane, but its angular momentum is sufficient so that, during collapse, the equatorial regions of the nebula spin up to high speeds and eventually approach orbital velocity. This centrifugal force very strongly inhibits further collapse toward the spin axis. Each flattened, collapsing disk shrinks so as to flatten itself further, accretes additional matter onto its surface, and radiates heat from its surface into space as its interior heats up (1).

The nebula takes on a flattened disklike shape, symmetrical about the spin axis. Rarely, a nebula with 20, 40, or even 60 solar masses collapses far enough to generate temperatures high enough for the fusion of hydrogen, and a highly luminous Main Sequence star is born. This star lights up, blows back the surrounding gases and any dust that has not agglomerated into larger bodies, runs through its entire evolutionary lifetime, and then explodes into the surrounding interstellar clouds. Any prestellar nebulae formed out of that shocked and chemically enriched cloud material will be chemically, elementally, and isotopically complex and heterogeneous.

Astronomical observations show many objects along the sequence from interstellar diffuse clouds to dense, flattened nebulae, but these dense prestellar nebulae are small targets and faint emitters, and tend to form in parts of the sky that are already stunningly complex and full of spectacular, more easily seen features. Moreover, the nebular stage in the evolution of a star is only a tiny fraction of the the star's life: as a rule, a Sun-like star spends only 0.0002% of its life in the nebular stage. For these reasons, few observations exist pertaining to the evolution of a flattened nebular disk into a planetary system.

Theory strongly suggests that within such a flattened disk dust particles must collide with each other so frequently that, even if the probability of sticking is small, the dust particles will rapidly agglomerate into meter-sized dustballs. These bodies, attempting to orbit the central star (hereafter referred to as the Sun), find themselves embedded in a gas with a pressure of a millionth to a thousandth of the Earth's present atmospheric pressure. Any initial motion that causes them to depart from the equatorial plane of the nebula will rapidly be damped out by gas drag, and the accreting bodies will soon be strongly concentrated in a very thin dust layer in the central symmetry plane of the nebula. There, the gravitational influence of this very dense dust disk will be so powerful that the small bodies will rapidly accumulate into asteroid-sized (100 to 1000 km) bodies (2). At some point late in this evolutionary sequence, temperatures and pressures in the center of the nebula become so high that nuclear reactions begin, the central star lights up, and it rapidly disperses into space any gas and unaccreted dust that may be left in the nebula. During this early brief stage of the life of a star it is excessively luminous and emits a powerful stream of protons and electrons, a million times stronger than our Sun's present solar wind. This stage in the life of a young star is called the "T-Tauri phase" after the first known star of this type.

The further accretion of solid material occurs in accordance with the laws of celestial mechanics. The solid bodies occasionally collide and accrete to form larger bodies. Rarely, they collide sufficiently violently to disrupt each other. Very commonly, they pass close enough to each other so that their gravitational interactions perturb both of them. Such interactions have the effect of pumping up the orbital eccentricities and inclinations of the smaller bodies, which forces them to cross the orbits of a greater number of the larger bodies, which in turn hastens their accretion. Theory tells us that the gas-free accumulation of asteroidal- and lunar-sized bodies into rocky planets takes place over a time scale of about 100 million years (3, 4, 5).

The materials available for planetary formation are by no means uniform in composition throughout the nebula. Just before dissipation of the gas and fine dust, temperatures in the deep interior of the Solar Nebula must have been high enough to vaporize rock completely not too far inside the present orbit of Mercury (6). A little farther out, only the most refractory (involatile) elements and minerals, such as tungsten, iridium, and minerals dominated by oxides of aluminum, titanium, and calcium would have been condensed and available for accretion into large solid bodies. Yet farther out, the very abundant elements iron, magnesium, and silicon would have joined the condensate, largely as metallic iron-nickel alloy and the magnesium silicate mineral enstatite. Yet farther from the center of the nebula, relatively volatile rock-forming elements such as sodium and potassium, the halogens chlorine and bromine, then sulfur, and finally chemically bound water (such as in clay minerals) will join the condensate and be available for incorporation into newly forming planets. At great distances from the center, temperatures will be so low that ice minerals such as water ice, solid hydrates of carbon dioxide, methane, ammonia, nitrogen and rare gases, and solid carbon dioxide itself will condense and be available for planet formation (7).

