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SPACE RESEARCH AND THE NEW APPROACH
TO THE MECHANICS OF FLUID MEDIA
IN COSMOS

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SPACE RESEARCH AND THE NEW APPROACH TO THE MECHANICS OF FLUID MEDIA IN COSMOS

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Abstract

Space research has increased our knowledge of fluid media in space in two ways.

1. It has made it possible to SEE our cosmic environment not only in visual light and radio waves but also in infrared, ultraviolet, X-rays and gamma rays. The picture we get in these now accessible wavelengths is drastically different from the pre-space-age view.

One of the results is that (at least by volume) our cosmic environment consists to more than 99% of magnetized, often dusty, plasma.

2. In situ measurements in the magnetospheres - including heliosphere - combined with laboratory experiments have given us new information about the properties of cosmic plasmas. This makes it possible to UNDERSTAND what we see. It turns out that a drastic revision of the classical theory of plasmas is necessary.

3. The new results are APPLIED to cosmogony (origin and evolutionary history of the solar system). Magnetospheric physics has matured to such an extent that it is possible to treat certain aspects of cosmogony as an extrapolation of magnetospheric physics. It is shown that certain events 4-5 billion years ago can be reconstructed with an accuracy of a few percent.

TABLE OF CONTENTS

1.0	NEW OBSERVATIONS	2
1.1	Is Hardware Or Theory Deciding The Progress Of Science?	2
1.2	The Cataract Operation	4
2.0	NEW UNDERSTANDING	5
2.1	Limitations Of Classical Mechanics	5
2.2	Theoretical Or Experimental-observational Approach?	6
2.2.1	Double Layers. The Present State Seems To Be -	11
3.0	NEW APPROACH TO COSMOGONY	13
3.1	Cosmogony As An Extrapolation Of Magnetospheric Research	13
3.2	Electric Currents In Interstellar Clouds	17
3.3	New Approach To The Evolution Of Interstellar Clouds	20
3.4	Properties Of The Solar Nebula	21
3.5	Basic Processes In Evolution Of Solar Nebula	22
3.6	Scenario Of The Cosmogonic Process	25
4.0	SCENARIO OF THE SATURNIAN RING FORMATION	27
4.1	Negative Diffusion And Stability	28
4.2	Non-Catastrophic Formation	29
4.3	Cosmogonic Shadow	29
4.4	Comparison With The Asteroidal Belt	31
4.5	Remarks On The Larmor Radius Of The Accreting Grains	32
5.0	CONCLUSIONS ABOUT THE PLASMA-PLANETESIMAL TRANSITION	32
6.0	REFERENCES	36
7.0	FIGURE CAPTIONS	41

1.0 NEW OBSERVATIONS

1.1 Is Hardware Or Theory Deciding The Progress Of Science?

The progress of science down through the centuries is usually illustrated by describing the important new ideas which have changed whole fields of science. The milestones in our way to increased understanding of the macroscopic world are the replacement of the Ptolemeian geocentric cosmology with the Copernican heliocentric one, and the work by Kepler and Newton, who built the foundation for celestial mechanics. More recently we have witnessed how Einstein's theory of general relativity has been the fundament of an at present rather generally accepted cosmology (big bang).

However, there is a complementary way of describing progress, viz., by focussing our attention on the development of the "hardware", the instruments which produced the data on which the new ideas were based. According to this "materialistic" view the scientific breakthrough during the 17th century was due to Galileo's introduction of the telescope. This was a more decisive factor in the "Copernican revolution" than the heliocentric theory of Copernicus. In fact, his system had been proposed by Aristarchos 2000 years earlier, but in the absence of telescopes it could not be proved. In other words, it was primarily a new instrument, not a new idea, which smashed the crystal spheres.

Similarly, it was the building of giant telescopes which made the heliocentric cosmology obsolete. The use of them made it possible to map our galaxy. It became inevitable to discover an increasing number of foreign galaxies, thus degrading the sun to an unimportant celestial body in a "peripheral" region of the universe. The introduction of radio telescopes has been another important technical achievement.

The leading role which the development of instruments plays is of course not confined to the field of cosmology. It was the construction of the spectroscope, the Geiger-Müller counter and the Wilson chamber which made it possible to understand the shell structure of the atom; it was the accelerators which gave us nuclear physics. Similarly, it was the microscope which introduced the modern era in biology and medicine. To claim that invisibly small bacteria could kill large animals, including men, was ridiculous before we had instruments to observe them.

We are now witnessing a new breakthrough of a similar nature. We are entering a new epoque in our understanding of our cosmic environment. This new era was introduced by Korolev, who launched the first spacecraft, and by van Allen, who introduced the technique of high quality in situ measurements in space - a technique which has been further developed by a large number of his brilliant students, including Krimigis and McIlwain. These two new types of "hardware" are changing our views of the macroscopic world as drastically as Galilei's telescope 350 years ago. Indeed spacecraft are now making it possible to observe the universe not only in visual light and at radio frequencies, but also in infrared, ultraviolet, X-rays, and γ -rays, thus about doubling the number of observable octaves (Fig.1). For every new octave which is added to the observable electromagnetic spectrum we see the universe in a new light.

Moreover, spacecraft make in situ measurements possible in the magnetospheres, including the solar magnetosphere (solar wind region). Such measurements have shown that the properties of cosmic plasma are drastically different from what we thought earlier. This is even more important than the increase in spectral range, because it is basic to the understanding of many of the astrophysical phenomena we observe.

