Exploring the Solar System (II): Models of the Origin

Speculations about the origin of the solar system have been proposed, modified, buried, and resurrected many times in the last three centuries. The best suggestion still seems to be the "nebular hypothesis" of Laplace, who theorized that the solar system formed from the contraction of an interstellar cloud. But the laws of celestial mechanics, hydrodynamics, modern chemistry, and thermodynamics require that many steps take place before a diffuse cloud forms into a lumpy solar system with a few heavy planets.

There is virtually no data on any of the intermediate stages of planetary formation and little evidence indicating how long the process took. In its first stage the solar system was presumably similar to the Orion nebula, a huge cloud of gas and dust in the Orion constellation, and the only source of data on the last stage is, by virtue of our limited observing capability, our 4½-billion-year-old solar system itself. For the many steps in between there is no direct evidence, and so the study of our origins is for the most part a dialogue in which models play the customary role of measurements.

Arguments rage over the mass of the nebula that formed the solar system, the forces that shaped it, the pressure and temperature that characterized it, and the role of the sun in its development. There seems to be no consensus about these things, although in several areas significant advances have been made in recent years. The two most popular models seem to be from the American school, which postulates that the planets formed first out of a massive solar nebula, and from the Russian school, which postulates that the sun formed first out of a very much smaller solar nebula. The scenario that follows incorporates most of the ideas of the American school, expressing one way the solar system could have formed.

A large interstellar cloud, perhaps 1000 times the mass of the sun, started to collapse more than 4.6 billion years ago. There was no sun in the cloud, nor anything even so large as a meteorite, only gas and very small grained dust. Perhaps the collapse started because the cloud drifted across one of the spiral arms of the galaxy, but after it did start the cloud must have fragmented and collapsed very fast. Some part, probably a blob about twice the mass of the sun, continued to collapse until it formed a thick disk somewhat larger than the orbit of Pluto; at that point, finally dense enough to begin absorbing its own infrared radiations, it heated up enormously. Temperatures at the center certainly rose to 2200°K, enough to vaporize any compound in the dust grains, but at the outer edges the disk probably stayed as cold as a few tens of degrees. After shrinking, the whole disk spun up to a high rate of rotation.

As the spinning nebula cooled, various minerals began to condense out of the gas to form grains again. Their compositions were determined by the temperature in the cloud, which was about 600°K at the radius where the earth is now. Small grains could be buoyed up by the pressure of the gas, but larger ones, perhaps pebble-sized, rained down from the inside of the cloud until they reached the midplane of the disk. In a very short time, probably only a few years, a much thinner disk of solids formed within the thick disk of gases. For the next several thousand years, the gases and solids pursued largely different histories, moving easily about, independent of each other.

The thin disk of solids did not remain a disk for very long. Large-scale instabilities proceeded to break it up into many fragments, which accreted into clusters of little planetesimals, perhaps 1 kilometer in diameter, orbiting about the center of the nebula. (At this point the sun might or might not have formed.) Those clusters combined to form protoplanets, smaller than the moon, which exerted substantial gravitational forces on one another. But the volatile elements, such as helium and hydrogen, still remained gases. Gravitational perturbations caused the protoplanets to collide and form the terrestrial planets, as well as rocky cores that would later become Jupiter and Saturn.

At this point the gases began to take part. They collected on the heavy rocky cores out past the earth to form the bulk of Jupiter (317 earth masses) and Saturn (95 earth masses). At the same time, the gases at the center of the system, still hot and still carrying vaporized grains as well as volatiles, collapsed to form the sun. The sun ejected much matter during its early phases, thus slowing its rotation, and probably blew away large amounts of gas and dust that were not swept up in the formation of the planets. Possibly, some of the material blown "out to sea" is still orbiting the solar system in the cloud of comets which is thought to extend roughtly one-quarter of the way to the nearest stars.

