# Origin of the Solar System

by
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## Creation Myths

### Old Myths

Speculation about the origin and evolution of the earth and the celestial bodies is probably as old as human thinking. During the millennia that are covered by the history of science, philosphy, and religion we can distinguish three types of approach to this problem.

The first is the "theocratic-myth" approach, according to which the evolution of the world was governed by gods who once upon a time created it. However, we must remember that the meaning of "creation" has changed. The earliest meaning of this term seems to have been that the gods brought order into a preexisting chaos. The world was "ungenerated and indestructible"—as Aristotle puts it—and the gods were part of this world and also eternal. According to Indian mythology the "creation" took place when Brahma woke up in the morning and, finding the world in a chaotic state, brought order into it, transforming chaos to cosmos. And when Brahma goes to sleep after a billion-year-long Kalpa, chaos will again prevail. But the world is eternal, just as are Brahma and the other gods.

The rise of the monotheistic religions changed this view. When one of the gods got a higher status than others (who in some cases became demons or devils), he continued to increase in prestige and power until he became the Supreme Lord, the undisputed ruler of the whole world. Then it was not enough for him to create the world in the sense of organizing a preexisting chaos; he had to create it all from nothing (*ex nihilo*) by pronouncing a magic word or by his will power. This is the meaning of "creation" when we use it today, but it is a relatively new concept. It was generally accepted in Christianity in the second century A.D. but the Genesis description of the Creation seems to have either meaning. The creation *ex nihilo* was not generally accepted by the philosophical-scientific community until the synthesis by St. Thomas of Christian dogma and Aristotelian philosophy.

In the theocratic mythologies the gods created the world and ruled its evolution according to their whims. We read in *The Odyssey* how Neptune was angry with Odysseus and generated storms to destroy him but how Pallas Athena saved him by producing other natural phenomena. In a similar way the actions of their parents or grandparents

(Zeus-Jupiter and Chronos-Saturn) had led to the creation of the world. There was no obvious reason why the world should be as it is. It was merely an accidental result of the activities of the gods. In the monotheistic religions God was sometimes thought to be a despot who did whatever He liked, and it was not allowed to question or analyze His acts.

### Mathematical Myths

With the rise of philosophy and early science, the gods became less despotic and increasingly philosophically and scientifically minded. The creation of the world and its evolution were parts of a master plan, and it was not unreasonable that man should be able to understand the plan. A breakthrough in this thinking came with the Pythagorean philosophy.

The Pythagoreans discovered how beautiful and powerful mathematics was. They found that musical harmonies could be explained as ratios between integers, and they demonstrated that there were five and only five regular polyhedra. I think there are few if any scientific discoveries that surpass these in beauty.

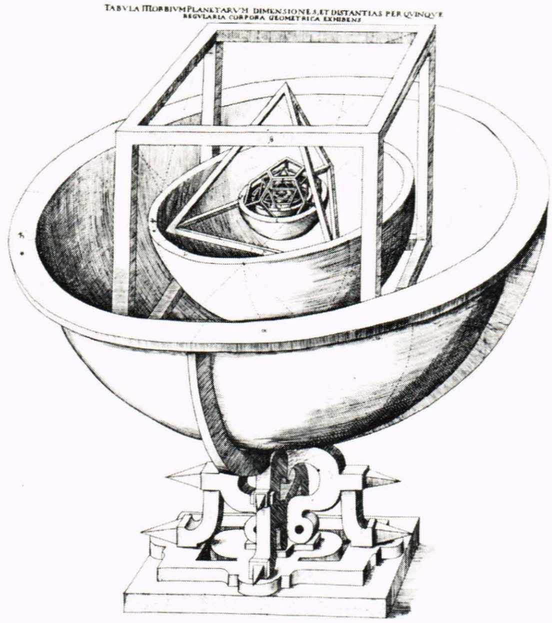

**Fig. 1— Relation between regular polyhedra and planets as demonstrated in a 1597 model of the universe. (The outermost sphere is Saturn's.)**

With such achievements it was quite natural that the Pythagoreans applied the same methods to other scientific and philosophical problems, one of them being the macroscopic structure of the world. They tried to explain it in terms of simple numerical relations and of logically and mathematically beautiful concepts. They considered the sphere to be the most "perfect" of all bodies and uniform motion to be the simplest and most beautiful type of motion. Thus the stars and the planets must be located on crystal spheres that revolved around the Earth with a uniform motion. The basic idea was that the macroscopic world must be structured according to simple mathematical laws—just like musical harmonies and geometrical figures.

Such views were not necessarily in conflict with religion. No one who studies mathematics can avoid the impression that the theorems have a beauty that may be called divine. Hence one could expect the gods to structure the world according to some mathematically and logically beautiful principles. It was the task of philosophers and scientists to find what these cosmological principles were. When they were found, the cosmological problem was solved. We need only one principle, one formula, in order to understand the whole world.

This second approach may be called the "mathematical myth" approach, developed during the centuries into the Ptolemaic cosmology. It is impressive in its logical reasoning and mathematical beauty. For example, it was demonstrated that there should be seven planets, including the sun and moon, revolving around the earth. For seven was a holy number, there being seven days in a week, seven tones in the scale, and so on. And excluding the sun and moon there were just as many planets as regular polyhedra (Fig. 1).

However, a comparison between this cosmology and observations led to a number of discrepancies. In order to account for the observed motions of the celestial bodies it was necessary to introduce a series of epicycles and other factors that made the system increasingly complicated. This did not diminish the credibility of the theory—it just demonstrated that the material world is imperfect.

### Empirical Approach

In the sixteenth and seventeenth centuries the Ptolemaic system broke down, and a new celestial mechanics was introduced that constitutes the third, "empirical", approach. It was based especially on the investigations of falling bodies by Galilei and the very accurate astronomical observations by Tycho Brahe. This injection of new empirical material is believed to have been fatal to the Ptolemaic system. However, there is another factor that seems at least equally important. A prerequisite for the breakthrough of the new approach was the collapse of the peer review system that previously had been powerful enough to prevent the rise of new ideas. When Galilei claimed that the earth moved, his peers in Italy reviewed his ideas and almost unanimously agreed that he was wrong; Galilei had to recant them publicly. But the scientific establishment in Italy was not powerful enough to prevent German, Dutch, and English scientists from accepting and developing them further. The birth of modern science was possible because of a decay in the power of the philosophical-scientific establishment and a breakdown of their peer review system that for centuries had preserved the dark ages in Europe.