The result is a "paradigm transition" in astrophysics. It is not a question of modifying one or two or three old theories, but of rewriting major chapters of cosmic plasma physics. Certainly the in situ measurements do not extend further than to the outer reach of spacecraft. However, as it is probable that the basic properties of plasmas are the same in more distant regions, large parts of astrophysics, including the origin and evolution of the solar system, and cosmology, must be revised.

The instrument designers have good reasons to be even more proud of the fact that they have ushered in a new era in the history of astronomy and astrophysics, including the history of the evolution of an interstellar cloud into a solar system of the present structure, and also of a new approach to cosmology.

1.2 The Cataract Operation

Fig. 1 shows that before the space age only the visual and the radio octaves were available for observations. High orbit rockets and spacecraft have added the infrared, ultraviolet, X-ray and gamma ray regions. Our X-ray eye which earlier was blind, has undergone a cataract operation, so that we can see our cosmic environment also in this new light. This has changed - or is beginning to change - our views of the universe.

Almost wherever we look we see drastically new unexpected phenomena. Compare our ordinary picture of the sun, an almost uniform disc (with the exception of a few tiny sunspots) with the X-ray picture which shows that often half of the sun is black (coronal holes) (Fig.2). Or look at the interstellar plasma which seen in X-ray and gamma rays sometimes is brighter than the stars (Fig.3). A still more striking contrast is obtained if we consider the majestic calmness of

the starspangled night sky which changes with time constants of months, years or centuries or millenia (except for the Moon) and compare this with a gamma ray burst, in which an enormous amount of energy is released in less than a minute with order of magnitude variation in milliseconds (Fig.4).

We can expect that this new information will introduce a new era in our views of the cosmic environment. Indeed it does.

Moreover, the increased sophistication of our measurements in the "old" octaves adds much new information.

2.0 NEW UNDERSTANDING

2.1 Limitations Of Classical Mechanics

As basically cosmic physics is an empirical science, new and unexpected observations will have a tendency to shake its foundations. Obviously the observations of e.g. gamma ray burst demonstrate that the venerable Newtonian (or Einsteinian) universe could not represent the final truth. There must be other phenomena which appear unimportant in the visual universe but definitely are dominating the X-ray - gamma ray universe. It turns out that most if not all of the X-ray - gamma ray phenomena must be due to plasma processes. Indeed, many if not all should be described by relativistic plasma physics.

Already visual and radio observations demonstrated that, at least by volume, our cosmic environment consisted to more than 99% of plasma. The new observations indicate that more than 99.99...% is plasma. This means that it is no longer Newton alone who governs the mechanics in space. He has to share the power with Maxwell and Langmuir.

Hence classical (Newtonian) mechanics which was sacresant up to the beginning of this century is now subject to three limitations:

1. Atomic phenomena required the introduction of quantum mechanics.

2. At velocities comparable to the velocity of light special relativity effects were decisive. (We are not discussing the general theory of relativity.)

3. In magnetized low density plasmas, hydromagnetics and plasma phenomena are often orders of magnitude larger than the mechanical effects. This is usually the case in most of the interplanetary, interstellar, and intergalactic space. Also in stars these phenomena are often very important.

2.2 Theoretical Or Experimental-observational Approach?

When it became obvious that (what we now call) plasma phenomena were decisive in many geophysical and astrophysical problems (first perhaps for magnetic storms and aurora) two different approaches were made:

Birkeland wanted to base the study on observations and on laboratory experiments.

Chapman and Cowling claimed that the properties of plasmas ("ionised gases" in their terminology) could be derived from basic physical principles by a sophisticated mathematical analysis.

Hence the approach to an understanding of low density cosmic plasmas has followed two different main lines.

(1) In the Chapman-Cowling approach, the plasma is treated essentially as a fluid. The general properties of non-ionized media (liquids or gases) are generalized by introducing electrically charged particles instead of (or together with) molecules. This lead to the classical Chapman-Cowling approach.

(2) The other alternative is to treat the motion of each individual electrically charged particle under the action of electric and magnetic fields which often are produced mainly by the particle population. This is basically the Birkeland-Störmer approach. To everyone who has studied the closest representative of a cosmic plasma, viz. the aurora with its extreme degree of variability both in space and time, it is not very natural to consider it as a fluid (Fig.5). The plasma in Birkeland's terrella experiments did not either give the impression of being a fluid. The relative merits of the two approaches are discussed in Cosmic Plasma (Alfvén, 1981a; in the following referred to as CP), Chapter I:1, p.1.

The classical approach is useful for treating waves in plasmas etc. However, many of the conclusions drawn from it have turned out to be in conflict with observations. Science is basically empirical. That this hold also for plasma physics is demonstrated by the list of new effects which we now know must be considered (see Table I). They are mainly due to experimental-observational discoveries. Very few of them have been predicted by the classical theory, and even post factum it is difficult to account for them using the classical formalism (see CP, Chapter I:4, p.8). As a summary, the classical theory has been rather sterile and quite often greatly misleading. This is due to the fact that a plasma is so complicated that in order to make a mathematically elegant treatment it is necessary to make a number of simplifying assumptions of which not all have turned out to be realistic.

The change in cosmic plasma physics is essentially the result of three factors:

- (a) In situ measurements in the magnetospheres (including the heliosphere)
- (b) Laboratory studies of phenomena of interest in cosmic plasma physics
- (c) Increased understanding of how to extrapolate results obtained in one field to other fields of plasma physics.

A survey of some of the "paradigm transitions" which this has caused or is causing has been published in a monograph (Alfvén, 1981a). Summaries of this have been presented in Alfvén, 1982, 1983a, 1983b. Table I gives a very brief summary.