Perhaps the most controversial aspect of the preceding scenario is the role of the sun. Most of those who manipulate ideas about the solar nebula assume that the sun existed before the planets. But no modelist of the solar system has described sun and planets in a common framework, even though they must have collapsed out of the same nebula. This oversight makes it much easier for some theorists to describe the development of planets, and for others to invoke peculiar and powerful occurrences, such as flares or cataclysmic solar storms, whenever needed. As with most aspects of solar nebula study, there is no agreement.

The Russian school of thought, based largely on the work of V. S. Safronov at the O. Y. Shmidt Institute of Physics of the Earth, Moscow, describes the formation of planets from a nebular disk rotating about an already present sun. Models of E. Schatzman at the Observatory of Meudon, France, contain similar assumptions. The most idiosyncratic model of the origin of the solar system, proposed by Gustav Arrhenius and Hannes Alfvén at the University of California, San Diego, suggests that the solar nebula was never very large, but was constantly renewed with interstellar matter swept up by the sun's magnetic field. This model is the only instance of a non-Laplacian view of the origin of the solar system (with different sources of material for the sun and planets) and is not generally accepted because the rate of capture of matter in this way is orders of magnitude too low.

The mass of the solar nebula is a question almost as controversial as the morphology of the manner of its collapse. Safronov and Schatzman postulate that the nebula contained just enough material to make the planets, after adjustment for gases that were apparently lost. The sun is mostly volatile gases, such as hydrogen and helium, while the planets, except Jupiter and Saturn, are mostly condensable materials rare in the sun, such as oxides and silicates of iron and magnesium. So the material of the terrestrial planets—and perhaps Uranus and Neptune—must have been associated with considerable quantities of volatiles that were lost. Such inductive reasoning gives a minimum mass for the nebula that produced the sun and planets of 1.01 to 1.05 solar masses. The mass of the present-day planets is about 0.1 percent of that of the sun.

The American school, particularly

in the work of A. G. W. Cameron at Harvard University, argues that the nebula that formed the sun and planets must have contained at least 2.0 solar masses. Cameron estimates that the typical interstellar cloud has quite a large amount of angular momentum of turbulent origin, which would prevent a fragment with only 1.05 solar masses from collapsing immediately into a central star system. On the other hand, the sun has much less angular momentum (per unit mass) than the typical cloud. Cameron is able to account for the lost angular momentum of the sun in his 2-solar-mass nebula. The gist of his idea is that half this mass formed the sun, while the rest remained in the disk, received most of the angular momentum of the early sun, and then—except for the relatively small bit of matter needed for the planets—was blown away by an intense solar wind similar to that occurring in the T Tauri stars. These young stars are known to eject large amounts of their mass in stellar winds. There is no direct evidence however, that the sun ever went through a T Tauri stage.

Massive Model vs. Minimum-Mass Model

The massive solar nebula model, proposed by Cameron and M. R. Pine, is a detailed numerical construction in which the nebula is approximated by a rotating sphere which flattens into a spinning disk and attains a balance of forces in both the radial and vertical directions. Finding such a force balance is the difficult part of the problem, and this numerical model is probably the most ambitious attempt at simulating the solar system origin, Once such a model is constructed, it can be used to find other important properties of the presolar nebula, such as temperature and density.

Critics of the massive solar nebula model suggest that even though the forces are balanced, the model may not be stable. A dense cloud need not collapse directly to form a disk, according to Richard Larson at Yale University, who was one of the first astronomers to model the collapse of clouds into stars. Relying on simulations he has computed, Larson concludes that instead of forming a solar system, a collapsing cloud like the one studied by Cameron and Pine would fragment into a binary or multiple system of stars. Jeremiah Ostriker at Princeton University has found that a rotating disk as flat as the one in Cameron's models would undergo catastrophic deformations and split into two or more separate fragments. The two studies suggest that a massive disk probably would not have formed, and, if formed, probably would not remain a disk for long.

Larson thinks it is more likely that the disk out of which the planets accreted was formed only after the embryo sun had acquired most of its present mass. Having an embryo sun's mass at the center of the disk helps to stabilize it, almost everyone agrees. Larson's point seems to be that multiple star formation is common in a collapsing cloud, and not all the material will be able to fall directly into the embryo suns. Some matter must inevitably be left behind, and will settle into circumstellar disks. These arguments give significant justification for the starting point of the Russian school, but Larson's discussions of what might subsequently happen to the circumstellar disk are quite limited.