### The Triumph of Science

With this breakthrough, the scientific age started. The old myths, both theocratic and mathematical, are dead forever. We live in the scientific age, the age of reason. That is at least how we generally depict our own time. But is it really true?

### Modern Myths

In most daily newspapers there is a column that analyzes how the planets influence our life. But these are not the planets that the astronomers observe and that are the targets of space research; they are the planets of Greek-Roman mythology. Thus Venus is not the planet with a thick atmosphere of carbon dioxide, it is the goddess of love; Mars is not the sandstorm-ridden sphere of rock, it is the old god of war. And these old gods are believed by the newspaper readers to rule our lives in the same way they once ruled the voyage of Odysseus. The theocratical myths of 2000 years ago flourish today more than ever.

Of course, I do not believe any respectable university in the world has astrology as part of its curriculum. The theocratic myth approach to cosmology is dead in the academic community.

### The Cosmological Formula

But what about the mathematical myths? Does the scientific community *intra muros* still subscribe to the Pythagorean belief that the structure of the universe could be solved by one simple mathematical formula? I am afraid the answer is "yes."

Although it is always dangerous to compare different cultures and epochs, I think there is an analogy between the special theory of relativity and the early Pythagorean results. In each case simple and beautiful reasoning led to an important breakthrough that stimulated cosmological speculations. When I was a young student I was very impressed when Eddington, no doubt one of the leading astronomers of his time, claimed that the number 137 contained *the* solution of the cosmological problem. And, in his fascinating book *The Philosophy of Physical Science,* he claims that sitting in his armchair he had counted the number of protons in the universe and found it to be $1.57477 \times 10^{79}$ or more exactly $136 \times 2^{256} =$ 15,747,724,136,275,002,577,605,653,961,181, 555,468,044,717,914,527,116,709,366,231,425, 076,185,631,031,296. Considered as a myth this is beautiful, but considered as science it is nonsense, and is nowadays generally recognized to be so.

However, the collapse of Eddington's cosmology has not discredited mathematical myths in general. On the contrary it seems rather to have acted as a fertilizer for a rich flora of mathematical myths, some of which are attractive from an aesthetic point of view but none scientifically. One of them, the "big bang" cosmology, is at present "generally accepted" by the scientific community. This is mainly because it was propagated by Gamow with his irresistible charm and vitality. The observational support for it that he and others claimed is totally obliterated; but the less scientific support there is, the more fanatical is the belief in it. As you know this cosmology is utterly absurd—it claims that the whole of the universe was created at a certain instant as an exploding atomic bomb much smaller than the head of a pin. It seems that in the present intellectual climate a great asset of the big bang cosmology is that it offends common sense: *credo quia absurdum* [I believe because it is absurd]. When scientists attack the astrological nonsense in the outside world it is wise to remember that much worse nonsense is propagated by the experts themselves.

### Big Creation—Small Creation

The old problem of how the world was "created"—if it was created—is today divided into two problems. One is the "big creation" or how the universe as a whole has originated and developed, which we have discussed to some extent. The other is the "small creation," how in a small part of a small part of a small part of the universe the solar system originated. We shall devote the rest of this discourse exclusively to the latter restricted problem.

**Modern Astrophysics: Myth or Science?**

As in many other areas of astrophysics, there is today a confrontation between a mythological approach and an empirical approach and it is the mythological approach that is "generally accepted" by the scientific community. To those who believe that the structure and evolution of the whole universe can be solved by a single formula, all phenomena in the universe should in principle be derivable more or less directly from that formula. For example, the formation of the solar system would be found to be a result of the big bang when all the consequences are drawn from the theory. There are few people bold enough to try this. Usually one does not go back further than to the formation of stars. In fact, the "generally accepted" theories start from a treatment of how stars are formed and try to derive the formation of the solar system as a by-product of stellar formation.

**The Formation of Stars**

By this approach the theory of the formation of the solar system becomes critically dependent on the mechanism for star formation. What do we know about this?

What we really know is not very much. It is likely that stars are formed in dark interstellar clouds. During the last few years infrared and radio astronomy have given us a wealth of information about such clouds. It has been demonstrated that they contain dust, gas, and rather complex molecules. As far as we know such molecules can be formed at a sufficient rate only in a plasma, so their presence gives a strong indication of the existence of electromagnetic phenomena. Observations of the Zeeman effect give further support for this. Lyman Spitzer, a pioneer in cosmic plasma physics, has devoted much attention to the formation of stars from an interstellar cloud and stressed the importance of hydromagnetic effects in this process. In spite of this there is a whole literature about the formation of stars and of solar systems in which hydromagnetic processes are neglected or treated erroneously.

**The Laplacian Theory**

Speculations about the formation of solar systems from interstellar clouds were initiated by Laplace. He was inspired by the great interest in the origin of the solar system that resulted from speculations by Descartes, Kant, and other leading philosophers and scientists a few hundred years ago. Astronomers had discovered that besides the