TABLE I: MAGNETOSPHERIC RESEARCH

is causing a paradigm transition in geophysics and astrophysics for the following reasons:

- #1. Electric double layers are realized to be very important.
- #2. The often misleading "magnetic merging" theories of energy transfer should be replaced by an electric current description, including the circuits in which the currents flow.
- #3. Homogeneous models often are found to be misleading and should be extensively replaced by inhomogeneous models.
- #4. It is realized that inhomogeneities are produced by filamentary currents
- #5. and by surface currents, dividing space into cells.
- #6. It is concluded that space in general has a cellular structure.
- #7. The introduction of the current-circuit description makes it impossible to neglect the pinch effect term in the pressure equation

$$\nabla(p + B^2/2\mu_0) - (B \cdot \nabla)B/\mu_0 = 0.$$

- #8. It is doubtful whether large-scale turbulence is of importance in diffuse media.
- #9. In a space plasma, electric currents may produce chemical separation.

#10. In a dusty plasma, gravito-electromagnetic effects are often important.

#11. The "critical velocity" is often decisive to the interaction of neutral gas and magnetized plasma.

Cosmological consequences will not be discussed here.

A few of these items will be discussed in 2.2.1.

2.2.1 Double Layers. The Present State Seems To Be -

- (a) Electric currents produce double layers if the drift velocity of the electrons exceeds the thermal velocity (Iizuka et al., 1979; Iizuka et al., 1982).
- (b) The properties of a double layer does not only depend on the plasma conditions but also on the outer circuit. If a double layer configuration has a negative volt-current characteristic ("negative resistance" R_i) it can still be stationary if the outer circuit contains a positive resistance (R_e) which is sufficiently large, e.g. numerically larger than $|R_i|$. Also a stationary double layer is usually "noisy", i.e. it produces erratic high frequency (sometimes also low frequency) oscillations (Torvén and Lindberg, 1980; Carpenter et al., 1984).
- (c) The voltage drop ΔV over a double layer is normally 3-5 kT/e (volt equivalent of thermal energy). This holds in such laboratory experiments where the ionisation is mainly produced by one plasma source (Torvén and Lindberg, 1980).
- (d) If there are one plasma source at each side of the double layer and there is little ionisation produced near the double layer ΔV may be several orders of magnitude larger (Torvén, 1982; Lindberg and Torvén, 1983; Sato et al., 1980).
- (e) A double layer in an inductive circuit has a tendency to explode. This occurs for example if $|R_i| > R_e$. At such an explosion practically all the inductive energy $1/2 L I^2$ (L = inductance, mainly in the outer circuit, I = total current) of the circuit is released in the double layer (Lindberg and Torvén, 1983).
- (f) In the magnetosphere normally stationary double layers accelerate the auroral electrons to energies of 3-5 keV. It is a matter of controversy whether the acceleration occurs in one single double layer or in a series of double layers. Magnetic

mirror produced electric fields may also be important. Exploding double layers in the magnetotail may be the cause of magnetic substorms.

(g) Exploding double layers produced by the prominence currents in sun are likely to be the basic phenomenon in solar flares. Also in small scale "flashes" double layers may be important (Carlqvist, 1982).

(h) Double layers in galactic circuits may generate the intense energy release observed as double radio sources. It is possible that they accelerate particles up to at least 10^{14} eV and may be responsible for generation of high energy cosmic radiation (CP, Chapter III:4.4 p.56; Carlqvist, 1982) .

Reviews of double layers have been given at the Symposium at Risø 1983 and at Innsbruck 1984.

#2. The switch from the magnetic field to the electric current-particle description was favoured by the Armstrong and Zmuda mapping of the magnetospheric current system followed up by Potemra, Bostrom and several others. This settled the half a century old dispute between the Birkeland school and the Chapman school to Birkeland's favour. (Dessler has appropriately called the field aligned currents "Birkeland currents".) Further, at Potemra's Conference on Magnetospheric currents 1983 the advantages of the latter description were demonstrated. It is a most important treatise of how the theory of the magnetosphere should be based on the particle description. The relation between the electric current (particle) formalism of energy transfer and the "magnetic merging" formalism seems now to be:

(a) When currents in a plasma change and hence the magnetic fields associated with them vary magnetic field lines merge (reconnect). There is no objection to using "merging" and "reconnection" as a purely geometrical description.

(b) The merging theories cannot be used generally for energy transfer calculations in cosmical physics. One of the reasons is that they do not take adequate account of boundary conditions (see CP Chapter II:5 p.26).

Of the other items #4 and 5 are rather well-known. #6 is of course very important for astrophysics in general and perhaps especially for cosmology. #7,8,10 and 11 will be discussed in the next section.

3.0 NEW APPROACH TO COSMOGONY

3.1 Cosmogony As An Extrapolation Of Magnetospheric Research

From what has been said in Sections 1 and 2 it is obvious that introduction of the new paradigm means a revision of large parts of astrophysics. We shall here confine ourselves to one of the fields viz. the origin and evolution of the solar system (cosmogony). Besides cosmology which we shall not discuss here (see CP Chapter VI and Alfvén, 1983d) this is probably the field of most far-reaching interest. Indeed it has a central position for geology, oceanography, paleobiology, evolution of interstellar clouds, the formation of stars and "solar nebulae", and for astrophysics in general.