Safronov and others in the Russian school differ with the Americans not only about the mass and shape of the early solar system, but also about the time required for formation of the planets. The Russians think that 100 million years was required to form the planets out of the swirling gas and dust, while the Americans estimate that a few thousand years was sufficient time. With the growing sun to stabilize their nebula, the Russians could afford a long time span, but convective processes expected by Cameron and his co-workers would disrupt the flow of gas and dust in their model nebula after 10,000 years. The only observational evidence sets a limit of 10^8 years or less for the formation of the earth and lunar and meteoritic material.

The two schools also differ in their approach to the problem. The Russian work, which began with O. Y. Shmidt more than 20 years ago, emphasizes the dynamical aspects of solar system evolution. Little attention is given to the chemical aspects, but the problem of the accretion of solids from dust to planets is treated as a continuous process with a powerful set of techniques. The American approach, on the other hand, has been to emphasize the chemistry of the problem, while the treatment of accretion has been more discontinuous, with discrete stages and hierarchies of planetesimals.

The Condensation Sequence

A considerable body of thought about the origin of the solar system now starts with the presumption that the solar nebula passed through a high temperature stage before coalescence of the planets occurred. Grains of iron compounds and silicates, which are believed to be typical of an interstellar cloud, would partly vaporize as the solar nebula contracted and heated, then condense out of the cloud again as it cooled. But the composition of grains condensing at different distances from the center of the nebula would be controlled by the temperatures there, and so the distribution of minerals throughout the early solar system is susceptible to a very rigorous chemical modeling.

But the presumption that grains vaporized in the primitive solar nebula was not always popular. The temperature typical of an interstellar cloud is only about 50°K, and the prevailing view for many years was that grains in the solar nebula would adhere to each other due to poorly defined forces, by a process called "cold welding." Gross differences in the compositions of the planets were attributed to differences in the "sticking forces" that acted at different radii in the solar nebula. Harold Urey first tried to explain planetary compositions by a condensation sequence about 1950, but the iron abundance of the solar nebula accepted then was eight times too low, so the attempt failed. The basic idea has not changed since then, but the quality of thermochemical data and the power of computing facilities have improved enormously.

The basic assumption of the condensation sequence calculations is that the bulk composition of condensates in the nebula is determined by equilibrium reactions between the condensates and gases. Finding the equilibrium temperatures for various condensates, including alloys, in an environment that may include 400 vapor compounds is not a simple calculation, but it has been done for a nebula containing the 15 most abundant elements in the primitive solar system (as determined from the compositions of carbonaceous chondrite meteorites). For purposes of predicting the bulk densities of planets, the other trace elements are unimportant because they only make up 0.004 percent of the solar system mass. The result of these complex calculations is a set of condensation curves, as functions of temperature and pressure, for all the various compounds that will form. The reason one can talk about a single condensation sequence, from

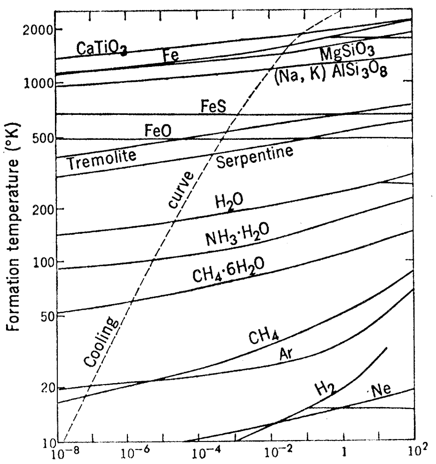

Fig. 1. The condensation sequence of the most abundant compounds expected in the solar nebula as a function of temperature and pressure. The cooling curve represents an adiabatic process.

high to low temperature, is that the calculations show that for most substances condensation is nearly independent of pressure (Fig. 1). Condensation sequence calculations for high temperatures have been done by Lawrence Grossman at the University of Chicago and John W. Larimer at Arizona State University, Temple; and calculations for high and low temperatures, over a large range of pressure, have been done by John Lewis at the Massachusetts Institute of Technology. The three sets of calculations overlap considerably in temperature and pressure, and agree with excellent precision.