As the temperature drops off with increasing distance from the center, so too do the tidal effects of the gravity of the central mass concentration, which would readily strip atmospheres from bodies orbiting close to the Sun. Further, lunar-sized bodies embedded in the inner nebula would be unable to capture the hot gas from the nearby nebula because their gravitational attraction would be small compared to the thermal energy of the gas. At great distances from the center, however, similar-sized solid bodies would be more numerous (many more elements, and much more of the total mass, is condensed at lower temperatures), and the thermal energy of the surrounding nebular gas, as measured by its temperature, could be up to ten times smaller than near Mercury's orbit (8). This means that objects little larger than the Moon, if present in the outer nebula, could capture vast masses of nebular gas, thus enormously multiplying their original masses, leading to a runaway accretion of gas to form planetary bodies. These outer planets would therefore not only be tens to hundreds of times more massive that the inner rocky planets, but would also be much less dense, since they would be dominated by hydrogen and helium, not rocks (9).

This is, in brief, our present qualitative physical and chemical understanding of the way the Solar System came into being. It is an essential part of science that such qualitative descriptions, once found free of obvious internal logical contradictions, be quantified as thoroughly as possible. They must then be subjected to the most exhaustive testing by confronting them with the full range of observed properties of the Solar System as deduced from modern Earth-based and spacecraft-based observations. The best of these theories, as judged by their ability to explain observations and make successful predictions of the outcome of future observational tests, will generally be imperfect and require revision. Each successive round of observation, and each new spacecraft encounter with a previously unvisited planet, asteroid, comet, or satellite, exacts its cost from theorists, and rewards them also, sometimes in astonishingly unexpected ways. By this iterative process, the theoretical and experimental feet of science take alternate steps toward the common goal of the understanding of nature.

For our present purposes, the most effective way to motivate a more detailed description of present theories is to provide a brief summary of the general properties of the Solar System as presently understood. Such an approach does not do justice to the historical development of our understanding, and leaves unexplained the apparently perverse fascination of many theorists with ideas that now seem to have no explanatory power. Almost without exception, however, even the most transient of these theories was invented for good, if not compelling, reasons to explain some small islands of observations that have now either been incorporated into the mainland, or discredited as being in error for either experimental or interpretive reasons.

Present Properties of the Solar System

We now face the difficult task of summarizing tens of thousands of publications dealing with the origin, evolution, composition and structure of every class of bodies in the Solar System. Prior to the advent of planetary spacecraft missions and the development of modern spectroscopic, radio, and radar techniques in the 1960s, a very large proportion of our knowledge of the Solar System was derived from the laboratory study of meteorites, the "poor man's space probes". Our understanding of the intrinsic properties of other planets was limited in the extreme: aside from the Moon, we had only a few dozen isolated facts at our command to characterize the geochemistry, geophysics, and meteorology of the other planets. Our understanding of the Earth, although incomparably better than that of the other planets, did not become truly modern until the emergence of sea floor spreading and global tectonics in the mid 1960s, coincident with the birth of the planetary sciences. Further, even today at least 99% of our geological and geochemical data on the Earth treat only the outermost, most accessible 0.5 to 1% of its mass. This nonrepresentative sampling of the Earth leads to its own biases and errors. Our task is to discriminate between those features and systematic trends that are universal to all planets and the individual idiosyncracies of the one planet we happen to know best. It is difficult to the point of impossibility to do so using only detailed data on a small part of one planet and extremely sketchy (and often erroneous) information on the other planets.

Meteorites

The reason that the study of meteorites first came into prominence, and one of the main reasons that research on them continues today, is that they appear to sample a considerable number of parent bodies from a wide range of locations in the Solar System (10). Many of them have retained their primordial compositions and structures and have ages that show that they were formed at the same time as the planets, some 4500 million years ago. As such they are the most ancient samples of Solar System material. If we could determine their exact times and places of origin, we could then reconstruct a sort of movie of the evolution of chemical and physical conditions in the Solar Nebula and in the post-nebular planetary accretion phase. Determining the ages of meteorites is now routine, but reconstructing their places of origin in the Solar System has proved to be an immensely difficult chore.