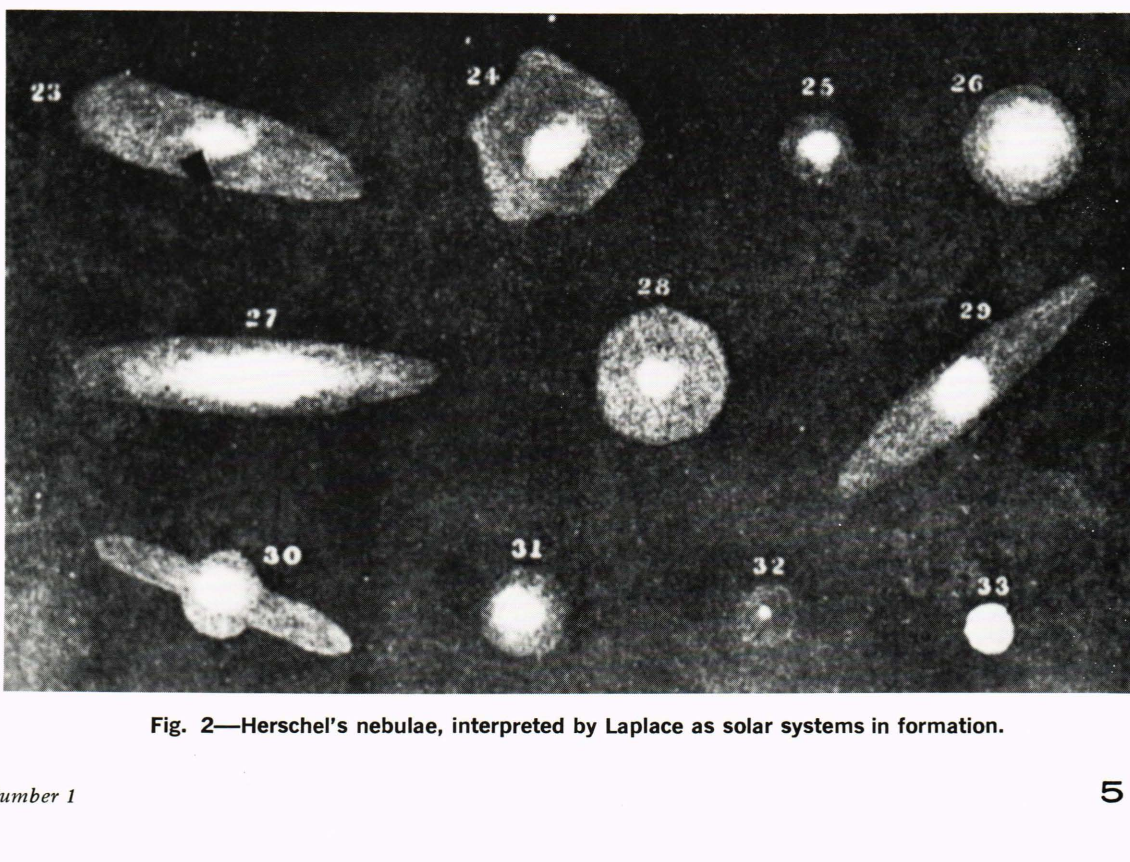


**Fig. 2—Herschel's nebulae, interpreted by Laplace as solar systems in formation.**

stars there were also many small nebular objects in the sky. Laplace understood that many of these consisted of a great multitude of stars—"galaxies" in modern terminology—but he thought that some of them and what he called "planetary nebulae" were solar systems in formation. With this as a background he developed a theory of the formation of the solar system (Fig. 2). When advanced observational techniques later showed that the disc-like objects that he observed were not solar systems in formation, the theory lost its observational foundation. But although the observational support for the "nebular theory" disappeared, the theory itself continued to live a life of its own and over the centuries has become a sacrosanct myth.

The Laplacian theory has been supplemented by the theory of gravitational collapse as a mechanism for the formation of stars and solar systems. This concept is as follows: If we consider a gravitating sphere of gas in which the variables (pressure, temperature, etc.) are functions of radius (r) and time (t) alone, the gas pressure gradient will balance the gravitational force and prevent the sphere from contracting. If the temperature decreases below a certain critical value, gravitation will dominate, and the sphere will begin to contract. When it does so, both the gravitational force and the pressure gradient will increase, but the latter not enough to compensate for the former. The result is a collapse that takes only several thousand years. It is generally believed that stars and solar systems are formed this way.

However, this kind of process has never been observed. From a theoretical point of view it depends critically on the *assumption* that the variables are indeed functions of only radius and time. This assumption is introduced only to make the problem mathematically easy to solve; if it is dropped, it is obvious that the state from which the collapse starts can never be established (it is unstable!). In other words, in order to obtain a mathematically elegant solution, assumptions are introduced that make the solution scientifically uninteresting. Another assumption is that the condensation from the nebula takes place in thermal equilibrium.

Here we have a typical example of how a mathematical myth originates. Developed on the basis of the Laplacian mistake, supplemented by three erroneous physical processes, the myth has become sacrosanct and is the basis of most current papers on the evolution of the solar system. It is defended by a strongly entrenched community that seldom admits the existence of any objection to their myths. The peer review system will probably give this myth the same eternal life among the experts as astrology enjoys among laymen.

## Empirical Approach

### Methodology

After this brief review of some of the most interesting myths—old and new—we shall approach the origin and evolution of the solar system in an empirical way. As has been pointed out by Gustaf Arrhenius, the construction of models is not as important as an analysis of the applicable methodology. Four general principles should be followed in this analysis:

1. Reduce speculation as far as possible by relating all processes to laboratory experiments or space observations.
2. Approach the problem not by making arbitrary assumptions about the primitive sun but by starting from the present state of the solar system and systematically reconstructing increasingly older states.
3. We should not try to make a theory of the origin of planets around the sun but a general theory of the formation of secondary bodies around a central body. It should be applicable both to the formation of satellites and of planets.
4. The aim is not primarily to develop detailed theories but rather to construct a general framework into which the rich empirical material could be fitted. The framework must be acceptable from many points of view including celestial mechanics, plasma physics, plasma chemistry, geology, and the theory of hypersonic collisions.

A realistic attempt to reconstruct the early history of the solar system must follow a procedure that minimizes speculation and connects the evolutionary models as closely as possible to experiment and observation. Because no one can know *a priori* what happened four to five billion years ago we must start from the present state of the solar system and reconstruct increasingly older periods step by step. This "actualistic principle," which emphasizes reliance on observed phenomena, is the basis for modern studies of the geological evolution of the earth: "the present is the key to the past." The principle should also be used in studying the solar system, especially now that NASA is supplying us with invaluable geological specimens from the space missions.

Hence we should proceed by determining which experimentally verified laws are of controlling significance in the space environment. For this purpose laboratory studies of processes that are likely to be important in space are essential. However, to apply laboratory results to cosmic conditions requires a thorough study of the relevant scaling laws. The rapidly increasing information on extraterrestrial processes that modern space research has provided in the last few years enhances the reliability of this procedure. If the large body of available empirical knowledge is interpreted strictly in terms of relevant scaling laws, the speculative ingredient of cosmogonic theories can be significantly reduced.

When analyzing the origin and evolution of the solar system we should recognize that its present structure is a result of a long series of complicated processes. The final aim is to construct theoretical partial models of all the processes. However, there is often a choice between different partial models that *a priori* may appear equally acceptable. Before the correct choice can be made it is necessary to define a framework of boundary conditions that the models must satisfy.

**Planetary System Satellite Systems**

Theories of the formation of the solar system must also account for its satellite systems in a manner consistent with the way in which the planetary system itself is treated. In certain respects the satellite systems provide even more significant information about evolutionary processes than does the planetary system, partly because of uncertainty about the state of the early sun.

Observing that the highly regular satellite systems of Jupiter, Saturn, and Uranus are essentially similar to the solar system, we should aim at a general theory of the formation of secondary bodies around a primary body. This principle was stated by Laplace, but seems to be forgotten by those who today work on the development of Laplacian-type theories.