We shall begin by a brief review of an approach to cosmogony which started in 1942. (See Table II). The new idea was that electromagnetic (or hydromagnetic) effects were of decisive importance for understanding how the solar system got to its present state. Because previous cosmogonies since Laplace considered mechanical forces alone, this was not reconcilable with the generally accepted types of cosmogonies. Certainly, these have changed drastically during the ages, but almost all of them neglected hydromagnetic and plasma effects. Few

cosmogonists had more than a superficial knowledge of hydromagnetics and plasma physics, with the result that the decisive importance of the 2:3 contraction and the band structure have not been appreciated.

Space research has now changed the situation by giving us new information about electromagnetic and plasma effects in space as has been discussed in Sections 1 and 2. From in situ measurements in the magnetospheres we know the properties of plasmas over five or ten orders of magnitude in density, in magnetization, in temperature, etc. and we also begin to understand what processes are possible and which are not. This has introduced or is introducing a new climate in cosmical physics which may be more favorable for a serious discussion about the evolutionary history of the solar system. In fact, we do not need to base cosmogonic theory on more or less reasonable assumptions about conditions at the time when the solar system was formed (probably 4-5 Gyears ago), or on uncertain interpretation of distant, marginally observable phenomena. We can instead treat cosmogony as an extrapolation of reasonably well-established processes from space research, often derived from in situ measurements (see Fig.6). The result is an approach in which the evolutionary history is decided by a combination of mechanical and electromagnetic (plasma) effects.

What has been summarized above leads to an evolutionary history of the solar system, which in some respects is similar to what is described in the Alfvén-Arrhenius monographs. This is not unexpected, because, as seen in Table II, the evolution of these theories has from the beginning been coordinated with the development in cosmic plasma physics (Alfvén, 1983b). A brief survey will be given here (compare Table II).

TABLE II

HISTORY OF THE SOLAR SYSTEM WITH ELECTROMAGNETIC EFFECTS
INTRODUCED

- 1942 It was shown that a cosmogonic model of this type required that three mechanisms be postulated:
- a. Electromagnetic transfer of angular momentum
 - b. The existence of a phenomenon which later was called "critical velocity"
 - c. A plasma-planetesimal transition associated with a 2:3 contraction. This produced "cosmogonic shadows".
- 1954 A survey of the theory was published as a monograph On the Origin of the Solar System (Alfvén, 1954). It included a development of the theory of Saturnian rings leading to a correction in the contraction factor by a few percent.
- 1960 Laboratory confirmation of critical velocity (Fahleson, 1961), essentially based on a technique developed by Bratenahl (Anderson et al., 1959).
- 1974 Zmuda and Armstrong (1974) (and Iijima and Potemra, 1978; for a survey, see Potemra, 1979) map the magnetospheric current system which gives the needed transfer of angular velocity.
- 1975, 1976 Cosmogonic theory systematically developed in two monographs by Alfvén and Arrhenius (1975, 1976).
- 1980 Space research calls for a "paradigm transition". A brief review is given in Alfvén, 1981, and further developed in 1982, 1983 (summarized in Table I).

- 1982 Critical velocity effect in space demonstrated by space experiment by Haerendel (1982).
- 1983 Holberg's treatments of Voyager results (Holberg et al., 1982) make possible a further confirmation of 2:3 contraction and cosmogonic shadow effect. This is also supported by earlier investigations of the asteroidal belt. All together the 2:3 fall-down ratio is found in seven cases, four in the Saturnian ring and three in the asteroidal belt. This is an encouragement to the further pursuit of this cosmogonic approach.

3.2 Electric Currents In Interstellar Clouds

There are good reasons for the general view that stars and solar systems are born out of an interstellar cloud of dusty plasma. However, the theory of the origin and evolution of such clouds and the formation of stars and solar nebulae is a field which must now be revised for the following reasons:

As we have seen in Section 2 in situ measurements in magnetospheric plasmas (including the solar wind) have caused drastic changes in our views of the properties of cosmic plasmas. What was considered sacrosanct ten or even five years ago is now hopelessly obsolete. This theoretical paradigm transition, which is summarized in Section 2.2 and Table I has penetrated as far out as in situ measurements are made; i.e. as far as spacecraft have travelled. Outside this limit the paradigm transition has not yet taken place. Plasmas in interstellar space are still being treated according to the old paradigm. This means in reality that the present theories of interstellar clouds and of the formation of stars and solar nebulae are based on the tacit assumption that the basic properties of cosmic plasmas change at the outer reach of spacecraft.

It is obvious that astrophysics cannot remain in this unstable state (indeed, a "universal instability" in plasma physics!). The new paradigm will sooner or later be extended to interstellar space. It will cause a revolutionary change in our view of the evolution of interstellar clouds, in the following respects.

(a) According to CP Chapter II:3 etc. cosmic plasmas cannot be described by the magnetic field picture alone. This must be supplemented by an electric current description. Astrophysicists are often reluctant to accept the existence and importance of electric currents in interstellar space, but none of them claims that the magnetic fields are curl-free. As a non-curlfree magnetic field means electric currents, they

implicitly accept that interstellar space is penetrated by electric currents. However, there is an immense difference between an implicit acceptance and an explicit description of the phenomena in terms of electric currents. The latter description calls immediately for models of the circuits in which the currents flow, and models of the dynamo which produces the currents. Such currents may transfer energy from one region to another, sometimes over distances comparable to the size of the whole galaxy. With regard to the circuit description, it has been objected that "there are no wires in space". But "circuits" do not necessarily mean an aggregate of simple linear elements. Especially in the "computer age", circuits often contain non-linear distributed elements. An example of a circuit with non-linear elements is given by Boström (1974) in his circuit of a magnetic substorm.

(b) As soon as electric currents are introduced explicitly, attention is focussed on the pinch effect, which is discussed in CP Chapter IV:8 p.93.