In the 1960s it was generally accepted that the primitive, ancient meteorite types, the chondrites, were mostly from the asteroid belt (11). The most common class, the volatile-poor and relatively unoxidized "ordinary" chondrites, were assumed to be from the belt, and the highly oxidized and volatile-rich "carbonaceous" chondrites were regarded as possible samples of cometary material. Estimates of the formation temperatures of these meteorite classes can be made from their measured content of a number of moderately volatile elements. When these temperatures were assigned to the asteroid belt on the assumption that the ordinary chondrites formed there, a very large temperature discontinuity was found between the belt and Jupiter. Further, the formation temperatures of the ordinary chondrites were so similar to that deduced for the Earth that one was forced to conclude that the entire inner Solar System was formed at nearly the same temperature. The terrestrial planets would then be formed of virtually identical material. In that case, the absence of oceans on Venus was very hard to understand. Further, the large observed density differences between the terrestrial planets presented a serious problem for a model in which they all formed at nearly the same temperature out of the same materials.

Spectrophotometric and spectroscopic studies of the asteroid belt began in 1970 with the discovery that the large, bright asteroid Vesta, in the heart of the belt, had a reflection spectrum indistinguishable from that of laboratory samples of a class of igneous, differentiated (achondritic) meteorite (12).

It was in this setting that I first proposed, in 1972, a model for the temperatures in the Solar Nebula at the time of formation of preplanetary solid materials (13). In a detailed presentation of this model in 1974 (14, 15), a number of specific interpretations and predictions were put forward. First, the high uncompressed density of Mercury was attributed to the accretion of Mercury out of material that had condensed and equilibrated in the Solar Nebula at such high temperatures that iron was mostly condensed, but the magnesian silicates were incompletely condensed. Second, the small apparent uncompressed density difference between Venus and Earth, with Earth actually slightly denser, was attributed to rather complete retention of the heavy volatile element sulfur by Earth and its depletion in Venus. Third, the low uncompressed density of Mars was attributed to a higher degree of oxidation and hydration. The formation of Mars at lower temperatures than Earth was a natural consequence of its greater distance from the Sun; and a higher initial volatile content was an unavoidable consequence of lower formation temperatures. Fourth, the primitive material of the asteroid belt was predicted (Vesta nonwithstanding) to be volatile-rich, similar to the highly oxidized carbonaceous chondrites.

The close satellite systems of Jupiter and Saturn were interpreted as having formed in the presence of strong radial temperature gradients centered on the planets, in planetary subnebulae that emulated the structure of the Solar Nebula itself. The outer Jovian and Saturnian satellites formed at temperatures controlled by local conditions in the Solar Nebula, where highly volatile ice-forming solids were present in amounts that increased with heliocentric distance. Pluto, the subject of contemporary models that interpreted it as an "iron-rich" body with Earthlike composition, was predicted to be the most ice-rich member of the Sun's family of planets, and the lowest-density body orbiting the Sun directly (except possibly some classes of comets, whose densities were and are unknown). The low density of Pluto has since been verified (16).

The density of each "solid" planet was viewed as having been determined by the composition of material that condensed very close to that planet's location. The volatile element contents of the planets, however, can be strongly influenced and even dominated by small additions of material originating at much greater heliocentric distances(14). A plausible accretion sampling model must accordingly be developed before definitive predictions of volatile contents could be made.

Discoveries in the planetary sciences have continued to accumulate since the early 1970s. I propose to conduct a brief tour of the planetary system, starting near the Sun, with emphasis given to those observations that seem to contain information on the origins of the planets.