Consequently, the theoretical framework we try to construct should be applicable both to the formation of satellite systems around a planet and to the formation of planets around the sun. Through this requirement we introduce the postulate that the processes are essentially analogous. Our analysis supports this postulate as reasonable. Indeed, we find evidence that the formation of regular systems of secondary bodies around a primary body—either the sun or a planet—depends in a unique way on only two parameters of the primary body: its mass and its spin. Although it is also necessary to assume that the central bodies are magnetized, the strength of the magnetic field does not appear explicitly; it must only surpass a certain limit.

**Five Stages in the Evolution**

Applying these principles we find that the evolutionary history of the solar system can be understood in terms of five partially overlapping stages (Fig. 3):

1. During the last four billion years, a slow evolution of the primeval planets, satellites, and asteroids has produced the present state of the bodies in the solar system. By studying this latest phase of evolution we prepare a basis for reconstructing the state established by earlier processes.
2. Preceding this stage, an accretional evolution of condensed grains moving in Keplerian orbits occurred to form planetesimals which, by continuing accretion, grew in size. Those planetesimals were the embryonic precursors of the bodies found today in the solar system. By clarifying the accretional processes we attempt to reconstruct the chemical and dynamic properties of the early population of grains.
3. To account for grains moving in Keplerian orbits around the sun and the protoplanets, transfer of angular momentum from these primary bodies to the surrounding medium must have occurred in the stage of evolution preceding accretion.
4. Gas and dust formed a medium around the magnetized central bodies in the regions where the planet and satellite groups later accreted.
5. The sun was the first primary body to form by accretion from the source cloud of the solar system.

**Extrapolation from Present-Day Space Conditions**

The next phase in our analysis is to try to discover what processes have been active during the different phases of evolution, or at least to give

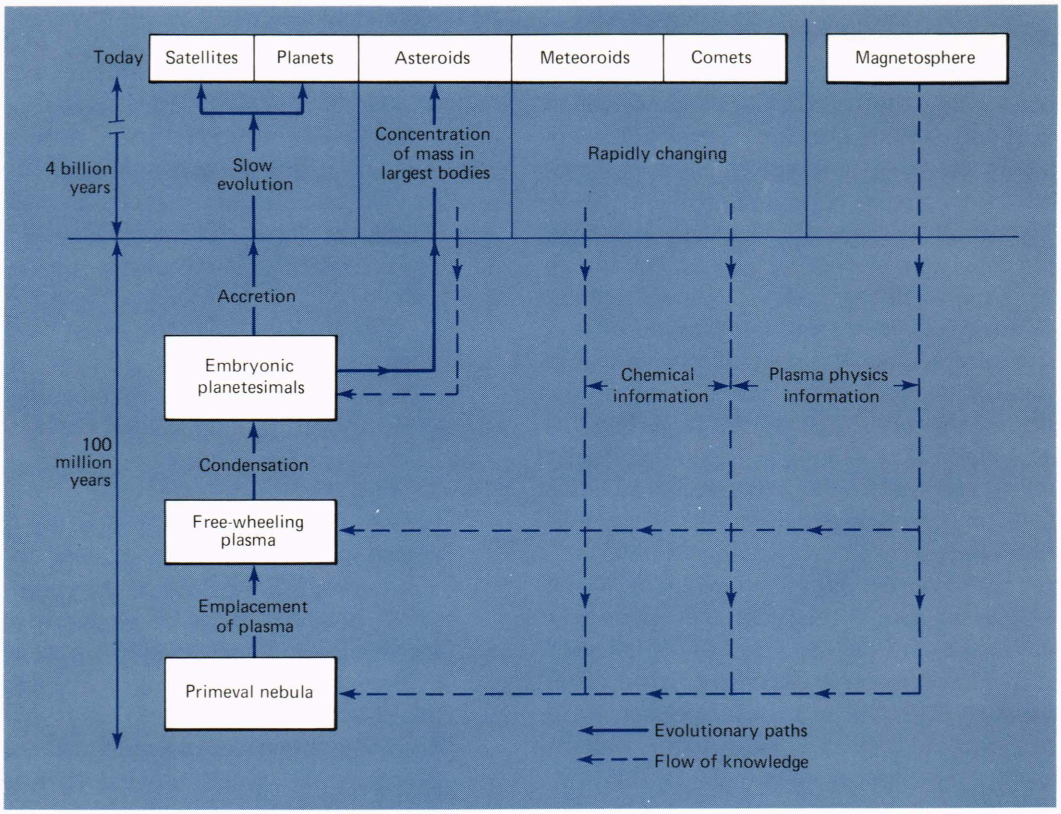


**Fig. 3—Diagram of the evolution of the solar system.**

examples of what type of processes deserve to be more closely analyzed. In doing so we must remember that much of the earlier work has been so speculative that it has lost touch with reality. In cosmology as in all other fields of science we can never avoid speculation; but when speculating, we must always keep in close contact with reality. If we forget that, we will at best substitute a new myth for an old one. It is essential to avoid that mistake.

We should first realize that when the solar system was formed the conditions in our part of space were different in many respects from what they are today, but that the same general laws of physics applied. Solid bodies, including grains, moved in Keplerian orbits similar to present orbits, although viscosity effects and mutual collisions between the grains introduced perturbations. Space contained a plasma whose parameters certainly differed from those now present, but not drastically so. The conclusion is that in important respects we can regard the cosmogonic state to be an extrapolation of present-day conditions.

In fact if we compare the existing plasma in interplanetary space and the magnetospheres with the cosmogonic plasma out of which the planets, asteroids, and satellites once condensed, we find that the earlier cosmogonic plasma no doubt was much denser. But we have enough knowledge of the behavior of dense plasmas from studies of the ionosphere and of the solar corona, chromosphere, and photosphere to be able to make reasonable extrapolations. By choosing such an approach we can largely avoid the introduction of chalkboard mechanisms, which are a nuisance in modern astrophysics.

## The Latest Period

Applying the foregoing principles we may now try to reconstruct the early history of the planets and satellites. We have good reasons for believing that during the last four billion years neither the chemical composition nor the orbital elements of the planets and satellites have changed very much. There has been a slow geological development at the surface of the earth and some other bodies. The orbital elements of the bodies have been subject to what is called "secular changes" of the semi-major axis (a), eccentricity (e), and inclination (i), but these are periodic variations within rather small limits. There are two exceptions: tidal effects have changed the orbit of the moon and of the Neptunian satellite Triton. In almost all other respects the solar system looked pretty much the same four billion years ago as it does today.

**How the Earth Accreted from Planetesimals**

Radioactive dating has demonstrated that this long and stable period was preceded by a period, perhaps ten to a hundred million years long, during which the solar system was formed. The matter that now composes the planets and satellites aggregated from an earlier embryonic or planetesimal state, in which it was dispersed as a number of small bodies. These moved in Keplerian orbits around the sun, but collided with each other and gradually accreted into the existing celestial bodies. The impact craters we see on the moon and other bodies bear witness to the rain of planetesimals that made the bodies grow to their present size.