In a typical Bennett pinch both the pressure and the magnetic field are large inside the pinch but zero outside. A typical Bennett pinch is produced when

$$\frac{\mu_0}{4\pi} I_z^2 > 2Nk(T_e + T_i)$$

(I_z = current, T_e , T_i are electron and ion temperatures, N = number of particles per unit length.) Figure 7 illustrates three typical cases of stationary and cylindrically symmetric currents (i) and magnetic field line (B) configurations. In most treatments of the evolution of an interstellar gas cloud, it is assumed that electromagnetic forces oppose the contraction, as in (a), whereas they just as well may assist or cause the contraction, as in (c). The intermediate case (b) may be a first approximation of a model of filamentary currents (e.g. see CP Chapter IV:8.1 p.95).

(c) According to #3, homogeneous models of plasmas are now increasingly replaced by inhomogeneous models. When a new field is opened, it is natural to approach it by making homogeneous models, in the belief that these will in any case be a reasonable first-order approximation to a final theory. In plasma physics we have the sad experience that this is very often not true. When a field has matured to such an extent that it is obvious that homogeneous models are no longer sufficient, it is often evident that inhomogeneous models give a drastically different description of the phenomena. The homogeneous model was of no use. Instead, it led the modeling into a dead-end from which it often is very difficult to turn back because a powerful establishment committed to the homogeneous model has already been formed.

(d) According to #4, there is often an association between electric currents and observed filaments. Examples of this in our close vicinity are auroral rays (probably) associated with filamentary currents, the filamentary structure of the solar corona, and the filamentary currents in the ionosphere of Venus (CP Chapter II:4.7 p.26). In interstellar clouds, there are often observed filamentary structures (especially in contrast-enhanced photographs). Such observations support our conclusion that interstellar space, and not the least interstellar clouds, are penetrated by a network of electric currents. Concerning clouds in which no filamentary structure is observed, it is an open question whether this depends on an absence of them or the inadequacy of observational methods to detect them. From the general picture of the new paradigm the latter interpretation seems to be preferable.

(e) #5 and #6: it is not obvious that these are decisive for the present development of cosmogony.

(f) #7: this has already been discussed in the beginning of this section.

(g) #8: turbulence is generally believed to be decisive for the evolution of interstellar clouds and the formation of the solar system. There seems to be no convincing observational evidence for this (see CP Chapter IV:4 p.84).

3.3 New Approach To The Evolution Of Interstellar Clouds

As stated above, sooner or later the new paradigm will penetrate also the field of the evolution of interstellar clouds. The theory of interstellar clouds should be treated as an extrapolation of magnetospheric research (CP Chapter IV:8 p.93; see Figure 6).

Very much work will be required for this transition, and it is difficult to predict in detail what the result will be. As a reasonable guess as to what a future model of the formation and evolution of interstellar clouds should be, we may suggest the following.

a. Electric currents in "void" interstellar space assist gravitation in collecting matter by the pinch effect, so that interstellar clouds are formed.

b. These develop under the combined action of mechanical and electromagnetic forces. The volume occupied by currents may constitute a very small fraction of the total volume, so that the plasma regions are not evident in the averages of measurements with insufficient resolution. Still, a network of filamentary currents may be decisive to the evolution of the clouds. It is correct to treat the evolution of an interstellar cloud independent of its surroundings only if there is no current connecting it with the surrounding (cf. Fig. 7e).

c. As stated above (cf. Fig. 7), the general belief that electromagnetic forces oppose the contraction of a cloud is not necessarily correct. Pinch effects may contribute to the contraction and, indeed, cause a collapse of clouds with a mass that is orders of magnitude smaller than the Jeans mass.

d. A "stellessimal" star formation out of a dusty cloud seems possible (cf. CP Chapter V p.110).

3.4 Properties Of The Solar Nebula

When the sun is formed it will be surrounded by a dusty plasma penetrated by a network of currents which partially support it (Fig. 8). This "solar nebula" is drastically different from the Laplacean nebula. It is possible that Oort's cometary cloud is a relic of this. The cloud is strongly inhomogeneous and contains regions of different chemical composition (compare #9). From this primeval cloud there rain cloudlets of different composition down towards the sun. Moreover, there is a rain of cosmic dust, perhaps similar to the present rain of meteoroids from the cometary cloud. For possible models, see Alfvén and Arrhenius, 1975, 1976.

From now on our attempt to reconstruct the evolutionary history of the solar system enters a new phase in two respects:

a. Up to this point we have discussed the evolution of an interstellar cloud as a unity, even if the cloud is very inhomogeneous. From now on we have to discuss the evolution of individual cloudlets as distinct from the evolution of the whole solar nebula. The latter process is an integration of the processing of cloudlets, and consists essentially of a slow transformation of the solar nebula into planetesimals (and later planets) during a long period of time.

b. The second reason why we are entering another phase is analytical. The process of planet formation around the sun is similar to the formation of satellites around some planets, especially Jupiter, Saturn and Uranus, which have well-developed satellite systems. Hence we should aim at a general theory of formation of secondary bodies around a central gravitating, rotating and magnetized body. This requirement has been referred to as the "hetegonic principle" (see Alfvén and Arrhenius, 1975, 1976. The arguments for this view are discussed in some detail there.) The principle is related to what now is usually called "comparative planetology" but should include also the formation of bodies around the sun. Galileo, when discovering the Jovian satellites, already called this system a "solar system in miniature".

