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ORIGIN OF THE SOLAR SYSTEM

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### Abstract

Part I and II. The methodology of the problem of the origin and evolution of the Solar System is analysed and it is pointed out that we can approach it in two different ways.

(1) We can postulate that long ago there was a certain more or less likely-state, and then calculate how this developed into the present state. In principle this approach is "mythological" and it differs from the old myths mainly in the respect that it is formulated in a mathematical way. (2) We can start from the present state and reconstruct increasingly older states. This is what the geologists call the "actualist approach" and is the only one which can claim to be scientific.

Part III. The "Laplacean" type of theories is criticized. There is no indication that there was a "Laplacean" homogeneous disc as an intermediate state, and there is no acceptable mechanism through which the present solar system could be formed from such a disc. The solar system today has a band structure, the planets as well as the satellites all fall in certain bands characterized by certain values of the gravitational potential.

Part IV. The band structure is explained as a result of the ionization of infalling matter when its velocity has reached the "critical velocity" for ionization.

It is shown that the position and the structure of the groups of planets and satellites is completely defined by two parameters:

1. Mass of central body.
2. Spin of central body.

This gives the complete matrix of the groups of bodies.

## ORIGIN OF THE SOLAR SYSTEM

### PART I CREATION MYTHS

#### 1. Old Myths of Creation

Speculation about the origin and evolution of the Earth and the celestial bodies is probably as old as human thinking. During the millenea which is covered by the history of science, philosophy, and religion we can distinguish three types of approach to this problem.

The first one 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 indestructable"--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 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 that he had created the world in the sense of organizing a preexisting chaos, he had created it all from nothing ("ex nihilo") by pronouncing a magic word or by his will power. This is the meaning of "creation" when we speak of it today, but this 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 Saint Thomas synthesis of Christian dogma and Aristotelean 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.



## 2. The 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 this plan. A breakthrough in this thinking came with the Pythagorean philosophy.

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

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 this in terms of simple numerical relations and in terms of logically and mathematically beautiful concepts. They considered the sphere to be the most "perfect" of all bodies and the uniform motion to be the simplest and most beautiful type of motion. Ergo the stars and the planets must be located on crystal spheres which 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. It was not necessary--although certainly possible--to question that the gods had created the world, because the gods no doubt understood the beauty of mathematics. Indeed, no one who studies mathematics can avoid the impression that the theorems have a beauty which 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 cosmologic 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 approach which may be called the mathematical myth developed during the centuries into the Ptolemaic cosmology. It is impressive by its logical reasoning and mathematical beauty. For example, it was demonstrated that there should be seven planets--including the sun and the moon--revolving around the Earth--seven was a holy number--seven days in a week, and seven tones in the scale, etc. Excluding the sun and the 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 etc. which made the system increasingly complicated. This was not diminishing the credibility of the theory--it just demonstrated that the material world is imperfect.

### 3. Empirical Approach

In the sixteenth and seventeenth century the Ptolemaic system broke down, and a new celestial mechanics was introduced. This represents the third type of approach, the empirical approach. This was based especially on the investigations of falling bodies by Galilei and the very accurate astronomical observations by Tycho Brahe. It is generally believed that it was the injection of this new empirical material which was fatal to the Ptolemaic system. This is of course partially true, but there is another factor which seems to have been at least equally important. A prerequisite for the breakthrough of the new approach was the collapse of the peer review system, which up to this time had been powerful enough to prevent the rise of new ideas. When Galilei claimed that the Earth moved, his peers in Italy reviewed these ideas and almost unanimously agreed that they were wrong, and 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 them 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 which for centuries had preserved the dark ages in Europe.

#### 4. The Triumph of Science

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

#### 5. Modern Myths

If we read a daily newspaper what do we find? There is normally a column devoted to an analysis of how the planets influence our life. But it is not the planets which the astronomers observe, those which are the targets of space research, it is the planets of the old Greek-Roman mythology. 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 as they once ruled the voyage of Odysseus. The theocratical myths of 2,000 years ago flourish today more than ever.

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

## 6. 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 that the answer is yes.

Although it is always dangerous to compare different cultures and different epoques, I think that there is an analogy between the special theory of relativity and the early Pythagorean results. In both cases a simple and beautiful reasoning led to an important breakthrough. In both cases the success 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. In his fascinating book The Philosophy of Physical Science he claims that sitting in his arm-chair 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 of which some no doubt are attractive from an esthetic point of view but none from a scientific point of view. One of them, the "big bang" cosmology, is at

present "generally accepted" by the scientific community. This is mainly because it was propagated by Gamov with his irresistible charm and vitality. The observational support for it, which he and others claimed, is totally obliterated but the less there is of scientific support, 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 with a size of much less than the head of a pin. It seems that in the present intellectual climate it is a great asset of the big bang cosmology that it offends common sense: credo quia absurdum (I believe because it is absurd!). When scientists attack the astrological nonsense extra muros it is wise to remember that there is still worse nonsense propagated intra muros.

#### 7. 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" or 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 lecture exclusively to this restricted problem.

#### 8. Modern Astrophysics: Myth or Science?

Like in many other parts of astrophysics, there is today a confrontation between a mythological approach and an empirical approach and like in many other parts of astrophysics it is the mythological approach which 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 this. The formation of the solar system would be found to be a result of, for example, the big bang when all the consequences are drawn from this theory. There are few people who are so bold to try to do 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.

## 9. 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, and 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 both dust and gas and that they contain 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, one of the pioneers in cosmic plasma physics, has devoted much interest to the formation of stars from an interstellar cloud and stressed the importance of hydromagnetic effects for 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 in an erroneous way.

#### 10. The Laplacian Theory

Speculations about the formation of solar systems from interstellar clouds were actually initiated by Laplace. He was inspired by the great interest for the origin of the solar system which resulted from speculations by Descartes, Kant and other leading philosophers and scientists 200-300 years ago. At this time the astronomers had discovered that besides the stars there were also an abundance of small nebular objects in the sky. Laplace understood that many of these consisted of a great multitude of stars--were galaxies with modern terminology--but thought that some of them, and also "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 later the advanced observational technique showed that the disc-like objects which were observed, were not solar systems in formation, the theory lost its observational foundation. But when the observational support for the "nebular theory" disappeared, the theory itself continued to live a life of its own and has over the centuries become a sacrosanct myth.



The Laplacian theory has been supplemented with the theory of gravitational collapse as a mechanism for the formation of stars and solar systems. The history of this concept is the following:

If we consider a gravitating sphere of gas in which the variables (pressure, temperature, etc.) are functions of  $r$  and  $t$  alone, the gas pressure gradient will balance the gravitation 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 gravitation and the pressure gradient will increase, but the latter not enough to compensate the former. The result is a collapse which takes only some thousand years. It is generally believed that stars and solar systems are formed by this process.

A process of this kind has never been observed. From a theoretical point of view it depends critically on the assumption that the variables are functions of only  $r$  and  $t$ . This assumption is introduced only to make the problem mathematically easy to solve, and 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 which make this solution uninteresting from a scientific point of view. This is a typical example of how a mathematical myth originates.

To this is added the assumption that the condensation from the nebula takes place in thermal equilibrium--another assumption of the same character.

The myth which is developed on the basis of the Laplacian mistake supplemented with these three erroneous physical concepts has become sacrosanct, and is the basis of most of the papers of today about the evolution of the solar system. It is defended by a strongly entrenched community, who seldom admits that there exists any objection to their myths. The peer review system will probably give this myth the same eternal life intra muros as astrology enjoys extra muros.

## PART II EMPIRICAL APPROACH

### 1. 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 so important as an analysis of the methodology which is applicable. (Fig. 3)

A realistic attempt to reconstruct the early history of the solar system must necessarily choose a procedure which reduces speculation as much as possible 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 step by step reconstruct increasingly older periods. This "actualistic principle," which emphasizes reliance on observed phenomena, is the basis for the modern approach to the geological evolution of the Earth; "the present is the key to the past." This principle should also be used in the study of the solar system, especially now when NASA is supplying us with most valuable geological specimens from the space missions.