First, we shall consider Mercury, the innermost known body orbiting the Sun. The high density bears witness to a metallic core with a mass equal to fully 60% of the mass of the planet, about twice as high a proportion as in Venus and Earth. While high-temperature condensation in a very narrow temperature interval may be capable of producing local condensates with the requisite composition and density, reasonable accretion probability distibutions would bring into Mercury so much material formed at lower temperatures that the observed high density becomes difficult to explain. Several special mechanisms have been proposed to account for Mercury's excessive density: very severe external bombardment which removed much of the crust and mantle; severe crushing of the brittle silicate component (and preservation of the malleable metallic component) during accretion; severe heating and boiling away of the crust and upper mantle by the superluminous phase of the early Sun; and so on. While it is not possible to disprove any of these mechanisms, each has an ad hoc flavor, and would lead to disastrous and as yet unconsidered effects on Venus and the other planets. Aside from the dramatic enrichment of metal, very little is known of the composition and structure of Mercury. We believe that the planet is differentiated and has a core because all plausible thermal history models predict it, but no experiment has yet been carried out that is capable of establishing whether it is truly there. The surface composition is very poorly constrained by remote spectral data. A very faint FeO absorption band in the near infrared near 0.9 micrometers wavelength may be present, but the evidence is marginal. In any event, no more than a few percent of FeO could be present in the crust without providing clear spectral evidence for its presence (17). The condensation theory outlined above suggests that the oxidation state (Fe oxide content) declines rapidly from Earth, with about 10% FeO, through Venus to Mercury. The only spacecraft to fly by Mercury to date, the Mariner 10 mission, added nothing to our understanding of the composition of the surface rocks.

Venus has a massive atmosphere rich in carbon dioxide, with about 2% nitrogen. Radiogenic argon-40, made after the formation of the planet by the decay of the radionuclide potassium-40 in the crust, is similar in abundance to terrestrial radiogenic argon. The primordial rare gases differ greatly from those found in chondritic meteorites and on Earth and Mars. First, the light primordial rare gases neon and argon (these are the non-radiogenic argon isotopes with weight 36 and 38) are roughly 100 times as abundant on Venus as on Earth. The neon abundance is lower than that of argon, as in meteorites and the atmospheres of the other terrestrial planets, and not larger than argon, as in the unfractionated rare gases in the Sun. No single effect seems plausible to account for these differences: an enhanced contribution of a solar-type rare gas component (to elevate the abundances of neon and argon relative to krypton, as observed) must be followed or modified by some other mechanism to deplete neon relative to argon in order to fit the observations of Venus (18). After these two processes, the neon:argon ratio must mysteriously end up similar to that in ordinary chondrites, bodies upon which neither of these effects has operated!

The reactive minor gases, especially sulfur and the halogens, are present in the atmosphere of Venus in amounts so small that they could be supplied entirely from the the observed infall rates of cometary and asteroidal material into the inner solar system, even if past fluxes were no higher than they are at present. Such a conservative model also provides an amount of water roughly equal to the present atmospheric water content. More reasonable estimates of past cometary and asteroidal impact rates suggest that these elements plus nitrogen could have been supplied with ease by late infall of volatile-rich impactors, perhaps in 100-fold to 1000-fold excess over their present amounts. Only carbon dioxide is difficult to provide by such a mechanism, and therefore only carbon dioxide can be plausibly identified as a volatile component of Venus at the time of planetary formation. The interesting conjecture that comets are a major source of at least the lighter rare gases on Venus remains untested, and must await the results of mass-spectrometric analyses of the rare gases in cometary comas.

Several of the major reactive volatiles on Venus can form stable minerals under present Venus surface conditions (20). The abundances of these solid carbonates, sulfates, sulfides, chlorides, fluorides and hydroxyl amphiboles are quite unknown, although some radar reflectivity data suggestive of volcanic sulfide deposits do exist (21). Reactions between atmospheric gases and these minerals regulate, or "buffer", the abundances of there active gases at levels very close to their observed proportions.

Only one isotopic oddity is known among the chemically active volatiles on Venus: the present concentration of heavy hydrogen (deuterium; D) relative to normal hydrogen (H) is about 100 times as high as on Earth or in chemically bound water in meteorites (22). Simple models, in which Venus is given an initial endowment of ordinary water but loses H more rapidly than D due to the preferential escape of the lighter isotope from the planet, show that Venus must once have had at least 100 times as much water as is presently found in the atmosphere. This is nearly 1% of the amount of water in Earth's oceans. More realistic models incorporating the effects of surface reservoirs of bound water and the powerful influence of cometary and meteoritic infall of water have yet to be developed: we do not in fact know whether the atmospheric water content on Venus is presently rising or falling. It is interesting to note that dynamical accumulation models for the terrestrial planets suggest that Venus should have accreted roughly 10% of its mass from Earth's vicinity (3, 5), and hence Venus should have formed with a few percent of Earth's water content.