As we have four well-developed systems to base our conclusions upon, we can speak with more confidence about the processes than for the earlier states of development. Hence, our model for all four systems should start from the assumption that a magnetized central body was formed already and surrounded by a dusty plasma from which cloudlets of different chemical composition, together with dust grains, fall in towards it.

3.5 Basic Processes In Evolution Of Solar Nebula

In this state there are three processes which were decisive for the present structure of the solar system (cg. Table II).

a. The transfer of angular momentum from the central body to the surrounding plasma. The transferred angular momentum is now found in the orbital moment of the secondary bodies.

There is a rather obvious candidate for this process, viz. the auroral current system, which is known to transfer angular momentum between a rotating central body and a surrounding plasma (Fig. 9). Essentially the same process is well known from the Jupiter-Io system (Hill et al., 1983). One of the processes which is claimed to account for the loss of momentum from the sun is turbulence, but with reference to #8, and especially what will be demonstrated later, this is not an acceptable cosmogonic process.

Another process to account for the loss of solar momentum is the solar wind. This is an interesting and perhaps partially correct suggestion. However, it is not clear how it can incorporate the band structure and the cosmogonic shadow effects.

With our present knowledge there seems to be no serious objection to accepting the electromagnetic transfer qualitatively as the basic process. When we come to a quantitative evaluation of the process there seems to be no serious objection to the view that the satellite systems were formed by such a transfer from the mother planet. However, for the planetary system the situation looks more difficult.

If we assume that the formation of the solar system was a very rapid chaotic process with a time constant of less than a million years, we would run into difficulties. The magnetic field must first support all the matter and then transfer angular momentum to it. This would require an enormously strong solar magnetic field. We can avoid such a difficulty by assuming that the planetary system was formed by cloudlets going through the momentum transfer process with a short time constant T_c while this processing led to a slow buildup of planetesimals and planets with a time constant T_i which may be many orders of magnitude larger than T_c . The result is that the density ρ of the plasma supported at a certain moment by the magnetic field need only be a small fraction of the total smeared-out density ρ_s of the produced planetesimals.

$$\rho = \rho_s T_c/T_i.$$

The distinction between the rapid processing of cloudlets and the slow integrated buildup means that ρ was so small that the momentum transfer processes could take place in a low-density plasma (collisionless plasma). This is fortunate because much of the study of magnetospheric plasmas has been and is concentrated on such plasmas. Hence we should be able to treat the transition from plasma to planetesimals as an extrapolation of present-day magnetospheric results (for details, see Alfvén and Arrhenius, 1976).

b. Band Structure of the Solar System. The second basic plasma process is the critical velocity.

When developing a tentative early theory of the possible importance of electromagnetic processes in solar system evolution, it was necessary to postulate the existence of "the critical velocity" in order to explain the band structure of the solar system (see Table II). Such a process was unknown at that time, but the cosmogonic evidence for its existence was considered so compelling that laboratory experiments to demonstrate it were started as soon as possible. These were successful, and there exists now a literature of some hundred papers regarding this phenomenon (Axnäs et al, 1982).

The existence of such a process in space is now confirmed by space experiments (Haerendel, 1982). As there are very few phenomena which have been discovered from a cosmogonic theory, this gives some confidence that this is the process responsible for the band structure.

However, in spite of all this, the problem of planetary formation remains difficult. The critical velocity is a phenomenon in pure gases, but how a dusty plasma behaves is not clear. The most serious problem is to understand how the planets and satellites have acquired their present chemical composition. Possible chains of processes have been discussed

but a convincing solution has not yet been found.

3.6 Scenario Of The Cosmogonic Process

The general scenario of the cosmogonic processes is shown in Table III. Plasma effects were of considerable importance for the evolutionary history of the solar system from the formation and evolution of cosmic clouds to the formation of the sun and a surrounding solar nebula. In the solar nebula the plasma effects were of decisive importance in two respects.

a) They transferred angular momentum from the sun to the plasma out of which later the planets (and asteroids) were formed.

b) The critical velocity produced the band structure of the solar system. The basic plasma processes which cause the critical velocity are still not very well clarified theoretically, but the phenomenon is extensively studied in the laboratory, and space experiments have demonstrated its importance for cosmic plasma physics.

c) After the plasma phase of the solar nebula came the plasma-planetesimal transition (PPT). This was not a sudden and violent turbulent transition, but a slow, continuous process working for a very long time, perhaps 10-100 million years. It discontinuously but persistently transformed in-falling matter of a dusty plasma into a planetesimal state. (However, the processing of individual cloudlets was a rapid process, see 3:5a.) In the pre-planetary period this process worked in the planetary system. At a later period (when the planets were formed) it worked around the planets, producing "satellitesimals".

d) The mass of matter in the planetesimal state increased slowly, until the planetesimals began to aggregate to planets. Later, similar processes led the "satellitesimals" to aggregate to satellites. Plasma processes are of negligible importance for these processes.

In one region in the planetary system, viz. the asteroidal region, and in one region in the satellite systems, viz. the Saturnian ring, the aggregation to planets or satellites has not taken place. The reasons for this are the low density in the asteroid region and the location of the Saturnian ring inside the Roche limit (Alfvén and Arrhenius, 1975). Hence, at least in certain respects, the state in these two regions represents the planetesimal state. This makes them of decisive importance for our attempts to reconstruct the plasma-planetesimal transition. Because much - or rather most - of the cosmogonic information initially stored in the planetesimal state is obliterated in the planetesimal-planet transition, they are of unique value for clarifying the early evolutionary history of the solar system.