Hence we should proceed by establishing which experimentally verified laws are of controlling significance in the space environment. For this purpose laboratory studies of processes which are likely to be important in space are essential, but applying the results of laboratory investigations to cosmic conditions requires a thorough study of the scaling laws. During the last few years the rapidly increasing information on extra-terrestrial processes that modern space research is providing, has increased the reliability of this method. If the large body of available empirical knowledge is interpreted strictly in terms of these 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 these processes. However, there is often a choice between different partial models, which a priori may appear equally acceptable. Before the correct choice can be made it is necessary to define a framework of boundary conditions which these models must satisfy.

## 2. Planetary System-Satellite Systems

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

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

The theoretical framework we try to construct should, consequently, 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 these processes are essentially analogous. Our analysis supports this postulate as reasonable. Indeed, we find evidence that the formation of the 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 spin. It is also necessary to assume that the central bodies were magnetized, but the strength of the magnetic field does not appear explicitly; it must only surpass a certain limit.

### 3. 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 stages, in part overlapping in time: (Fig. 4)

1. Most recently--during the last four billion years--a slow evolution of the primeval planets, satellites and asteroids which produced the present state of the bodies in the solar system. By studying this latest phase of the evolution (post-accretional 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 Kepler orbits to form planetesimals, which by continuing accretion, grow in size. These planetesimals are 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 Kepler 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. Emplacement of gas and dust to form a medium around the magnetized central bodies in the regions where the planet and satellite groups later accreted.

5. Formation of the sun as the first primary body to accrete from the source cloud of the solar system.

## 2. Extrapolation from Present Day Space Conditions

The next phase in our analysis is to try to find what processes have been active during the different phases of the evolution, or at least to give examples of what type of processes deserve to be closer analyzed. In doing so we must take warning of much of the earlier work which has been so speculative that it has lost contact with reality. In this field as in all other fields of science we can never avoid speculations, but when speculating we must all the time keep close contact with reality. If we forget this we will at the best substitute an old myth by a new one--and this is what necessarily must be avoided.

First of all we should 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 were working. Solid bodies, including grains, moved at that time in Kepler orbits similar to the present ones, although viscosity effects and mutual collisions between the grains introduced perturbations. Space contained a plasma the parameters of which certainly differed from the present parameters but the differences were not so drastic. 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 present 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 latter no doubt was much denser. But we have enough knowledge of the behavior of dense

plasmas from studies of the ionosphere, the solar corona, chromosphere, and photosphere to be able to make reasonable extrapolations. By choosing such an approach we can to a large extent avoid the introduction of black-board mechanisms, which are pests in modern astrophysics.

## 5. The Latest Period

According to these principles we may try to reconstruct the early history of the planets-satellites in the following way:

We have good reasons to believe 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 orbits 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.

## 6. How the Earth Accreted from Planetesimals

Radioactive dating has demonstrated that this long and stable period was preceded by a period--perhaps some ten or a hundred million years long--



during which the solar system was formed. The matter which 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 Kepler orbits around the sun, but collided mutually, with the end result that they accreted to the present celestial bodies. The craters we see on the moon and other bodies bear witness of the rain of planetesimals, which 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 with respect to cratering that we may conclude that all of these rocky bodies have developed in a similar way, and in some respects just represent different phases of an evolution. This makes it possible to reconstruct the history of the Earth. (Fig. 5)

The Earth must have passed through a stage as a very small body, similar in size to--say--Phobos, the smallest body yet observed. We see that Phobos has a number of craters which after all have been produced by impacting planetesimals. When Phobos reached its present state it had exhausted all the planetesimals in its surroundings. For the Earth, however, this 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 one percent of its present mass. Mercury and Mars show later phases of its 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 also modified by other geological effects. Such effects become more pronounced when the body grows and when it reaches the size of the Earth or Venus the geological evolution has obliterated most of the surface evidence of its planetesimal accretion.

## 7. Reconstruction of the Planetesimal State

From a study of the impact craters we can draw some conclusions about the planetesimal state. For example, we can derive the size distribution among the planetesimals. But this information is not enough to give us a very clear picture of what the planetesimal state was like. In order to clarify this it is important to observe that in the asteroidal region between Mars and Jupiter we have at present a state which in essential respects must be similar to the planetesimal state out of which, for example, the Earth was formed. Hence we need not make a speculative arm-chair 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 is a large number of small bodies moving in orbits with rather high eccentricities (up to 0.30-0.35) and inclinations (up to  $30^{\circ}$  or more). A few thousand of these

have been observed, but their total number is likely to be some orders of magnitude larger. They necessarily collide with each other. There has been a controversy whether these 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 at the present state the three biggest bodies contain 80% of the total mass. This concentration of mass will continue, and 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 in the region of the terrestrial planets and the present one in the asteroidal belt is that the mass density in the former was a ten or hundred thousand times larger, with the result that the Earth was accreted relatively rapidly--perhaps in 10 or a few 100 million years--whereas the similar evolution in the asteroidal belt will 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 and 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 the understanding of

the accretion of planets and satellites. They are equally essential for our next step backwards in time--the reconstruction of how planetesimals accreted from grains which were formed in a plasma or captured by it.

## 8. 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 been associated with 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 has taken place when the matter was in a dispersed state; i. e., formed a plasma, more specifically a dusty plasma containing a large amount of dust grains. If we speculate about what mechanisms may have produced this transfer, we find that a likely mechanism is a hydromagnetic transfer by the means of electric currents flowing in the way as depicted in Fig. 6.

This is a nice model and we can demonstrate that it produces the effect which is necessary in order to understand how the matter which the secondary bodies now consists of once was put in orbit. However, the model is of a speculative character. 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, and the change in the

situation is largely due to work by Zmuda, Armstrong, and their colleagues at the Johns Hopkins University. They have 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. 7) From this follows that the current system observed in the magnetosphere actually transfers angular momentum from the earth to a surrounding plasma. Hence the mechanism which is necessary in order to understand how natural satellites were put in orbit is no longer founded on armchair speculations but from actual observations from spacecrafts.

#### 9. The Free-Wheeling Plasma

Hence we see that under present conditions there exists a plasma mechanism which 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 which tend to establish this are producing field-aligned electric fields and electrostatic double layers which decouple the plasma from the ionosphere. In this way only a partial corotation is attained. This means that when a certain quantity of angular momentum is transferred the surrounding plasma becomes essentially free-wheeling.

In a free-wheeling plasma an equilibrium is established between the main forces, acting on the plasma, viz, gravitation, centrifugal force, and the electromagnetic forces. Fig. 8 shows that these balance each other in such a way that the plasma is supported against gravitation partially by the centrifugal force and partially by hydromagnetic forces. As an elementary calculation shows the kinetic energy of the free-wheeling plasma is  $2/3$  of the kinetic energy of a body in Kepler motion. The factor  $2/3$  derives from the geometry of a dipole field.

What will happen to grains produced by condensation or capture in such a free-wheeling plasma? We find that when the grains are large enough to move independently of the magnetic field, these will form bodies orbiting in Kepler 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, for example, by collisions, 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  $2/3$  of the distance 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 Kepler motion:

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

We have started from the conditions in the magnetosphere of today and made a fairly straight-forward extrapolation to a cosmogonic plasma, which has a much higher density so that we can expect a condensation to take place. As all extrapolations this is necessarily dangerous, and 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 also observe that in the Saturnian rings we have another example of matter in a dispersed state which should have been generated by condensation from a freewheeling plasma.

## 10. Dynamics of the Asteroidal Belt

The asteroidal belt is usually represented by the  $(n, a)$  diagram ( $n$  = number,  $a$  = semi-major axis). This gives the impression of a rather chaotic state, the only regular feature being the Kirkwood gaps which are 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 mass, except the Hilda group at  $a = 3.95$ . This is produced by a resonance with Jupiter, which we shall not discuss here.

There is no known process acting today which 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 so that they spread to adjacent parts of space. However, this picture is not correct, because inelastic collisions between bodies in Kepler 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 the mass in those regions where the mass density already is high.



Moreover, the largest asteroids ( $R > 100$  km) are so few that for them the chance for a disruptive or orbit-changing collision is statistically not very large. In fact, the largest asteroids probably represent a sample of the original condensed material, rather unaffected by planetary differentiation, and modified mainly by the sequence of collisions that they have undergone during accretion.

11. The Asteroidal Belt as Derived from a Grain Assemblage in a Freewheeling Plasma

With this as a background we can test the hypothesis that the primordial grains are derived from, or captured by, a freewheeling plasma. The results of a detailed analysis can be summarized in the following way:

1. The eccentricities of the main belt asteroids never exceed  $e = 1/3$ . This is what we should expect. Of course most of the asteroids have lower  $e$ -value, 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  $30^\circ$ . This is a natural result of a condensation if they derive from a freewheeling plasma, but it is impossible to reconcile with a 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. This explains why its outermost limit is almost exactly  $2/3$  the orbital radius of Jupiter.