The most important result of the condensation sequence calculations is that the densities of the planets can be very well explained with a single idea and a continuous temperature gradient. No physical fractionation process is needed—such as preferential sticking forces—to separate metals and silicates, and no hypothesis that some planets have accumulated involatile components incompletely is required. There is an implicit assumption that each planet is mainly composed of material that condensed in a fairly narrow temperature range—perhaps 100° or 200°K for the terrestrial planets. Some theorists worry that the range is too small, and wonder why there wasn't more mixing of high and low temperature particles during the accumulation of planets and satellites.

The relationship of solid particle density with condensation temperature is illustrated in Fig. 2. The trend toward decreasing densities in the inner planets is strikingly reproduced, even the 1 percent increase in the density of earth relative to Venus. The compositions and densities of the well-known condensed bodies in the solar system are all consistent with a smooth, steep temperature profile for the solar nebula (see box). The model of Cameron and Pine predicts a very steep temperature gradient, so the condensation sequence results probably provide the best support for the massive nebula model of the origin of the solar system.

Accumulation of Small Grains into Large Planets

The chemical data that link the condensation sequence for the planets to the temperature profile in the solar nebula probably represent the most impressive single advance in recent years. (Still to come is a consistent picture of the chemistry of the meteorites.) But advances have also been made in solving the physical problems in the evolving solar nebula, namely, the mechanisms of particle accretion.

Until very recently, many observers thought that there was no attractive proposal for a mechanism whereby the condensed particles could accrete into larger bodies. Objects a few centimeters in size have no appreciable gravitational effect on each other, and celestial scientists seemed to be stuck for a good way to bring such condensate pebbles together quickly (just as they were stuck with cold welding as the way to form the pebbles before the results of condensation sequence calculations). It may not be unreasonable to suppose that colliding pebbles would adhere to form slightly larger pebbles, and these in turn would be even more likely to sweep up more material. But if these pebbles were spread throughout the gaseous nebula, their densities would be so low that collisions would be extremely rare. At the nebular densities expected in the regions of Jupiter and Saturn, the buildup of planets would take more than 10^8 years. The accretion of planets from pebbles takes very much less time in Cameron's model because he postulates that the effect of the gas drag slowed down objects and made them spiral inward. The differential motion induced by gas drag will aid the larger particles in sweeping up the smaller ones. However, in Cameron's picture, it is unclear what starts the accumulation process going, and what makes the pebbles stick after collision.

An attractive model that actually gets the accumulation of matter started was proposed last year by Peter Goldreich at California Institute of Technology and William Ward at Harvard University. Although two pebble-sized condensates have no appreciable gravitational attraction for each other, large distributions of them do respond to collective gravitational forces and some distributions are not stable against collapse. Previously, planetary scientists had found that the particulate matter spread through the whole planetary nebula, which is a fairly thick disk, was too stable to collapse. But Goldreich and Ward found that a thin disk of particles forms at the central plane and fragments very quickly. The gravitational instabilities of a thin disk account for the growth of objects up to several kilometers in diameter, and because no sticking forces are needed to make grains adhere to one another, the process is totally democratic. Iron grains, magnesium silicates, and ammonia-water ice—whatever happens to have condensed out of the gas in a certain region—will accrete together if they are available. Thus, the Goldreich and Ward process coexists nicely with the idea that the solid composition of the early nebula is determined by the chemical condensation sequence: whatever proportions of material condense at a given radius will be collected into larger solid bodies in the same proportions.