Venus and Earth are near-twins in several respects, but very dissimilar in others. Although their atmospheres are grossly different, the two planets are very similar in their distance from the Sun, size, mass, density, surface gravity, and escape velocity. Mercury has a much higher density than either, and Mars has a much lower density than either. The uncompressed density, which is a crude but useful measure of composition, proves Venus to be rather similar to - but actually slightly less dense than - Earth, thus breaking the general trend of decreasing density with increasing distance from the Sun exhibited by the solid bodies that orbit the Sun. This is actually a quantitative prediction of equilibrium condensation theory, which gives Earth several times as much of the dense element sulfur. Note that sulfur (atomic mass 32) is much heavier than the prevalent element in the terrestrial planets, oxygen (mass 16), which dominates the mantles of the inner planets.

Mars differs clearly from Earth not only in density, but also in the distribution of density within the planet. Not only is the Martian core relatively less massive and less dense than the core of Earth, but the Martian mantle is relatively more massive and denser than Earth's. Equilibrium condensation theory attributes these differences to formation of Mars at lower temperatures, at which metallic iron is nearly fully oxidized to FeO and the volatile content of the planet is greatly enhanced (14). Less free metal means a core dominated by iron-nickel sulfides and a mantle rich in dense iron oxides. Higher volatile content suggests (but does not prove) massive and easy early outgassing.

The atmospheric composition of Mars is full of oddities. The primordial rare gases look remarkably similar in composition to terrestrial and chondritic gases, except that their absolute abundances (grams of gas per gram of planet) are about 100 times lower than on Earth or in chondrites. Nitrogen is also very severely depleted relative to the same reference bodies. The surface of Mars bears powerful evidence of the effects of vast amounts of water and ice, and even the greatest of the canyons on its surface, which are closed and have no drainage outward onto the surface, may be karst features caused by the extraction of vast amounts of underlying carbonate rock by acidic ground water. Insofar as water and carbon dioxide are concerned, it is easy to believe that Mars once was extremely volatile-rich, and even now harbors quite remarkable reserves of subsurface volatiles. But the rare gases and nitrogen seem to tell a different story (23). The radiogenic isotope argon-40, made by decay of radioactive potassium-40 within Mars after planetary formation, is 3000 times as abundant as primordial argon on Mars (vs. 300 times on Earth). Thus it is necessary to conclude that either (24):

a. Mars formed deficient in many volatile elements,
b. Mars is very inefficiently outgassed, or
c. the early volatiles on Mars were somehow lost catastrophically.

Of these, the first is least credible. Everything we know about the solar system associates increasing distance from the Sun with lower formation temparatures, higher oxidation state of iron, and higher volatile content. It seems pointless to throw out this powerful generalization without very good reason. The second can hardly stand alone: why should late-forming argon-40 be outgassed more efficiently than primordial argon? Until recently, the third possibility was dismissed out of hand because no mechanism for catastrophic (non-selective) loss of volatiles was known. More importantly, the idea smacked of catastrophism, a view of geology rejected two centuries ago in favor of uniformitarianism, the view that all the work of geology is done by the very slow, continuous operation of everyday processes like orogeny, weathering, transport, and sedimentation, operating over vast expanses of time. The crucial element for the success of uniformitarianism was that it had no need to postulate external (cosmic, celestial, divine) intervention in terrestrial affairs. The choice thus was made more on theological or philosophical than evidential grounds.