4. Because the material in the asteroidal belt itself will sweep up plasma, the density will fall at  $2/3$  of the outer limit, and become negligible at  $2/3$  of the  $a$ -value, where the density has increased sufficiently. This means that the inner limit to the asteroidal belt is given by its "own shadow". See Fig. 12.

Hence the dynamic 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 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.

## 12. The Saturnian Rings

The Saturnian ring system gives us a second possibility 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 which necessarily is lost at the accretion of large bodies.

The fine structure of the Saturnian ring system, for example 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 rather much in detail as a result of condensation from a free-wheeling plasma.

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

### 13. The Emplacement of Plasma

There are two more steps in our progress along the negative time-axis, which should only be mentioned briefly here.

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" which has been explored extensively in the laboratory and theoretically.

#### 14. 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 formation of satellites around them we have got a valuable insight in 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. This information 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 very 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 a "gravitational collapse"

## 15. Concluding Remarks

As a concluding remark it is interesting to observe how unpredictable the evolution of science and technology is. When in the beginning of this century exploration of the atomic nucleus started, this was considered to be pure science without any practical applications. Its aim was to clarify the microscopic structure of our world. This research has now led to the nuclear technology which 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 which earlier have been referred to as the creation.

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### Captions

- Fig. 1 Relation between regular polyhedra and planets
- Fig. 2 Herschel's nebulae, interpreted by Laplace as solar systems in formation
- Fig. 3 Methodology of empirical approach
- Fig. 4 Diagram of the evolution of the solar system
- Fig. 5 Photographs of Phobos, Moon, and Mercury showing cratering presumably from planetesimal impact. It is highly desirable to obtain similar photographs from asteroids
- Fig. 6 Transfer of angular momentum
- Fig. 7 Zmuda-Armstrong current system
- Fig. 8 Equilibrium of free wheeling plasma
- Fig. 9 Mass distribution in asteroidal belt
- Fig. 10 Eccentricities of asteroidal orbits
- Fig. 11 Inclinations of asteroidal orbits
- Fig. 12 "Shadow" effects in the asteroidal region
- Fig. 13 "Shadow" effects in the Saturnian ring system



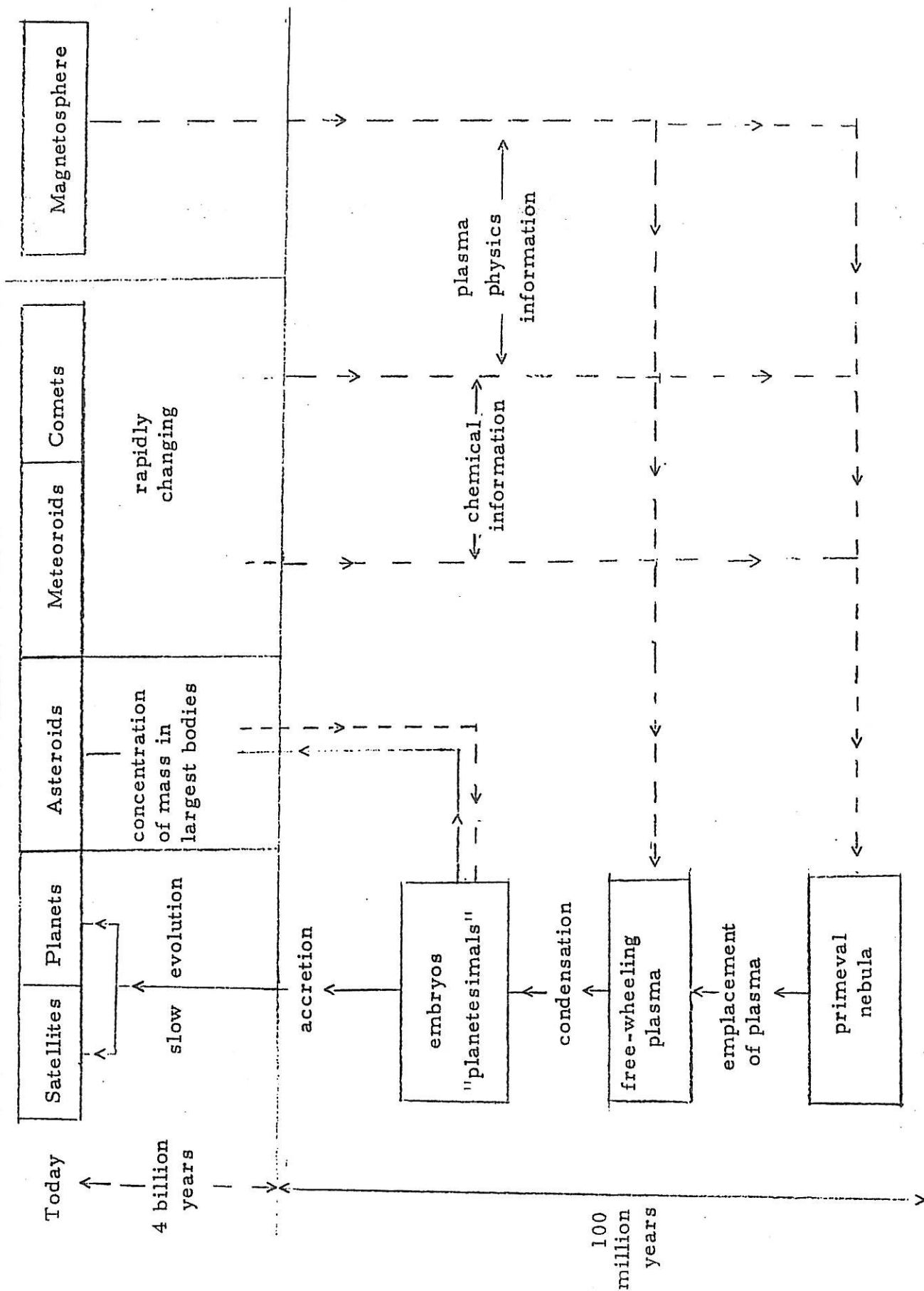
## Origin of the Solar System

### General Principles

1. Reduce speculation as far as possible by relating all processes to laboratory experiments or space observations.
2. Approach the problem not by making more or less arbitrary assumptions about the primitive sun but by starting from 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. This theory should be applicable both to the formation of satellites and the formation of planets.
4. The aim is not primarily detailed theories but more a general framework into which the rich empirical material could be fitted. This framework must be acceptable from the point of view of celestial mechanics, plasma physics, plasma chemistry, geology, theory of hyper-sonic collisions, etc.

Fig. 3





EVOLUTION OF THE SOLAR SYSTEM

— Evolutionary paths  
 - - - Flow of knowledge

Fig. 4.