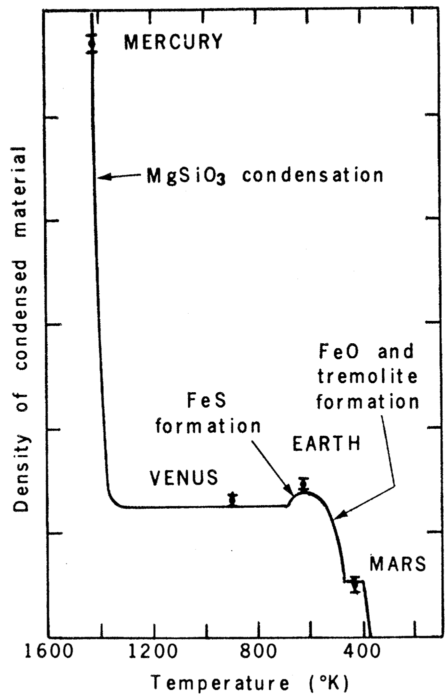

Fig. 2. The density of condensed material in equilibrium with a solar-composition gas (solid line) agrees very well with the data for the inner planets. For the curve shown here, an iron to silicon ratio of 1.06 was used.

Chemical Condensation Sequence in the Solar Nebula

If the solar nebula was at some time hot enough to vaporize the solid grains it contained, then the composition of solid material that reformed as the nebula cooled was determined by the prevailing temperatures. Exhaustive chemical models give the precise order in which various compounds and elements would have condensed out of the cooling solar nebula (see Fig. 1 on page 816) and also predict the bulk density of the mixture of condensates for any temperature. By working backward, the compositions of most of the planets and a few satellites can be reconstructed from their densities, plus whatever chemical observations are available.

The initial accumulation of condensed material is presumed, in condensation sequence models, to have produced homogeneous planets. After accumulation, bodies larger than a few hundred kilometers may have melted and acquired a layered structure. But the condensation sequence calculations specify nothing about such processes, except to note which radioactive elements would be available for heating and which minerals would sink to form the core or rise to form the surface.

The following objects are those whose densities are known with enough precision to be useful for limiting their bulk compositions. Since this analysis applies only to condensed bodies, Jupiter and Saturn—which are more than 95 percent volatiles—are not included.

The moon? The highest temperature materials to condense anywhere in the solar system would have been refractory oxide minerals, such as $CaTiO_3$. These materials would have given rise to a class of protoplanets with a high concentration of calcium, aluminum, titanium, and rare earth elements. Large amounts of uranium and thorium, also condensed at high temperatures, would have been sufficient to melt the interiors of these protoplanets. Cameron at Harvard and Anderson at Caltech have both suggested that the moon is perhaps an object in this class, formed elsewhere in the solar system, but if so, the observed abundances of iron oxide and sulfide on the moon must be explained by something other than condensation. The percentage of high temperature condensates in the lunar composition is still greatly debated, and so the moon's origin is too.

Mercury. With a density of 5.4 g/cm^3, Mercury must have a large component of metallic iron. Iron-nickel alloy may make up 60 to 65 percent of the mass of the planet. The density of Mercury is explained if its constituent material condensed at a temperature so high that $MgSiO_3$ was not fully condensed. But at such temperatures alkali metals and sulfur should have been absent, and the concentration of FeO should have been less than 0.01 percent. The high albedo of Mercury observed by the Mariner Venus-Mercury spacecraft seems to indicate that considerably more FeO is present. Perhaps it came from infalling debris after the planet was basically formed, perhaps some material condensed farther out, near the earth, and became mixed with high temperature condensates when Mercury accreted, or perhaps the temperature of condensation in the vicinity of Mercury's orbit was not above 1400°K after all.

Venus. Material condensing at about 950°K would have included alkali metals in addition to the magnesium silicates (in the mantle) and iron-nickel alloys (in the core) expected for Mercury. The Russian Venera 8 probe has measured the amount of potassium in a small sample on the surface of Venus as about 4 percent. On the basis of the estimated condensation temperature, no sulfur is expected, although some planetary scientists find that a small amount of sulfur is present in the form of clouds of sulfuric acid.