But planetary scientists understand that catastrophic processes of external origin are a natural part of the operation of nature. We have seen the impact scarring of Mercury, the Moon, Mars and its satellites, and the satellites of the outer planets, and we have come home to Earth with new eyes capable of discerning the badly weathered scars of equally titanic explosions here as well. Applying the knowledge of catastrophic bombardment processes won from the comparative study of the planets, we have recently come to realize that the intense impact bombardment associated with planetary accretion will almost certainly trigger massive volcanic outgassing and volatile release from severely shocked and disrupted impactors (25). A growing planet will be surrounded by an envelope of freshly released gases. But the impacts occurring on Mars when grown to, say, 99% of its present size, will have a devastating effect on its atmosphere. Powerful shock waves from the impact explosion of a kilometer-sized asteroid or comet will blast a hole in the atmosphere, hurling up to 1% of the atmospheric mass off into space at speeds above the escape velocity of the planet. Such events are much rarer on Earth because of Earth's much stronger gravity: Earth's atmosphere should accumulate without massive loss. Present crude models for the behavior of large ensembles of such impact events suggest that it is not difficult to blast away some 99% or its primordial atmosphere. The present atmosphere then is a combination of the last trace of released primordial volatiles with a contribution from radiogenic gases formed after planetary accretion.

The asteroid belt, between the orbits of Mars and Jupiter, is strongly zoned according to composition (26). Based on recent spectrophotometric and spectroscopic data on over 600 asteroids, we now know that a narrow ring at the inner edge of the asteroid belt is composed of stony material having the same basic minerals as the stony meteorites. Attempts to match the spectra of these stony (S-type) asteroids to laboratory spectra of ordinary chondritic meteorites, the most common classes of primitive meteoritic matter falling on Earth, have been unsuccessful, and it is generally claimed by experts in this field that these bodies are more similar to stony-irons and achondrites (that is, igneous secondary materials) than to chondrites. The only asteroids that look like pieces of metal (M-class) are also present in this part of the belt. The heart of the belt is dominated by C-type asteroids, so named because of their strong spectral resemblance to laboratory samples of carbonaceous chondritic meteorites. Ceres, the largest asteroid, looks somewhat like an altered C type. Its reflection spectrum contains strong bands due to chemically bound water in clay-type minerals (phyllosilicates). Among meteorites, the presence of such minerals is diagnostic of C chondrites. Beyond the C chondrites in the asteroid belt are the D and P classes, with spectra that look like "super-carbonaceous" variants of C chondrites, containing the same materials as the most volatile-rich chondrites, but in somewhat different proportions. Interestingly, Vesta, the first asteroid to be spectrally characterized, is now known to ne highly atypical and possibly unique!

Beyond the orbits of the asteroids the only solid bodies we have observed are Pluto, the satellites of the outer planets and the possible escaped satellite Chiron. The satellite system of Jupiter shows a strong dependence of density (and volatile content) on distance from Jupiter: it seems certain that there was a strong radial temperature gradient in the Jovian subnebula analogous to that in the solar nebula itself. Callisto, the outermost of the large Galilean satellites of Jupiter, which was formed at temperatures close to those in the surrounding unperturbed solar nebula, is made mostly of water ice. The Saturnian satellite system is dominated by ices except perhaps in the region closest to the planet. The only other regular satellite system, that of Uranus, also appears to be dominated by ices. The Voyager 2 Uranus encounter next year should permit a vast increase in our knowledge of Uranus and its satellites.

The frontier of our planetary system, the realm of Pluto, its satellite Charon, and Neptune with its two strange satellites Nereid and Triton, is even less known, but all available evidence points to the domination of ices there as well. The atmospheres of Saturn's largest satellite, Titan, of Neptune's larger satellite, Triton, and of Pluto contain significant amounts of solid methane, a very low-temperature condensate.

Beyond the planets we have only the comets, which clearly are rich in water ice, other ices, and simple organic molecules. Their location(s) of origin are not well understood, but it is likely that they span a wide range of compositions and originate from throughout the expanse of space stretching from

Jupiter to Neptune.

Systematic Trends and Conditions of Origin

By far the simplest interpretation of present data on the nature and composition of solar system bodies is that these bodies formed from ensembles of small solid planetesimals that had compositions that varied strongly with distance from the Sun. The formation of the outer (Jovian) planets seems most readily explained by the accumulation of solid bodies with masses a few times that of the Moon. These bodies then accreted nearby nebular gases gravitationally and ran away to very large masses.