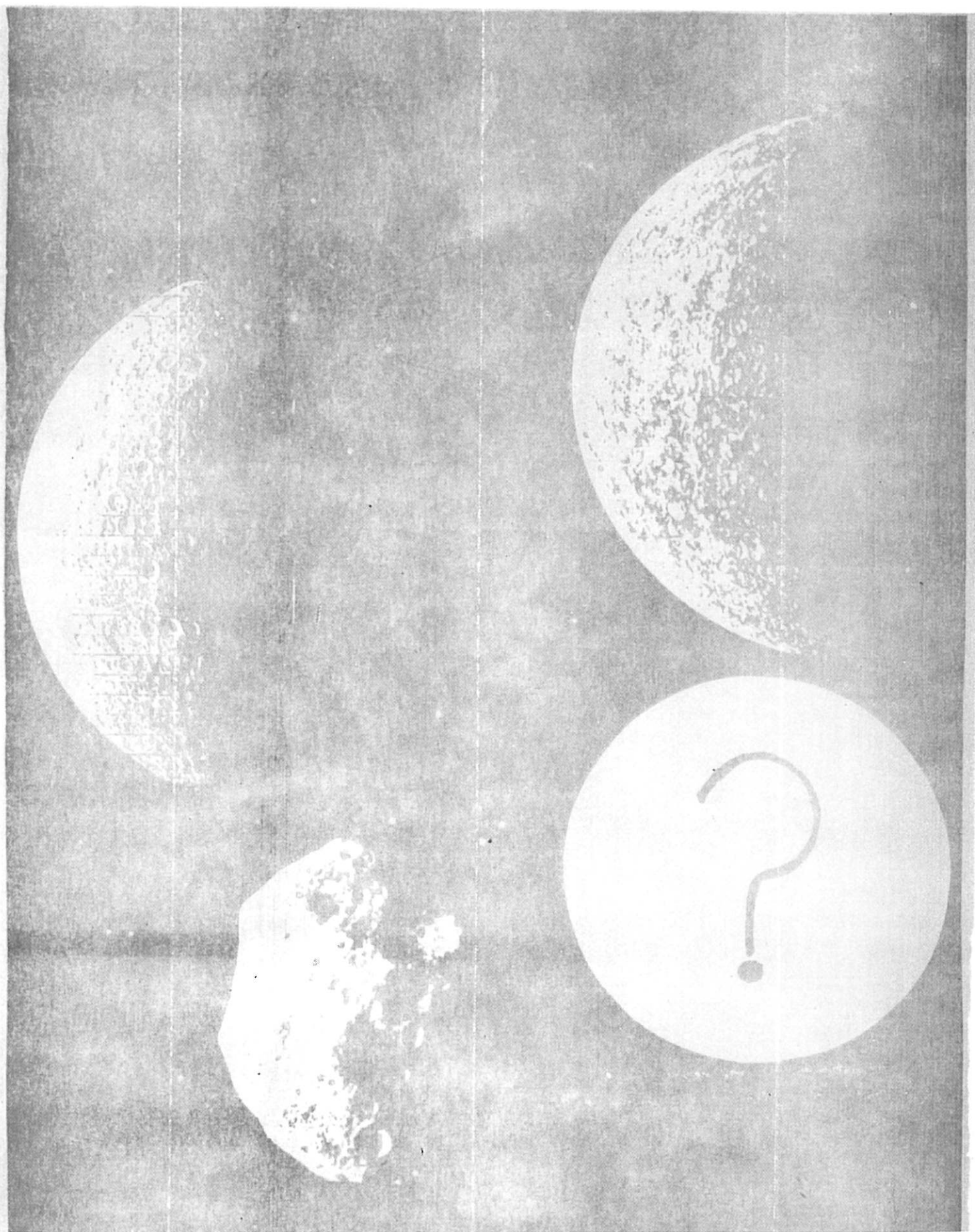


Fig. 5

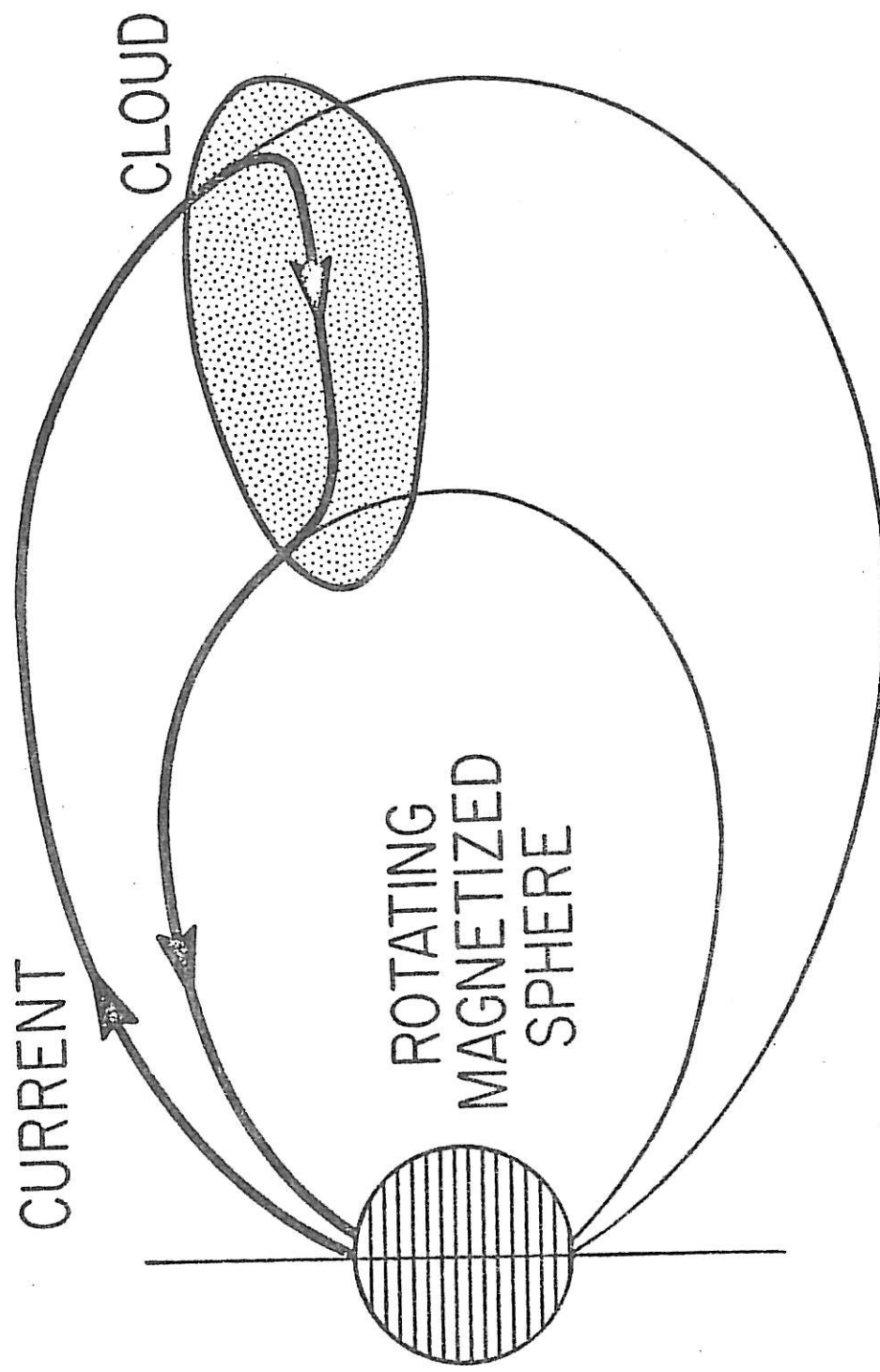
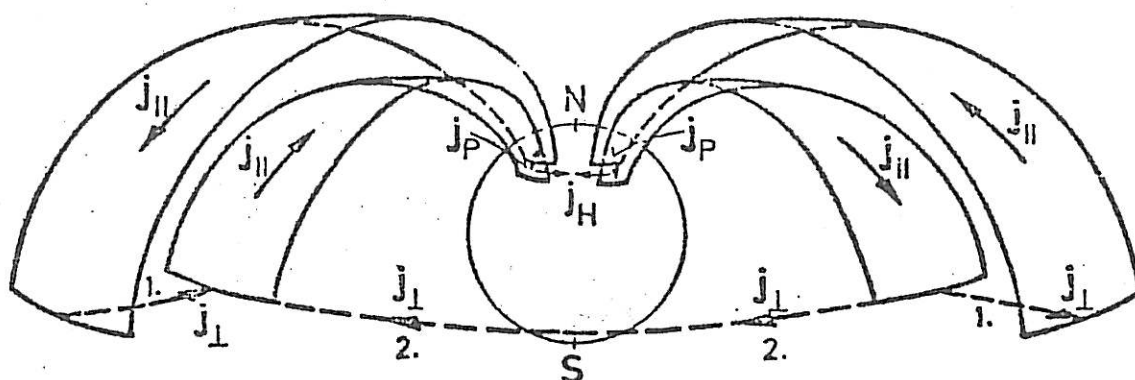


Fig. 6



Large-scale Birkeland current sheets shown schematically for a dipolar field geometry with alternative closure paths for the lower latitude sheet currents