In the following, our approach to cosmogony is to a large extent based on a study of the plasma-planetesimal transition (PPT). It turns out that the Saturnian ring and the asteroidal belt contain information which is decisive for our reconstruction of the history of the solar system. In this paper we concentrate our attention on the Saturnian ring.

TABLE III: FORMATION OF PLANETS/SATELLITES FROM INTERSTELLAR CLOUDS

State of matter which is located at present in planets/satellites	Evolutionary Process	Main Evolutionary Mechanism	References
Dusty Plasma	Evolution of Interstellar Cloud Formation of Sun and Solar Nebula	Gravitation Pinch Effect	3.2
	← Evolution of Solar Nebula →	Electro-Magnetic Transfer of Angular Momentum Critical Velocity	3.5(a), 3.6 3.5(b), 3.6
	Plasma-Planetesimal transition ↑	2/3 Contraction Cosmogonic Shadow Effect Rosseland Field	4.0 Fig.10.4.3
Planetesimals	Accretion of Planetesimals to Planets ↑	Mechanical Effects Plasma Processes not Important	
Planets Satellites	← Formation of Satellites around Planets occurs by a Repetition in Miniature of these Processes (starting with formation of nebula around planet). →		

4.0 SCENARIO OF THE SATURNIAN RING FORMATION

The Pioneer and Voyager exploration of the Saturnian rings has given us most valuable material about its structure. For reasons given in Alfvén 1983b we concentrate our attention here on the bulk structure, which seems to give information of decisive value for clarifying the origin of the rings. That paper relied on Holberg's curves (Holberg et al., 1982; Holberg, 1983). Now similar curves (Esposito et al., 1983) have also been published. In the points that are of interest to us the newly published curves agree very well with those we have used.

What has been said above leads to the following scenario for the formation of the ring system (see Alfvén and Arrhenius, 1975, 1976; Alfvén, 1983b,c).

1. Saturn was already formed, with approximately its present mass and present spin. Its magnetic field may also have had the present shape (close to a dipole field) but we do not know its strength.
2. Cloudlets of gas and dust from interplanetary space fell in towards Saturn. They became ionized, which led to current of the same type as mapped in the planetary magnetosphere by Zmuda and Armstrong (1974) and later by Iijima and Potemra (1978). The Jupiter-Io circuit is similar (see Hill et al., 1983). This current system transferred angular momentum from the planet to the plasma (Alfvén and Arrhenius, 1976, Chapter 16; Alfvén, 1981a, p. 52,120).
3. This brought the plasma into a state of partial corotation so that Saturn's gravitation was compensated to two-thirds by the centrifugal force and to one-third by electromagnetic forces (from the Saturnian magnetic field; see Fig. 10).

4. At the transition from the plasma to the planetesimal phase the electromagnetic forces vanished, which caused a contraction by a factor $\Gamma = 2/3$. (This factor is given by the geometry of Saturn's magnetic dipole field, see Fig. 10.) Early Voyager results have already demonstrated that there is strong evidence for this process in the present structure of the Saturnian ring (Alfvén, 1983b).

Further development of this approach has shown that it is possible to account for more than 30 signatures in the Voyager diagrams.

4.1 Negative Diffusion And Stability

The first question we have to answer must be: is it reasonable that essential parts of the present ring structure are "fossils" from cosmogonic times (4-5 billion years ago)?

Baxter and Thompson (1971, 1973) have demonstrated that under certain conditions the diffusion in a population of grains in Kepler orbits is "negative" (see Fig.11). This result is confirmed by Lin and Bodenheimer (1981). The present ring system consists of 1000, if not 10,000, ringlets (cf. Fig. 12). This indicates that the negative diffusion mechanism is active today. There seems to be no obvious objection to the assumption that the same mechanism was active in the past. This means that the present structure may derive from cosmogonic times (Alfvén, 1983b). Hence, it is meaningful to try to reconstruct essential events in the evolutionary history from "fossils" stored in the Saturnian ring. There are reasons to believe that this holds also for the asteroidal belt.

4.2 Non-Catastrophic Formation

The general scenario must be, consequently, that the Saturnian satellites and ring system was formed not as a result of a sudden event, but by a slow injection of diffuse matter during a period of many millions of years. Very early during this period a ring-satellite system was already formed which was qualitatively similar to the present one, but with only a small fraction of its present mass. When more mass accumulated the bodies became more massive, but the same structure was retained. Hence, during most of the time of accretion shadow-producing bodies were located at the same places as today.

4.3 Cosmogonic Shadow

In the cosmogonic model we discuss it was assumed that in the Saturnian magnetosphere there was a dusty plasma which, to some extent, was concentrated at the euqatorial plane. At the Saturnian distance of Mimas, this satellite (or the jet stream out of which it was formed) swept the plasma so that a "hole" - in realite an empty ring - was produced.

During the Pioneer mission, Fillius and McIlwain (1980) actually observed this kind of phenomenon. In fact, at the distance of Mimas, the counting rate went down by orders of magnitude (see Fig. 13). Janus produced a similar although more narrow and shallower "hole". The shepherd satellites and the A ring gave an almost complete cut-off in the plasma density. Hence, actual measurments have shown that the "hole" formation is not an ad hoc assumption of a new process, but was actually observed in the magnetospheres. (Other observations in different energy regions show similar phenomena, although sometimes blurred, presumably by radial electric field drifts.)

When, at the plasma-planetesimal transition the 2:3 contraction takes place, the hole should be transferred to $2/3$ of the distance of Mimas. This is indeed the location of Cassini's division. Similarly, Janus should produce a marked minimum which now should be found at $2/3$ of their distance. This can be identified with the Holberg minimum* in the B ring (Holberg et al, 1982). The Shepherd satellites should produce a hole in a similar way. The A ring also produces a shadow which extends so far out that it joins the shadow produced by the shepherd satellites.