Earth. Compared to Venus, the earth has significant amounts of sulfur and water. In these models it has an outer core of iron, presumably containing 15 percent sulfur in the form of an Fe-FeS melt, and a mantle with about 10 percent FeO. The earth's hydrosphere and crust contain water equal to about 0.05 percent of the mass of the planet. At temperatures of about 600°K or below, water could have been retained, bound in the crystal structure of tremolite. The overall composition of the earth is rather close to that of a certain group of meteorites, the H-group ordinary chondrites, but is not identical with them.

Mars. The density of Mars is so low that all the iron is probably oxidized to FeO, but the planet is far too dense to contain an appreciable amount of serpentine. Its material was probably formed at a temperature between the condensation curves for tremolite and serpentine, or about 450°K. At that temperature, hydrous minerals would have been retained in significant quantities—up to 0.3 percent by mass could be water. Estimates of the rotational moment of inertia from the motion of its satellites suggest that the core is FeS and the mantle is rich in FeO. Lack of a metallic iron core is consistent with the lack of a magnetic field on Mars.

Asteroids. The density of one of the few asteroids whose masses are known, Ceres, suggests that the composition is similar to serpentine. Specifically, the densities of the asteroids, which are near 2.4 g/cm^3, suggest that they belong to the same class as the most volatile-rich meteorites, the carbonaceous chondrites. Whether some of the asteroids are ordinary chondrites—with compositions like that of the earth—is a debated point. Both types of chondrites are found among meteorites, but hard evidence on meteorite origins is lacking.

Ganeymede and Callisto. With densities of 1.7 and 1.4 g/cm^3, these two satellites of Jupiter must be largely composed of ices. Evidence for deposits of ice on their surfaces has been reported, and no evidence for methane has been found on either satellite. Both must have been formed below the condensation temperature of H_2O ice, but above the formation temperature of methane clathrate hydrate $CH_4 \cdot 6H_2O$. The lower density for Callisto may indicate a component of solid ammonia hydrate $NH_3 \cdot H_2O$ as well as H_2O. A mixture of ammonia hydrate with ice begins to melt at 173°K, only a few degrees above the daytime surface temperature at Callisto.

Titan. Methane has been known in the atmosphere of this satellite of Saturn for many years, suggesting that Titan's bulk material condensed below the condensation temperature of methane clathrate hydrate. Heat generated in radioactive materials in the core of Titan could have melted the solid hydrate $CH_4 \cdot 6H_2O$, releasing methane gas to form an atmosphere.—WILLIAM D. METZ

After the condensed particles rain down into a thin disk, which will be rotating, the long-range gravitational forces will quickly overpower the rotational forces in small regions about 100 kilometers in diameter. The particles within such a region will collide and lose energy as the region collapses, and there will be nothing to stop it from contracting further until it reaches solid density, a lump about 0.1 kilometer in diameter and 10^{14} grams in mass. This process will occur within 1 year, and the resulting disk will still be gravitationally unstable. Clusters of first-generation planetesimals, containing about 10^4 members, will continue to contract slowly, assisted by the gas drag, and after a few thousand years they will have formed a second generation of planetesimals about 5 kilometers in diameter. If the rotating clusters of first-generation planetesimals interpenetrate rather than remain equidistant from each other, the second-generation objects could be as large as 10 percent of the lunar mass (10^{25} grams). This number is particularly interesting, because there is some evidence that certain types of meteorites came from differentiated parent bodies with one-tenth the mass of the moon, and Urey suggested many years ago that similar "lunar-sized objects" would be the basic building blocks of the planets.

Last Stage of Planet-Building Obscure

The Goldreich and Ward process does not complete the problem of building planets and moons, but it does produce objects large enough to be gravitationally active and does produce them quickly. After that stage is completed, presumably the condensed matter in the nebula is collected into few enough bodies that no more large-scale gravitational instabilities will develop. Further coalescence could result from gravitational perturbations among these bodies which would scatter them into crossing orbits and increase the probability of eventual impacts. Goldreich and Ward do not consider the final stage of accretion but their model seems able to accumulate planetesimals quickly, fast enough to avoid the expulsion of small grains by a solar wind.