All other solar system bodies failed to become large enough, or were in regions of the nebula that were too warm, for gravitational gas capture. These bodies perturbed each other gravitationally, collided, and accreted. As a result of gravitational interactions, the orbits of small, unaccreted bodies were constantly being stirred up to higher eccentricities and inclinations. This assures every small body a good chance of being perturbed into an orbit that crosses the orbit of at least one growing planet. Ultimately, the smaller body is accreted in a collision.

Thus every planet samples the surrounding population of small bodies in a statistical, rather than deterministic, way. A small proportion of the mass accreted by a given planet will have been derived from distant, volatile-rich regions of the nebula. In the case of the Earth, the local "background" material was sufficiently volatile-rich that we cannot today discern with any confidence the signature of such a very-low-temperature (cometary) component. In the case of Venus, formed of much "drier" local material, and having so massive an atmosphere that explosive blowoff of gases is virtually impossible, the chances of discerning a cometary component are much better. It is only our ignorance of comets that prevents us from testing this idea today.

One apparently essential feature of planetary accretion is the coupling of outgassing with accretionary impacts. Students of the evolution of Mars have almost unanimously returned to the idea that Mars was formed of volatile-rich material, and the role of very large impacts in shaping the evolution of the terrestrial atmosphere is now being actively debated. It has become clear that secondary (post-accretion) events can affect the volatile element inventories of the planets, as suggested many years ago by Fred Whipple. The quantitative assessment of these effects is now a burgeoning area of research.

A corollary of recent ideas on impacts is the realization that there must be an important stochastic component in the composition and mass of volatiles brought into a growing planet. The mass distributions of the early planetesimal swarms were so steep that the largest one or two impacts carried most of the mass. If, as suggested by spectroscopic studies, comets are indeed compositionally diverse, then the effects of the two largest impacts might be very different on two otherwise indistinguishable planets.

Future Prospects for Exploration

Data to solve several parts of this puzzle may soon be at hand. First, several terrestrial spacecraft (from the European Space Agency, the Soviet Union, and Japan) are on their way to Halley's comet for flyby missions early in 1986. An American spacecraft, designed for a wholly different mission, has been dispatched from very high Earth orbit and has already performed a flyby of another comet, Giacobini-Zinner. The famous Voyager 2 spacecraft, old and at least a little infirm years after its exciting encounters with Jupiter and Saturn, will reach Uranus during 1986. It will fly through this previously unvisited system and provide crucial information on the composition and thermal balance of Uranus and on the chemical and physical properties of the Uranian satellites and rings. Voyager, which was optimized for performance at thelighting levels and temperatures of the Jovian and Saturnian systems, was dispatched to Uranus because the United States decided not to send a dedicated spacecraft optimized for the study of Uranus. If Voyager 2 is successful at Uranus, it will continue on to intercept Neptune, which is at present the most distant planet from the Sun. (Pluto, in its eccentric orbit, will remain inside Neptune's orbit until the end of the century.)

There are no spacecraft missions planned to go to Mercury. The USSR will undoubtedly continue its extremely active and fruitful program of Venus exploration, and the USA will send a

Venus Radar Mapper mission to examine the surface geology unimpeded by the dense, perpetual cloud cover, extending the radar mapping program begun by recent Soviet Venera spacecraft. After a gap of 13 years, both the USA and the USSR will be resuming flights of unmanned spacecraft to the Moon. Both missions will be geophysical and geochemical mapping spacecraft in high-inclination orbits, capable of covering the entire lunar surface with their instruments and cameras. Other lunar-orbiting spacecraft are planned for the next decade by both the European Space Agency and Japan. The opportunities for meaningful international cooperation in lunar science are now unusually rich.

Mars has also again become the focus of renewed unmanned exploration. The USA will send a Mars Geosciences/Climatology Orbiter to map not only the surface geology and chemistry, but also atmospheric phenomena. In 1988, 15 years after their last Mars mission, the USSR will fly two large spacecraft into orbit about Mars. Each of these vehicles will carry a small landing vehicle. Unlike earlier Soviet and American Mars misssions, however, these probes will be dispatched to land on the surfaces of the Martian moons Phobos and Deimos, not Mars itself.