Fig. 7

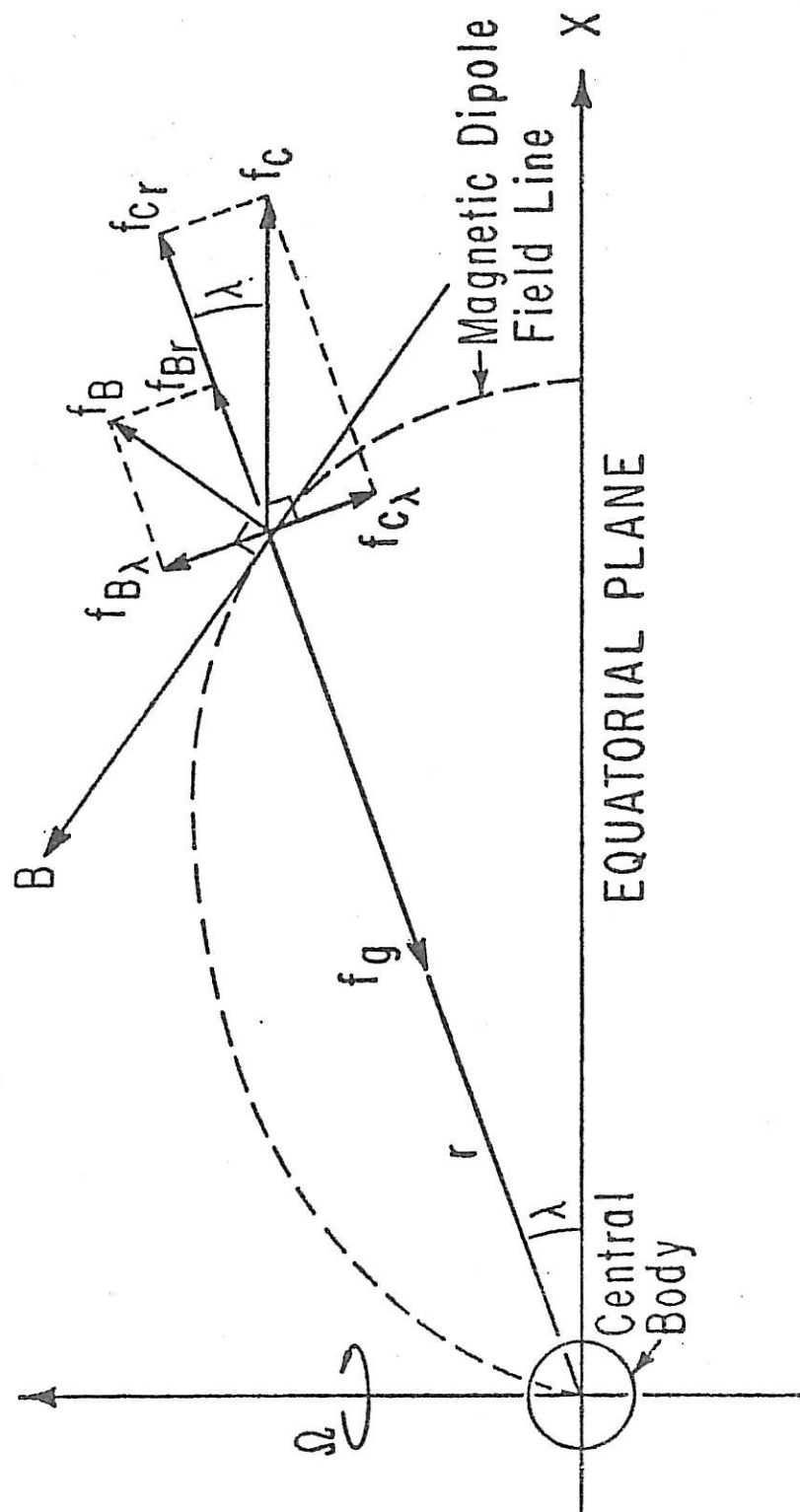


Fig. 8

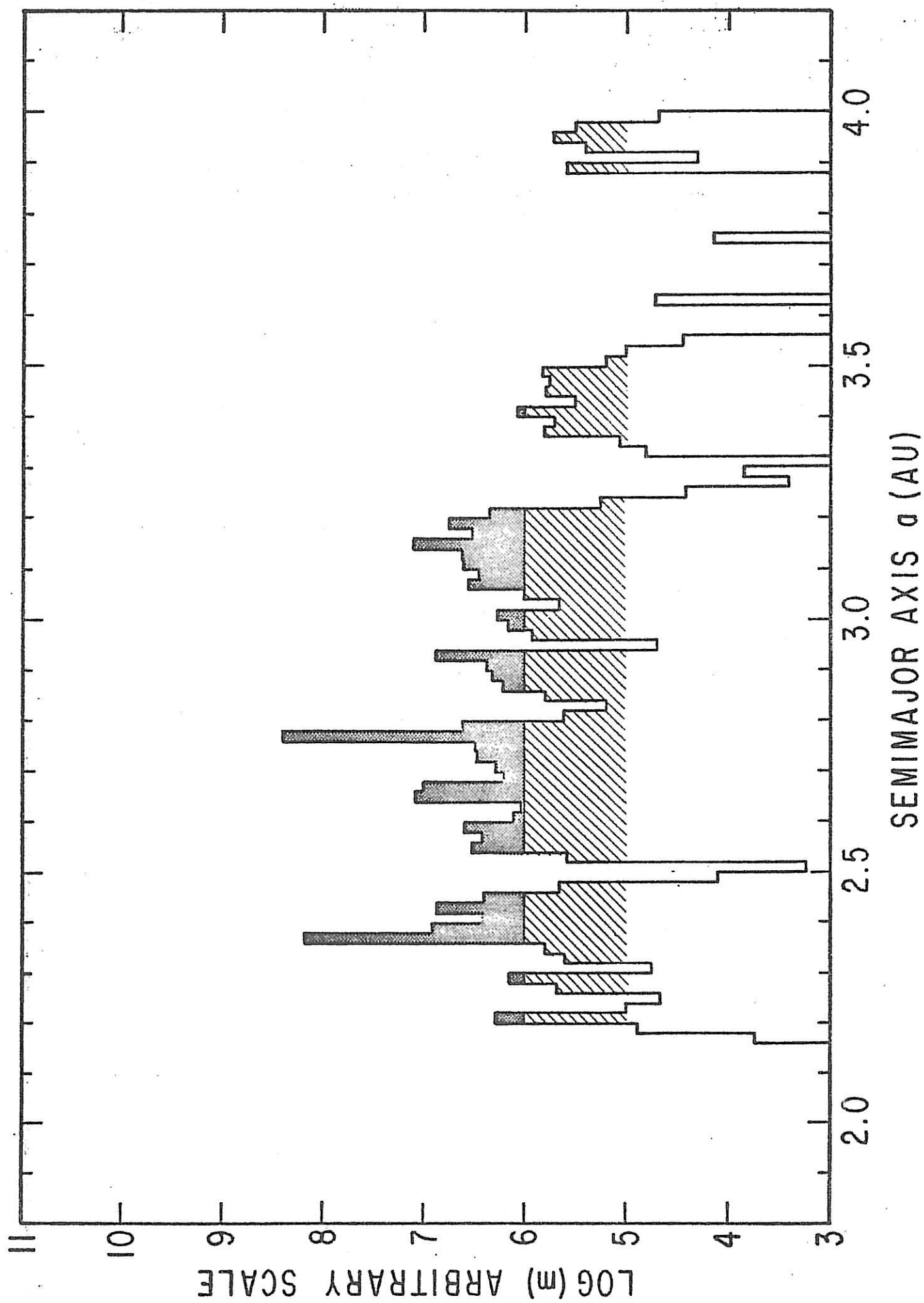


Fig. 9

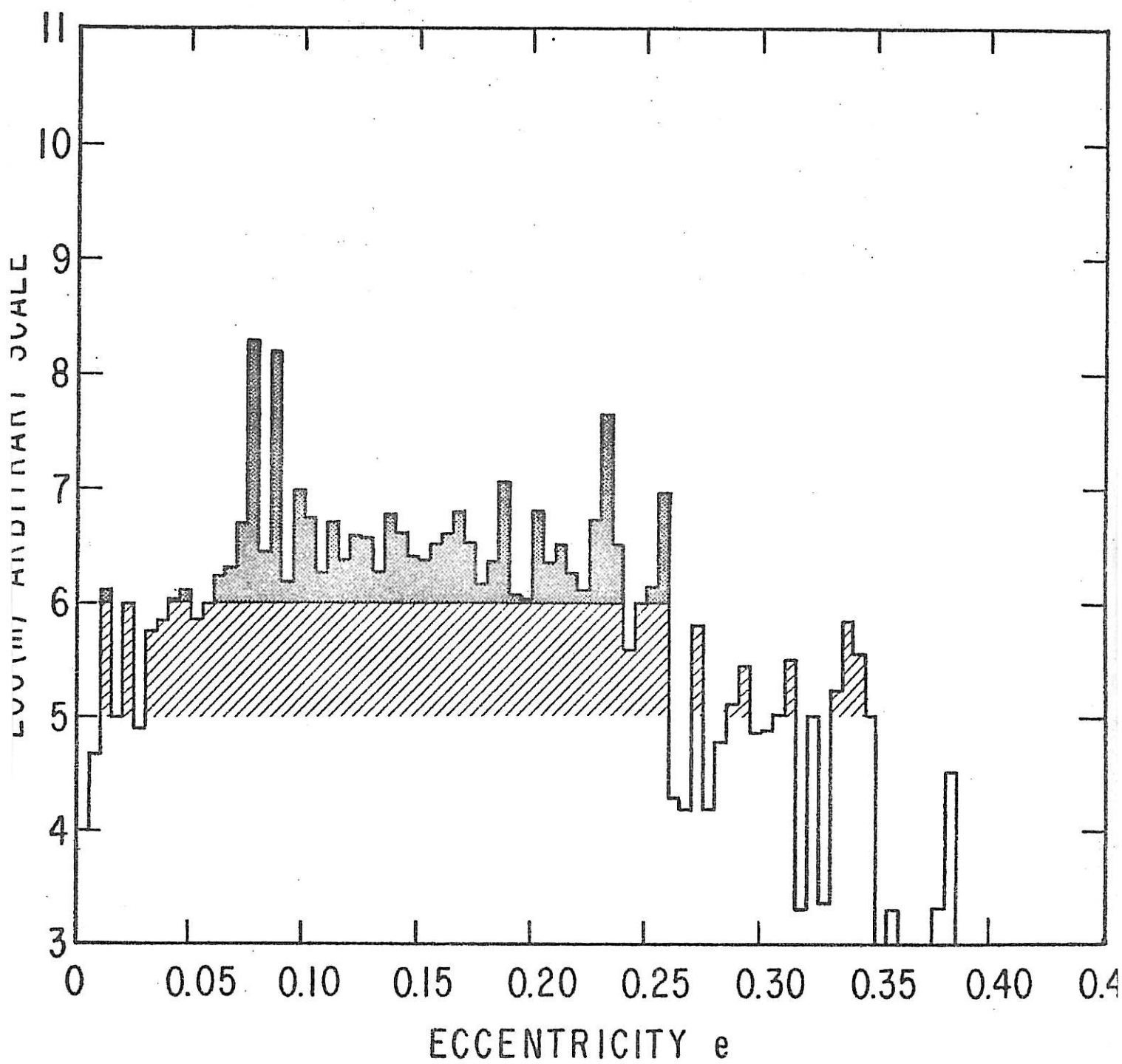


Fig. 10

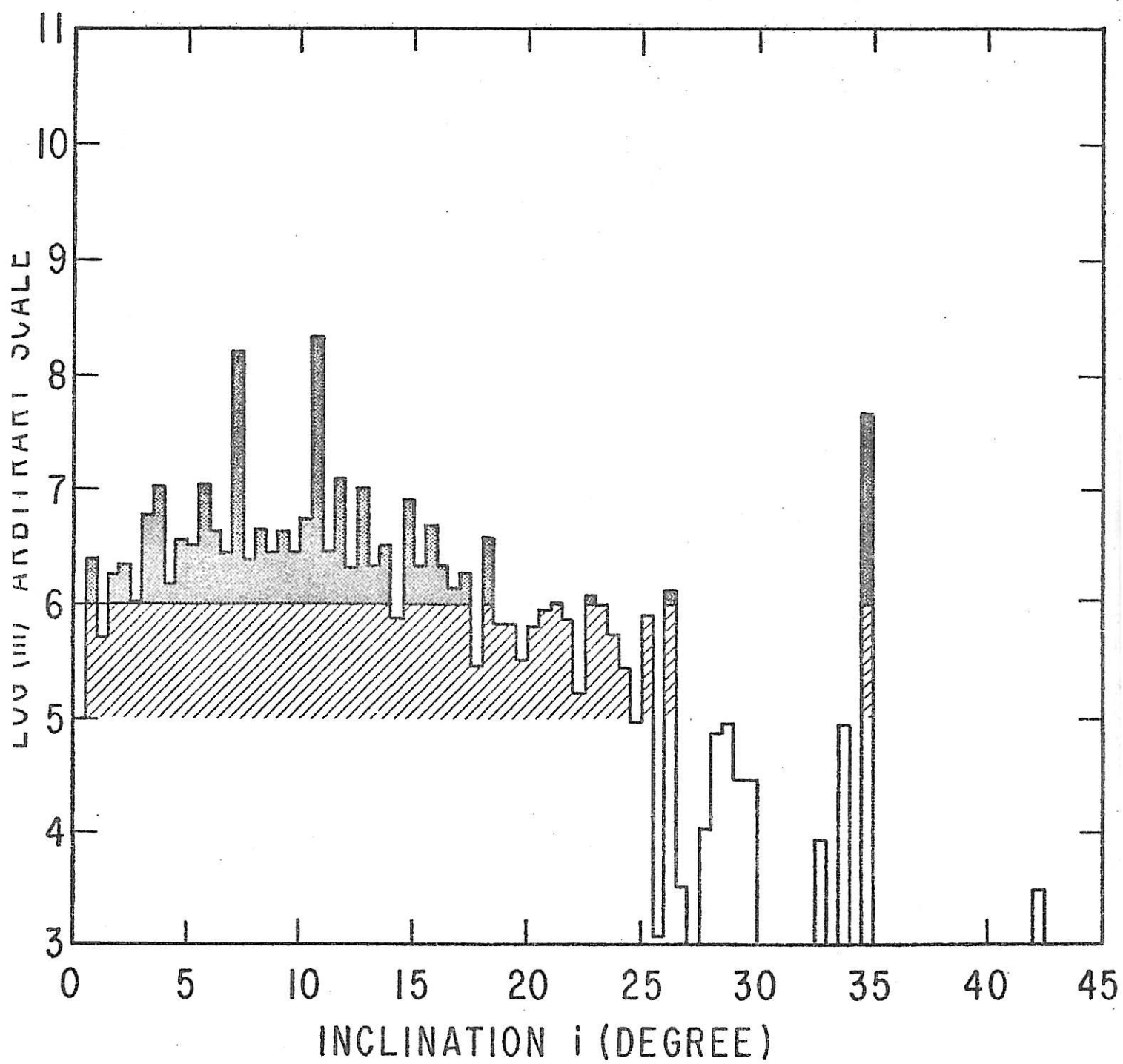


Fig. 11



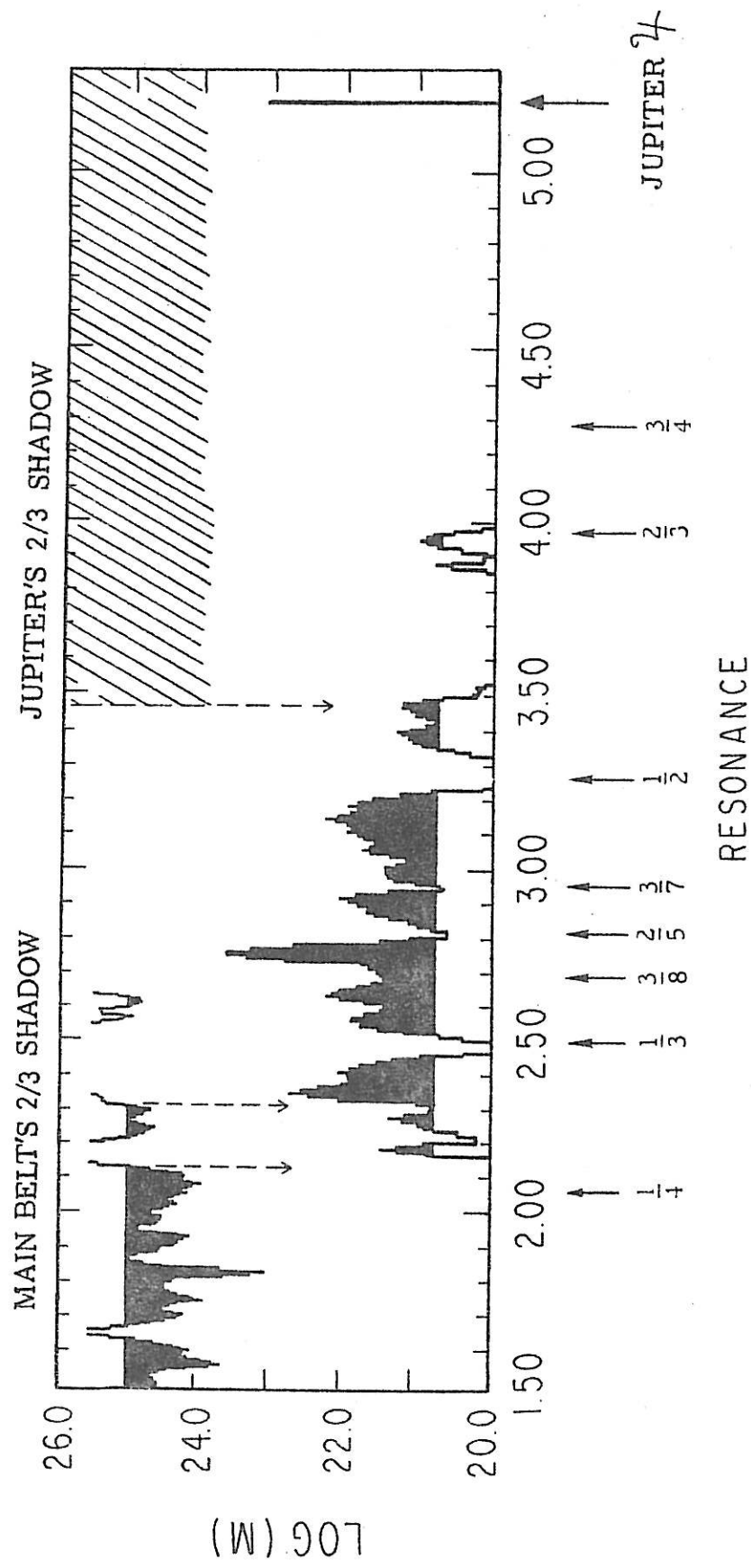


FIGURE 12

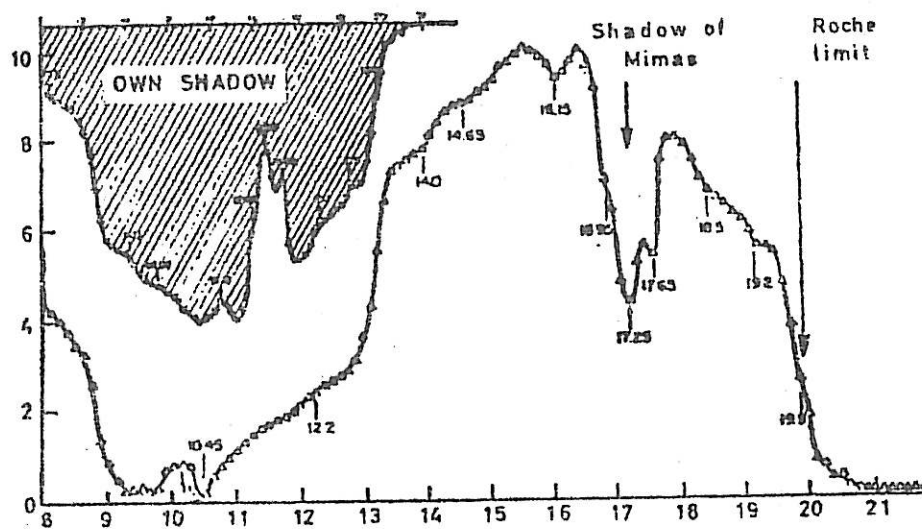


Fig. 13

### PART III      CRITICISM OF "LAPLACIAN" THEORIES

#### 1. Laplacian type theory as a two-step process

Laplace interpreted Herschel's observations of what we now know to be galaxies as solar systems in formation. Hence he concluded that in an early phase a forming solar system should be a rather uniform gaseous disc. When it became obvious that the objects Herschel observed had nothing to do with the formation of the solar system, it would have been logical to take a fresh look at the problem, and, among other things, question whether a cosmogonic theory should aim at the formation of a uniform disc. Instead a school of thought was developed in which the belief in a uniform disc became sacrosanct. Hence the "Laplacian models" assume a two-step process: 1) The evolution of an interstellar cloud into a uniform disc. 2) The evolution of this disc into the present structure, which differs drastically from uniformity.

#### 2. Formation of a uniform disc

Centuries of research have clearly demonstrated that it is impossible to find physically reasonable processes by which an interstellar cloud develops into a more or less uniform disc. This seems how to be generally recognized by all who work out theories in a scientifically stringent way. The result is that the Laplacian<sup>x)</sup> approach is nowadays exclusively advocated by people who substitute an empirically based analysis by purely hypothetical calculations.

The Laplacian school also violates the scientific tradition that objections to a theory must be taken up to discussion. The difficulties about the angular momentum distribution have never been solved, only swept under the rug. The obvious fact that the planetary system as well as the satellite systems have a pronounced banded structure and hence is