In fact, by comparing the different space mission photographs of the moon, Mercury, Mars, and Phobos, we find that their surfaces look so similar that we may conclude that all of these rocky bodies developed in a similar way and, in some respects, just represent different phases of evolution. This makes it possible to reconstruct the history of the earth (Fig. 4).

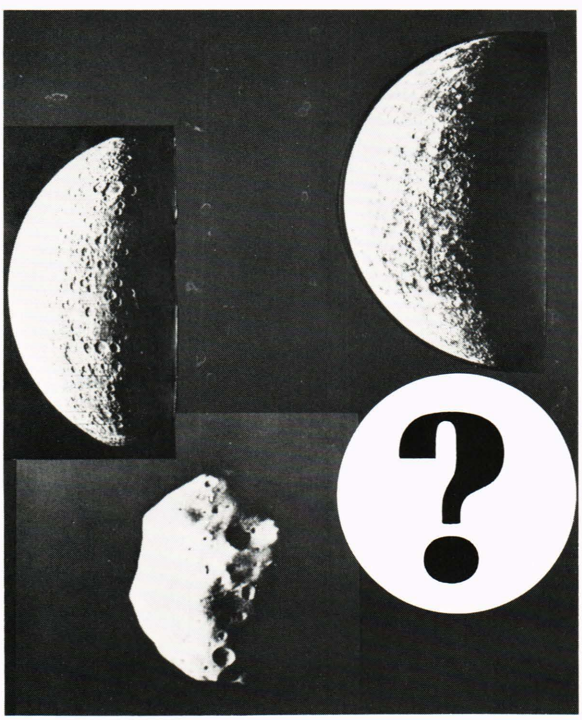


**Fig. 4— Photographs of Phobos, Mercury, and the Moon showing cratering, presumably from planetesimal impact.**

The earth started as a very small body, similar in size to Phobos, the smallest body yet observed. We see that Phobos has a number of craters produced by impacting planetesimals. When Phobos reached its present state it had exhausted all the planetesimals in its surroundings. For the earth, however, that state was only transitory. The rain of planetesimals continued and the earth grew bigger and bigger. By looking at the moon we get a snapshot of the earth when it had accreted 1% of its present mass. Mercury and Mars show later phases of the earth's childhood when its mass was 4% and 10% of the present mass. From these photographs we conclude that the early history of the earth was rather monotonous, consisting of a perpetual rain of planetesimals. We further conclude that when a body reaches the size of Mars it begins to retain or accrete an atmosphere; the craters at its surface are weathered and are modified by other geological effects. Such effects become more pronounced when the body grows; when it reaches the size of the earth or Venus, geological evolution has obliterated most of the surface evidence of its planetesimal accretion.

**Reconstruction of the Planetesimal State**

From a study of impact craters we can draw some conclusions about the planetesimal state. For example, we can derive the size distribution of the planetesimals. But that information is not enough to give us a very clear picture of what the planetesimal state was like. In order to clarify the picture it is important to observe that the asteroidal region between Mars and Jupiter is presently in a state that essentially must be similar to the planetesimal state out of which the earth and other bodies were formed. Hence we need not make a speculative armchair model of the planetesimal state. We can derive it as an extrapolation of the present state in the asteroidal region.

In the main belt of the asteroidal region there are many small bodies moving in orbits with rather high eccentricities (up to 0.30 to 0.35) and inclinations (up to 30° or more). A few thousand have been observed, but their total number is likely to be several orders of magnitude larger. They necessarily collide with each other. There has been a controversy about whether the collisions result in fragmentation or in accretion. The answer no doubt is "both." There are good reasons to believe that the end result will be that most of the matter contained in the asteroidal belt will be concentrated into one or a few bodies. Already the three biggest bodies contain 80% of the total mass. This concentration of mass will continue; the eventual result of the evolution will be the formation of one or perhaps a few planets. In other words, in the asteroid belt we see something like a photograph of the earth at an embryonic stage, before it had accreted.

The main difference between the early planetesimal state of the terrestrial planets and the present one in the asteroidal belt is that the mass density in the former was $10^4$ to $10^5$ times larger, with the result that the earth was accreted relatively rapidly, perhaps in 10 million to a few hundred million years, whereas a similar evolution in the asteroidal belt would take $10^{11}$ years or more.

The picture of the planetesimal state we get in this way is drastically different from the Laplacian disc. The planetesimals actually move in highly eccentric and inclined orbits, not in the circular orbits of a Laplacian disc (which a recent myth even claims to be an extremely thin Saturnian-like sheet of grains). These differences are essential for understanding the accretion of planets and satellites. They are equally essential for our next step backward in time—the reconstruction of how planetesimals accreted from grains that were formed in a plasma or captured by it.

### The Plasma Phase

One of the central problems in all attempts to reconstruct the origin of the planetesimal state is how the grains were put in orbit. This must have resulted from a transfer of angular momentum from a spinning central body—the sun or a planet—to the surrounding planetesimals. As there is no known mechanism for the transfer of momentum to a solid body, it is likely that the transfer took place when the matter was in a dispersed state, i.e., when it formed a plasma, more specifically a dusty plasma containing a large number of dust grains. If we speculate about what may have produced this transfer, we find that a likely mechanism is a hydromagnetic transfer by means of electric currents flowing in the way depicted in Fig. 5.

This is a nice model; we can demonstrate that it produces the effect needed to understand how

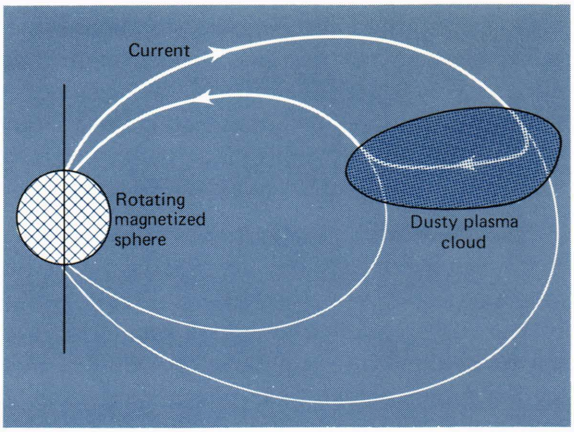


**Fig. 5—Transfer of angular momentum.**

the matter that the secondary bodies now consist of was once put in orbit. However, the model is speculative. Do we have any evidence that processes of this kind really occur in space? Only a few years ago the answer would have been "no." Today it is "yes." The change in the situation is largely due to work by Armstrong at the University of Kansas and by Zmuda and his colleagues at the Applied Physics Laboratory of The Johns Hopkins University. They measured the so-called Birkeland currents flowing along the magnetic field lines to the auroral zone and found that there are sheet currents flowing in opposite directions (Fig. 6). From this it follows that the current system observed in the magnetosphere actually transfers angular momentum from the earth to a surrounding plasma. Hence, the mechanism needed to understand how natural satellites were put in orbit is no longer founded on armchair speculations but on actual observations from spacecraft.