The idea that a gravitational instability could start the process of accretion was also developed in the Russian school, initially by Gurevich and Lebedinskii in 1950. The opinion of Safronov, in his book *Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets* (1972), seems to be that mutual collisions will cause clusters to coagulate. One of the most sweeping contributions of Safronov is that he has developed formulas for the mass and velocity distributions of objects. Out of the mass distribution that builds up as a result of collisions, he expects that the largest body will capture the greatest share of mass because of its gravitational field and become a planet embryo. Of course, Safronov, like Goldreich and Ward, assumes the preexistence of a central star that will later become the sun.

When the Goldreich and Ward process is applied to the massive nebula without a central star, the result seems to be an overpopulated solar system. As might be expected, objects far larger than a few kilometers would be produced at both the first and second stages of accretion. Ward found that at the distance of Saturn, the first-generation objects would be 100 kilometers in diameter, and the second-generation planetesimals would be on the order of one earth mass, even without interpenetration of clusters. Tens of thousands of these objects would form in the outer solar system, and the proponents of the massive solar nebula would be left with the almost insurmountable problem of getting rid of them. (You can't blow the earth away, even with the primordial solar wind.) Since the total amount of solid material in the massive solar nebula model is nearly 100 times that contained in the planets, an instability process that rapidly accumulates all the solid matter into planetesimals seems to be a liability. However, if the bulk of solid material never settled to the midplane, it could still conceivably be blown away or eliminated in some other way. But it is clear that models of the massive solar nebula need a very light-fingered process to steal away a mere 1 percent of the matter available for making planets without disturbing the rest.

Jupiter and Saturn obviously require different explanations from the dense inner planets. Some of the gaseous outer planets could have been formed when protoplanets of rock and ice grew so large that gases from the solar nebula collapsed around them. The existence of a rocky core cannot be proved for Jupiter and Saturn, but indirect evidence suggests that they are not entirely composed of gas—as many scientists long assumed. Jupiter is a little too heavy to be constituted of hydrogen and helium in the same ratio as occurs in the sun, and Saturn's gravitational moments are thought by some to be difficult to explain without a solid core. Cameron and M. Podolak estimate that Jupiter has a core of 50 to 60 earth masses, and that Saturn has a core with about 30 earth masses. According to other work by Cameron and F. Perri, the cores inferred for Jupiter and Saturn exceed the critical mass necessary for the collapse of a gaseous envelope onto a planetary body—several tens of earth masses. Some sort of gaseous collapse seems essential to explain Jupiter and Saturn, and some of the gas could have gone into orbit and contributed to satellite formation.

While a few of the steps in formation of the solar system now seem to be more firmly elucidated, the first and the last steps are still as vague as ever. Simple arguments first proposed by Sir James Jeans show that not even the massive solar nebula represents a large enough chunk of interstellar material to collapse by itself. At least 1000 solar masses are required. Until the process of fragmentation and collapse of the interstellar nebula is better understood, it seems that estimates of the size of the primitive solar system will continue to vascillate by factors of 100 or more. At the other end of the process, the problem of treating many planetesimals orbiting and randomly colliding in the final stage of planet-building is almost completely unsolved. Under this heading come the challenges of explaining the origins of various sorts of meteorites, the distribution of debris that caused the massive cratering seen on all the inner planets, the reason that the asteroid belt never accreted (or accreted and was later destroyed), and the almost unbelievable fact that all the rest of the planetesimals (except the asteroids) somehow managed to coalesce into a mere 40 objects.

Studies of the solar system seem to be at the point where, for the first time, knowledge of the compositions of various objects, particularly meteorites, can be used to put constraints on the movement of matter. Conversely, models of mass transport and accretion may soon be firm enough to put constraints on the chemistry. Judging from the diversity of assumptions, models, and predispositions among those hardy scientists who venture to try to outguess the course of evolution of the nebula that presumably predated us all, more constraint is precisely what is needed.

—WILLIAM D. METZ