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x) Of course the criticism of the Laplacian school is not criticism of Laplace. Being a first class scientist he would no doubt have retracted his theory had he lived when it became obvious that his interpretation of Herschel's observations were not correct.

very far from a uniform disc (Alfvén 1943, 1954) has never been mentioned. The break-through of magneto-hydrodynamics around 1950 had only a transient effect on the Laplacian tradition (Hoyle's theory, which because of a neglect of the already well-known kink instability led to obviously erroneous results) and it has now retreated to the pre-hydromagnetic era (Cameron 1976, Safranov 1972, Goldreich and Ward 1973). The motivation given for the neglect of plasma effects is that the ionisation due to cosmic rays and radioactivity in a dark cloud is not enough to give an appreciable conductivity. This is irrelevant because a main cause of ionisation in cosmic physics is the transfer of kinetic energy to electromagnetic energy. For example, the ionisation in interplanetary space, solar corona and chromosphere derives ultimately from the kinetic energy in photospheric convection, which supplies the energy for the heating of the corona, etc.

It is difficult to see how similar phenomena can be avoided at the contraction of an interstellar cloud which even representatives of the Laplacian approach now admit to be ionised. The contraction must be opposed by electromagnetic effects, as pointed out especially by Spitzer (1968). This leads necessarily to a conversion of kinetic (ultimately gravitational) energy into electromagnetic energy, so that the contraction results in an increase in magnetic energy. Magnetic fields are necessarily associated with electric currents (except in the special case of curl-free fields which is not of interest here).

In principle magnetic energy may be dissipated either by accelerating a large number of electrons only to very low velocities, so that they produce heat but no ionisation, or by accelerating a smaller number of electrons to so high energies that they also ionise. It is doubtful whether the first process is very important in cosmic physics.. One of the reasons is that currents normally are contracted to thin filaments, either by pinch effect or by other mechanisms (example: auroral rays).