### The Free-Wheeling Plasma

Hence we see that under present conditions a mechanism exists that transfers angular momentum from a central body to a surrounding plasma. From a purely hydromagnetic point of view we expect such a process to continue until the angular velocity of the plasma is the same as that of a central body, a state called "Ferraro corotation." However, we know today that such a state is not necessarily reached, because other spacecraft observations have demonstrated that the Birkeland currents that tend to establish Ferraro corotation are producing field-aligned electric fields and electrostatic double layers that decouple the plasma from the ionosphere. Thus only a partial corota-

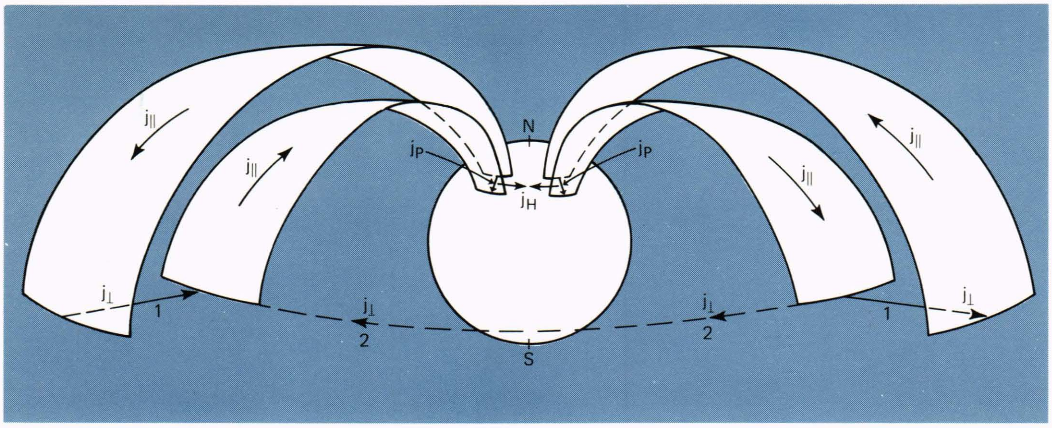


**Fig. 6—Zmuda-Armstrong current system. Large-scale Birkeland sheet currents $J_{||}$ flowing along the magnetic field lines are shown schematically for a dipole field geometry, along with alternative closure paths 1 and 2 and corresponding sheet currents $J_\perp$ for the lower latitudes, and sheet currents $J_P$ and $J_H$ for the auroral latitudes.**

tion is attained. This means that when a certain quantity of angular momentum is transferred, the surrounding plasma becomes essentially free-wheeling (Fig. 7).

In a free-wheeling plasma an equilibrium is established between the main forces—gravitational, centrifugal, and electromagnetic—acting on the plasma. Figure 8 shows that they balance each other in such a way that the plasma is supported against gravitation partly by centrifugal force and partly by hydromagnetic forces. An elementary calculation shows that the kinetic energy of the free-wheeling plasma is two thirds of the kinetic energy of a body in Keplerian motion. (The factor "⅔" derives from the geometry of a dipole field.)

What will happen to grains produced by condensation or captured in such a free-wheeling plasma? We find that when the grains are large enough to move independently of the magnetic field, they will form bodies orbiting in Keplerian ellipses with eccentricity $e = 1/3$ (again a factor deriving from the geometry of a dipole field). If a number of such bodies are produced in the same region of space they will interact by collisions, for example, with the result that both e and i will diminish. The end result of this process is that the condensed bodies will move in circular orbits at two thirds of the distance from where the free-wheeling plasma condensed.

Hence we find the important laws of transition from a state of free-wheeling plasma to a state of Keplerian motion:

1. The first result is solid bodies orbiting with $e = 1/3$;
2. The end result is less eccentric orbits; and
3. There is a general contraction by a factor of two thirds.

We have started from the conditions in the magnetosphere of today and made a fairly straightforward extrapolation to a cosmogonic plasma, which has a much higher density, so that we can expect a condensation to take place. As with all extrapolations this one is necessarily dangerous; unfortunately we cannot check the results by the study of present-day processes because no similar condensation can be expected to occur in our solar system under present conditions.

However we can check our results by studying whether the structure of the asteroidal belt, being a present-day representation of the planetesimal state, can be explained by this process. We should

**Fig. 7—Free-wheeling plasma.**

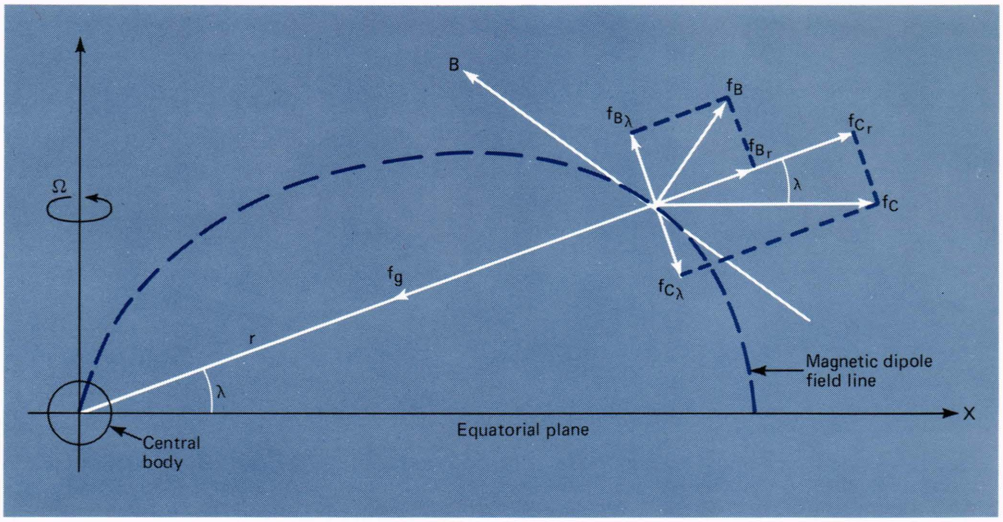


**Fig. 8—Equilibrium of free-wheeling plasma. As shown in the resolved force diagram, equilibrium of the plasma is established by a balance between the gravitational force $f_g$, the centrifugal force $f_C$ due to the angular rotational velocity Ω of the plasma, and the hydromagnetic force $f_B$ produced by the magnetic dipole field B.**

also observe that the Saturnian rings are another example of matter in a dispersed state that should have been generated by condensation from a free-wheeling plasma.