There is only one future mission planned to the vast reaches of the outer solar system; Galileo, a Jupiter orbiter and probe, scheduled for launch in 1986. The spacecraft will enter an orbit about Jupiter than takes it through at least a dozen close encounters with three of the four huge Galilean satellites, and will also drop a probe into the turbulent and brightly-hued atmosphere of Jupiter. On its way to Jupiter, several months after launch, the Galileo spacecraft will fly by the asteroid Amphitrite and examine it with its powerful complement of instruments and cameras. In the early 1990's a Soviet spacecraft will carry out landings on two asteroid. The actual targets have not yet been chosen, but it is believed that a main-belt asteroid is preferred. Preliminary discussion has centered on Vesta. This mission would venture much farther from Earth than any previous Soviet spacecraft mission.

The beginning of the era of exploration of comets, asteroids, and small satellites is the beginning of a new ability to examine ancient, primitive bodies, many of which (such as the readily accessible Martian satellites Phobos and Deimos) are so small that they have been unaffected by thermal and geological evolution. These are the most primitive, ancient, and unaltered objects left in the inner solar system today. Their testimony of conditions during the time of formation of the planets will be more complete, more direct, less inferential than the genetic conclusions gathered from the study of the larger, evolved bodies that has until now been the focus of our efforts in space exploration. We must expect that many of our favorite notions about the origin of the solar system will need to be altered or rejected, and that our understanding will soon greatly surpass our present level.

These small, nearby objects, especially the near-Earth asteroids and the Martian moons, are also of great interest for a wholly different reason: these bodies are energetically much more accessible than the surface of the Moon, and they are composed of much more valuable and useful materials. They could readily serve as sources of life-support materials, propellants, structural metals, and radiation shielding for any form of human activity in near-Earth space. From several of these bodies it is possible to return materials to low Earth orbit with tiny amounts of propulsion energy. Thus two strong and fundamental motives, basic scientific inquiry and economic interest, combine to direct our future attention to these small bodies. The Soviet Union's recently announced plans for missions to Phobos, Deimos, asteroids and the Moon fit perfectly with these considerations. Also, just two years ago NASA's Solar System Exploration Committee recommended in its formal report (27) that the search for and characterization of extraterrestrial resources should henceforth be given priority equal to basic scientific research. Such research programs will surely tell us volumes about the ancient history of the Solar System. They may also provide us with a new vision of the future.

It is never wise for scientists to issue dogmatic statements about Truth without caveats: it is the nature of scientific inquiry that we are constantly learning more, and constantly inventing new ways to learn yet more. While most of our present ideas will probably find a comfortable home in the explanatory constructs of the next century, we may rest assured that there is much, much more to it than we presently know. The formation of a solar system is necessarily an extremely complex chain of events, with many opportunities for variations. Chance may well have dealt us a few features that, on the cosmic scale of things, are quite rare. Likewise, certain very common phenomena in other planetary systems may by chance have been omitted or obscured during the assembly of our own.

The true test of the validity of our theories is not the ability to explain and predict the features of our own system, but to provide a broad and statistically reliable interpretation of the formation of planetary systems in general. By a curious "coincidence" of history, the maturation of our study of the solar system with automated spacecraft is occurring simultaneously with the invention of a variety of new techniques to search for and characterize planetary systems about other stars. In the past year we have already seen the first pictures of dust disks forming intoplanets, and the first detection of a nonstellar "planetary" body in orbit around another star. The coming years will see the emergence of several of these powerful techniques, and with them will come the first information on the masses and orbits of planets in other stellar systems.

How common will other solar systems prove to be? Will about 20% of all stars have planetary systems, as I would currently guess, or is it 1%, or 90%, or perhaps 0.001%? Will these planetary systems generally resemble our solar system, with several rocky inner planets and several massive, gas-giant planets farther out, all orbiting in roughly the same plane? How massive is the biggest planet in each system: will it be Jupiter-like, or much smaller, or much larger? How variable are these general features from one system to the next? Within a few years we should know the answers to many of these questions, and we will be in a position to ask new questions that we presently know too little to formulate. At the very least we will have begun to discern which of the features of our solar system are mere local idiosyncracies, and which are the cosmic norm. This distillation of the general from the particular is the true mission of science: now we shall at last be able to stand before Descartes, Kant, and the others who pioneered our craft and report to them how it really happened - and how unique we really are.

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