As an example how a cosmic plasma gets ionised we can take the ionospheric-magnetospheric plasma in the auroral zone.

The conductivity in the auroral zone is much higher than in the surrounding, but this excess is not produced by radioactivity, cosmic rays or solar light, the only ionisers the Laplacian school takes account of. Instead it is produced by precipitation of energetic particles which have been accelerated by processes related to the auroral current system, which derives its energy ultimately from the relative motion between the solar wind and the magnetosphere. For example the electric currents may produce electrostatic double sheaths which accelerate particles to some keV. Moreover, electric currents under cosmic conditions seem seldom to be uniform. In most, if not all, cases they flow in thin filaments (due to ion contraction or pinch effect). The result is that when magnetic energy is dissipated a large fraction normally goes into ionisation.

Another example is the solar corona. It is obvious that the energy source of its very high temperature and its ionisation is photospheric convection. How this energy is transferred to the corona is perhaps controversial; it may be through sound waves, hydromagnetic waves or - most likely - through electric currents. But independent of the transfer mechanism the solar corona gives another example of conversion of kinetic energy (in photospheric convection) into ionisation.

There seems not to exist any competent study of the ionisation at the contraction of cosmic clouds. Very large quantities of gravitational energy is released, and a large - possibly the largest - part of it must be converted into magnetic energy because magnetic fields oppose the contraction. From what we know about the behaviour of cosmic plasma it is difficult to avoid the conclusion that a large fraction of the gravitational energy goes into ionisation.