## Dynamics of the Asteroidal Belt

The asteroidal belt is usually represented by an (n,a) diagram (n = number, a = semimajor axis). This gives the impression of a rather chaotic state, the only regular feature being the Kirkwood gaps, a resonance phenomenon produced by Jupiter. However, if we instead plot the cosmogonically more relevant (m,a) diagram (m = mass, calculated under the assumption that the density and albedo are constant) we find that the belt has a much more regular structure, with a sharp cut-off both at the inner and outer edge (Fig. 9). In fact, outside $2.2 < a < 3.5$ there is no appreciable

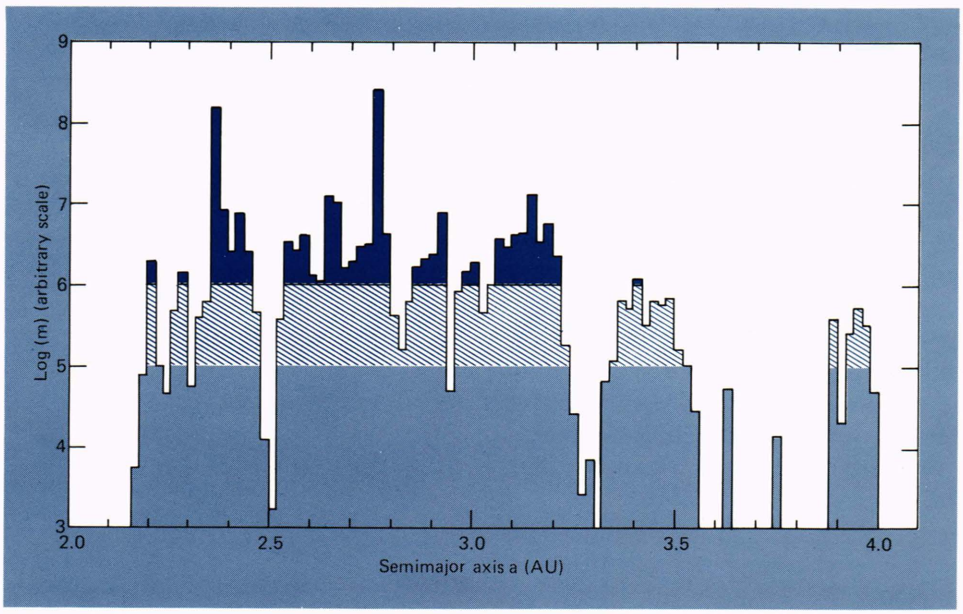


**Fig. 9—Mass distribution in asteroidal belt. One astronomical unit (AU) equals the mean distance from earth to sun ($1.495 \times 10^8$ km).**

mass, except the Hilda group at a = 3.95. This is produced by a resonance with Jupiter that we shall not discuss here.

There is no known effect acting today that can account for the sharp cut-offs of the main belt. Hence there are reasons to suppose that they are of cosmogonic origin. An objection to this is that there are frequent collisions between asteroids and one would suppose that even if the asteroids originally were formed in a well-defined belt, the collisions would cause a diffusion to adjacent parts of space. However, this picture is not correct, because inelastic collisions between bodies in Keplerian orbits will produce a negative diffusion. This means that if the asteroidal belt originally had sharp borders, the diffusion will tend to make mass move away from the borders and concentrate it in those regions where the mass density already is high.

Moreover, statistics show that the largest asteroids (R > 100 km) are so few that for them the chance of a disruptive or orbit-changing collision is very small. In fact, the largest asteroids probably represent a rather unchanged sample of the original condensation.

### The Asteroidal Belt as Derived from a Grain Assemblage in a Free-Wheeling Plasma

With this as a background we can test the hypothesis that the grains subsequently formed are derived from a free-wheeling plasma. The results of a detailed analysis can be summarized in the following way:

1. The eccentricities of the main belt asteroids never exceed e = ⅓. This is what we should expect. Of course, most of the asteroids have lower values of e, which is a natural result of collisions (Fig. 10).
2. Asteroids containing a considerable part of the total mass orbit with inclinations as high as 30°. This is a natural result of condensation if they derive from a free-wheeling plasma, but it is impossible to reconcile with formation from a flat Laplacian disc (Fig. 11).
3. The fall-down ratio of 2:3 explains the outer limit of the asteroidal belt as due to the "shadow" of Jupiter. Because grains condensed outside Jupiter's orbit are perturbed or captured by Jupiter, the asteroidal region derives from a condensation and plasma capture of grains inside Jupiter's orbit. This explains why the belt's outermost limit is almost exactly two thirds the orbital radius of Jupiter.
4. Because the asteroidal belt itself will sweep up plasma, the density will fall at two thirds of the outer limit and become negligible at two thirds of the value of a, where the density has increased sufficiently. This means that the inner limit to the asteroidal belt is given by its own shadow (Fig. 12).