Instead of analyzing this problem in a serious way adherents to the Laplacian approach simply postulate an "expulsion" of magnetic field with essentially no other motivation than that this is necessary in order to allow them to play around with pre-hydrodynamic models.

After the break-through of quantum mechanics people who claim that they can explain atomic structures by classical mechanics are generally considered to carry the burden of

proof that their approach deserves to be taken seriously. Twentyfive years after the break-through of magnetohydrodynamics, those who claim that the dynamics of cosmic clouds can be treated by pre-hydromagnetic formalism have in a similar way the burden of proof.

### 3. Transition from uniform disc to present state

The second step - the transition from the hypothetical Laplacian disc to the present state in the solar system meets also seriously difficulties which can be overcome only by postulating a depressingly large number of often unreasonable ad-hoc assumptions. In order to account for the almost void region between Mars and Jupiter a number of "instabilities" are postulated, bodies which have been formed once are "exploded", and the debris are thrown out by processes, which in some cases are violating well-known laws, in other cases are purely ad-hoc.

A process of the latter type is the hypothesis of a "solar gale" which should sweep out all the left-overs of the postulated processes, including a too high solar angular momentum. This hypothesis is sometimes motivated by a reference to observed outward motion of matter in T Tauri stars. However, what is observed is a Doppler effect of neutral hydrogen indicating that the moving medium is different from the fully ionized solar wind - at velocities of 50-100 km/sec - far below solar wind velocities (Herbig 1976). As the moving medium may be close to the star, the velocity may be below the escape velocity and there is no proof that the matter is ejected to infinity.

Another observational fact which is claimed to support the Laplacian theories is that some stars are surrounded by gas and dust which probably form a disc. However, all cosmogonic theories envisage a disc of matter in some stage of evolution. What distinguishes the Laplacian theories from other is that the disc is supposed to be uniform. There is no observational support for this.

## PART IV THE BAND STRUCTURE OF THE SOLAR SYSTEM

### 1. Band structure diagram

As pointed out already by Laplace (but forgotten by his epigones) the satellite systems of Jupiter, Saturn, and Uranus are so similar to planetary system that they should be treated in a similar way. Such a procedure leads to the diagram of Fig. 1 which shows the gravitational energy of all planets and satellites in relation to the central bodies. It is obvious that the mass distribution in both the planetary and the satellite systems is characterized by a band structure (Alfvén 1943). All planets and all prograde satellites are located in one of three or four horizontal bands. The total mass outside these bands (asteroids and the Martian satellites) is less than  $10^{-6}$  of the total mass.

The band structure implies that there are void (or almost void) regions in the systems. One such region is the asteroidal region where the smeared out density is about  $10^{-5}$  of the density in the adjacent regions.

Other void regions are found in the satellite systems. In the Saturnian system there is a regular sequence of satellites from Rhea inwards, continued by the ring system, indicating a reasonably uniform mass injection into the region from the surface of the planet out to Rhea. In striking contrast to this there is a void region inside Miranda in the Uranian system, and a similar void region between Io and the surface of Jupiter (or the orbit of Amalthea, if this very small body is taken into consideration). The void gap between Rhea and Titan and the sharp outer border of the Galilean satellite group - and also the Uranian group of satellites - are other examples of striking features accounted for by the band structure. All these features are embarrassing to the Laplacian school and hence they are never discussed. Even the remarkable fact that Saturn and Saturn alone has a ring is swept under the rug because it is a confirmation of the band structure but not easily explained with the Laplacian approach.



## 2. Theory of the band structure

Although already at an early state a theoretical explanation of the band structure was suggested fifteen years of experimental and theoretical work has been required in order to understand it. As soon as the "thermonuclear" technique became available a series of plasma experiments were started in Stockholm with the purpose of clarifying the band structure. These lead to the discovery of the "critical velocity", a phenomenon which later independently has been discovered at several other laboratories (see Danielsson 1973, Axnäs 1976, Danielsson and Brenning 1975). The theoretical explanation of the critical velocity has been very difficult and half a dozen different theories have been proposed. Sherman (1972, 1973) has given a survey of the theories, and his own theory further developed by Raadu (1975) seems to give what probably is the final explanation. Hence we now understand reasonably well the behaviour of pure atomic gases. However, the critical velocity of gas mixtures and molecular gases are still not completely understood.

We know by now enough about the relation between plasma experiments in the laboratory and in the cosmos to be able to conclude that the critical velocity should be of importance also in cosmic physics. To some extent this is confirmed by observations of certain lunar phenomena (Manka et al. 1972).

## 3. The complete matrix of planet-satellite groups

The application of the critical velocity phenomenon to the cosmogonic problem leads to the conclusion that the solar system should consist of groups of bodies produced by four clouds of different chemical composition. This is summarized by the matrix of Fig.2. Whenever a cloud falling in towards a central body, which is magnetized, reaches the critical velocity at a sufficiently large distance from the surface of the central body, a group of secondary bodies is formed. The structure of a group of bodies is completely defined by two parameters:

1. The mass of the central body
2. The spin of the central body

Furthermore the central body must have had a magnetic field above a certain limit at the time of the cosmogonic processes.



Groups of secondary bodies are found at all places where we theoretically expect them to be found and have the expected structure (except for two of the uttermost groups which are "irregular"). "Double planets" (planets with abnormally massive satellites) are found in the regions where two bands overlap. This accounts for the Earth-Moon and the Neptune-Triton systems. However, the details of the capture process are far from clear.

At its present state of development the theory gives a framework and defines boundary conditions for a number of models of the cosmogonic processes which are still not worked out in detail. In several cases this cannot be done until space research has supplied us with more empirical data.

As far as one can judge from the present state of development of the theory one may hope to explain the present structure of the solar system as the direct result of an evolution from an interstellar cloud without introducing the unnecessary and drastically misleading intermediate step of formation of a uniform disc.

In contrast to the Laplacian theories there is no obvious need for ad hoc assumptions. The planets and satellites are formed in approximately the present state, and hypothesis about "protoplanets" several times more massive than the present planets are not necessary or rather counter-indicated (by the isochronism of spins). No planet need to be "exploded" no ejection of superfluous bodies need to be postulated, nor is any "solar gale" necessary in order to clean our region of space from the vestiges of the Laplacian disc.

This paper is a summary of a monograph

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Values of  $\tau_{ion}/T$  where  $\tau_{ion}$  is the Kepler period of a body at the ionization distance and  $T$  is the period of axial rotation of the central body

Central body		$\tau_{ion}/T$ for secondary bodies			
$T$ $10^{-5}$ sec		in cloud:			
		B	A	C	D
Sun	21.3	8.5 $\frac{1}{2} - \frac{1}{3}$	28 $\frac{1}{2} - \frac{1}{3}$	520 $\frac{1}{2} - \frac{1}{3}$	5000 $\frac{1}{2}$
Jupiter	0.354	0.50	1.6 Amalthea	29 Galilean satellites	286
Saturn	0.375		0.45	8.4 inner satellites	81 outer satellites
Uranus	0.385			1.3	12 Uranian satellites
Neptune	0.568			1.0	9.5
Earth (prior to capture of the Moon)	0.14 ?				2.2 ?

According to the theory, bodies are produced only in the groups above the line in the table.

Fig. 2

TRITA-EPP-76-08

Royal Institute of Technology, Department of Plasma Physics,  
Stockholm, Sweden

# ORIGIN OF THE SOLAR SYSTEM

H. Alfvén

April 1976, 55 p incl. illus., in English

The methodology of the problem of the origin and evolution of the Solar System is analysed and it is pointed out that we can approach it in two different ways. We can postulate that long ago there was a certain more or less likely-state, and then calculate how this developed into the present state. We can start from the present state and reconstruct increasingly older states.

The "Laplacean" type of theories is criticized. There is no indication that there was a "Laplacean" homogeneous disc as an intermediate state, and there is no acceptable mechanism through which the present solar system could be formed from such a disc. The solar system today has a band structure, the planets as well as the satellites all fall in certain bands characterized by certain values of the gravitational potential.

The band structure is explained as a result of the ionization of infalling matter when its velocity has reached the "critical velocity" for ionization

Key words: Methodology, Origin of the solar system, Critical velocity, Actualist approach, Laplacean theory.