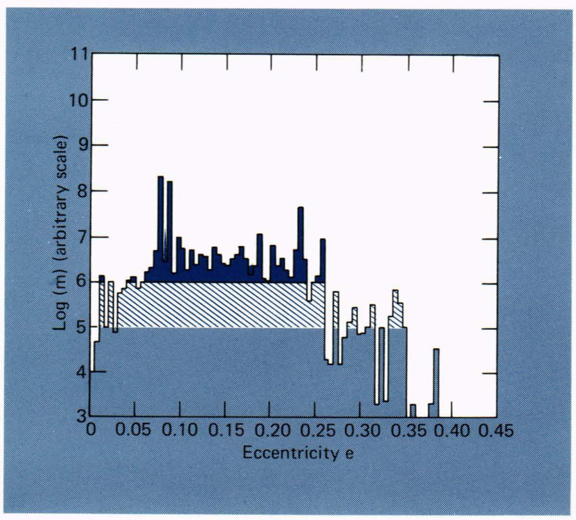


**Fig. 10—Eccentricities of asteroidal orbits.**

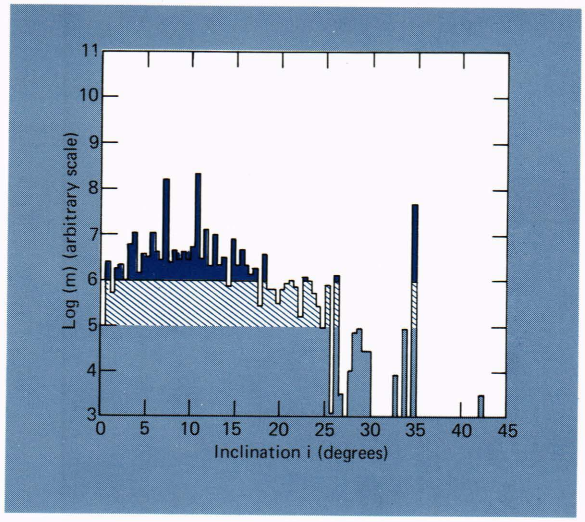


**Fig. 11—Inclinations of asteroidal orbits.**

Hence the dynamical structure of the asteroidal belt supports the view that it has been formed from grains in a free-wheeling plasma. We can also understand how the excess energy associated with high eccentricities and inclinations is dissipated by collisions. This process leads slowly to

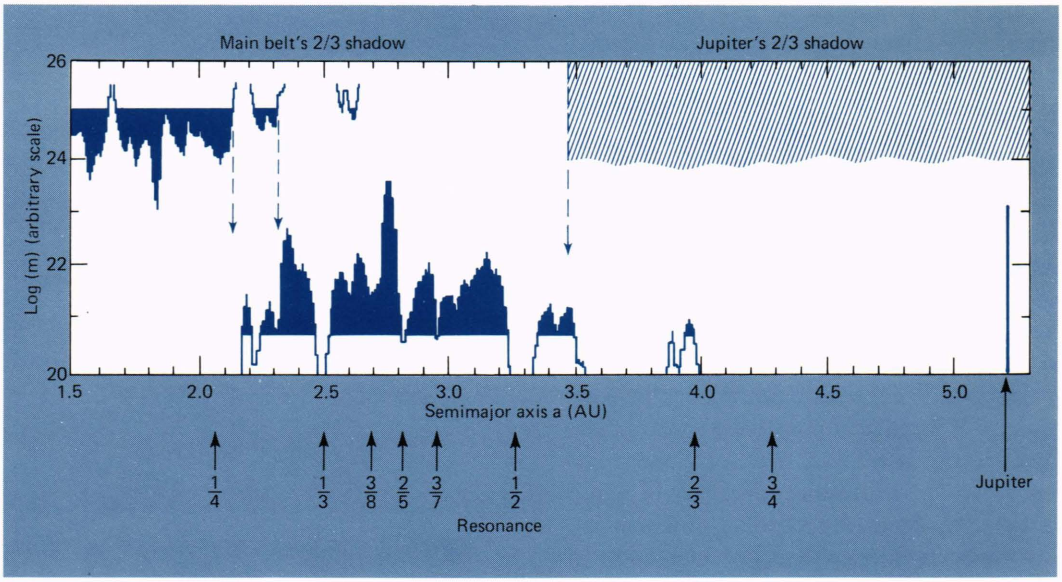


**Fig. 12—"Shadow" effects in the asteroidal region.**

the accretion of all the mass into one or a few planets.

These conclusions are very important. They mean that we can study the basic process of planetesimal accretion under present conditions in the asteroidal belt.

### The Saturnian Rings

The Saturnian ring system gives us a second way to study the condensation from a free-wheeling plasma. In this case the final accretion to planets or satellites is prohibited because the rings are located inside the Roche limit. Hence they still contain information that necessarily is lost at the accretion of large bodies.

The fine structure of the Saturnian ring system (e.g., the Cassini division) has been thought to be due to resonances produced by Mimas. Modern observational data rule out this possibility. Also, a theoretical study demonstrates both qualitatively and quantitatively that the observed structure cannot be explained by resonance effects. On the other hand, as shown by Fig. 13, the structure can be understood in fairly good detail as resulting from condensation from a free-wheeling plasma.

This means that the Saturnian rings should be considered a beautiful time capsule, telling the physicists of today about the state of the plasma from which it condensed some billion years ago.

### The Emplacement of Plasma

There are two more steps in our progress along the negative time axis that should only be mentioned briefly.

One is the problem of how the plasma was emplaced in different regions of the solar system. This will explain the differences between the systems of secondary bodies around the different primary bodies, and also account for the chemical differences between the bodies in the solar system. The key to this seems to be a plasma phenomenon called the "critical velocity" that has been explored extensively both in the laboratory and theoretically.

### Formation of the Sun

In an empirical approach the formation of the sun should be the last problem we discuss. By first studying the formation of planets and the forma-

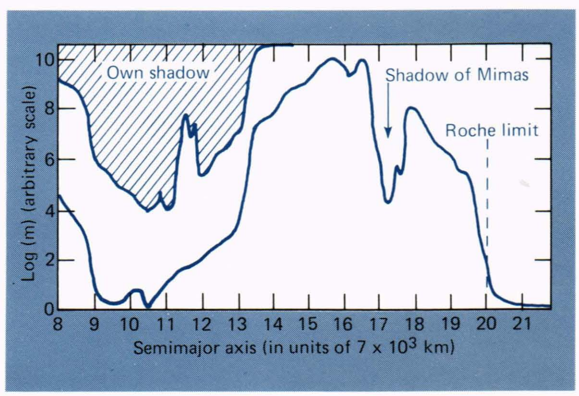


**Fig. 13—"Shadow" effects in the Saturnian ring system.**

tion of satellites around them we have obtained valuable insight into the general character of the formation of secondary bodies around a primary body. This knowledge allows us to define the constraints on theories of star formation. It should be combined with the rapidly increasing observational data about the dark interstellar clouds in which stars probably are formed.

It is premature to draw definite conclusions about the formation of stars. Only one thing can be stated with a high degree of confidence: they were *not* born by what is usually meant by "gravitational collapse."

## Conclusion

In conclusion, it is interesting to observe how unpredictable the evolution of science and technology is. When exploration of the atomic nucleus started at the beginning of this century, it was considered to be pure science without any practical applications. Although its aim was to clarify the *microscopic structure* of our world, the research has led to the nuclear technology that threatens us all with radioactive poisoning and annihilation.

Space research has gone the opposite way. It started as a by-product of a military technology but it is now the main tool for clarifying the *macroscopic structure* of our world. For the first time we have an empirical approach to the fascinating complex of problems that earlier were referred to as the creation.

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