The result of the combined action of the shepherd satellites and the A ring (and perhaps also of the F ring) is an extended region of low intensity which accounts for the C ring. Hence the rapid decrease in intensity at the border between the B and the C ring should be $2/3$ of the position of the shepherds. Finally, the outer edge of the very massive B ring should give the strong decrease in intensity which marks the inner edge of the C ring, which is located at $2/3$ of the outer limit of the B ring.

The combined actions of these four cosmogonic shadows give the bulk structure of the Saturnian ring. (See Fig. 14; for details see Alfvén, 1983b).

When the ring particles produce the shadows, it implies that they absorb plasma with a smaller angular momentum. This leads to a decrease in their distance. Hence, the contraction factor $\Gamma = 2/3 = 0.667$ should decrease by a few per cent. Theoretically we should expect the value to go down to 0.63-0.65 (Alfvén, 1954; 1981b). In the following we shall use the value 0.64 instead of 0.67. This 4% difference is theoretically motivated, but since we never claim a higher

*A proposed name for the minimum at 1.58 Saturnian radii, motivated by the fact that J. Holberg has drawn attention to its importance in this connection.

accuracy than a few percent, it is not very important for the main discussion.)

4.4 Comparison With The Asteroidal Belt

The hetegonic principle states that all systems of secondary bodies should follow a general theory. This means that our results for the Saturnian rings should also be applicable to the asteroid belt around the sun, which is the other important case where the initial planetesimals have not accreted to larger bodies (see Fig. 15; Alfvén, 1984).

A similar analysis of the asteroidal belt has given three identifications of cosmogonic shadows (see Table IV). The small correction to should not be applied to the asteroidal belt (see Alfvén and Arrhenius, 1976, Chapter 11.8, 18.5 and 18.8; Alfvén, 1983b).

Also in this case the mutual agreement and the agreement with theory is surprisingly good.

TABLE IV

Cosmogonic shadows		
Saturnian ring from Holberg's data		
	<i>a</i>	<i>Γ</i>
Mimas	3.075	0.646
Co-orbitals	2.510	
Shepherds	2.349	
	2.310	
Cassini Center	1.984	0.63
Outer B	1.945	
Holberg min	1.58	0.655 (0.650–0.660)
Inner B	1.525	
Inner C	1.235	
Average $0.642 \pm 2\%$		
Asteroidal region		
Jupiter	5.18	0.676
Main belt		
outer limit	3.50	0.674
High density		
outer limit	3.22	0.683
High density		
inner limit	2.36	0.667
Main belt		
inner limit	2.20	
Theoretical value		

(Alfvén, 1981b)

4.5 Remarks On The Larmor Radius Of The Accreting Grains

The basis for the derivation of the 2:3 contraction has been that electrically charged particles to a first approximation are bound to move along a magnetic field line (seen from a coordinate system in which the electric field perpendicular to B is zero). This is correct as long as their Larmor radius is small compared to the relevant size parameter. However, we have changed the model from the early simple picture of an electron-ion plasma to a treatment of the behaviour of a charged dust in a dusty plasma. The dust grains have q/m (charge to mass) ratios, which are orders of magnitude smaller than for electrons or protons. In fact, their Larmor periods may exceed the Kepler period and their Larmor radii may be large compared to the characteristic parameters of the dipole field. This seems to make it difficult to treat their motions as we have done. However, this difficulty is often fictitious, as is shown in some detail in Alfvén (1984). A further analysis of this important problem is in progress (Carlqvist, personal communication).

5.0 CONCLUSIONS ABOUT THE PLASMA-PLANETESIMAL TRANSITION

We have shown that essential features of the bulk structure of the Saturnian rings can be understood as a result of the cosmogonic shadow effect produced by a 2/3 contraction which probably took place at the transition from the plasma to the planetesimal phase (PPT), presumably 4-5 billion years ago. The 2:3 ratio appears in four cases. Adding to this the three cases from the asteroidal belt, we have no less than seven identification. This means that we can state with considerable confidence that the cosmogonic shadow effect must have been essential at the formation of the solar system.

Besides the cosmogonic shadow effect, gravitational resonances were important, especially in the asteroid belt, where they produce the Kirkwood gaps. Due to the very small ratio of Mimas/Saturn in comparison to Jupiter/Sun, corresponding resonance effects in the Saturnian rings are small but clearly identifiable (Holberg et al., 1982). (Also, some other effects are important (see Alfvén, 1983b).) Hence, a 2:3 contraction should be characteristic for the plasma-planetesimal transition (PPT). It seems difficult to interpret the above results as being due to any other effect. The surprisingly high degree of agreement between the observational and theoretic values means that we have a possibility of reconstructing certain features of the PPT with an accuracy within a few percent.

The work on doing this is in progress. A straightforward development of the theoretical model shows that the "holes" produced by plasma absorption by the satellites must be associated with radial electric fields both at the inside and outside of the depleted region. These electric fields will change the Γ -values so that both the Cassini division and the Holberg minimum would exhibit "banks" (i.e. maxima) both inside and outside of the minima. Such structures are actually visible in the Holberg curves (Figs. 13 and 15).

Further, important features in the bulk structure of the rings (discussed in Alfvén, 1983b) are analyzed, including why the center of the B ring is so massive, why there is a structure inside the Cassini division, and how the several maxima in the C ring are produced. Also, the importance of the Northrop and Hill (1982) instability and the possibility of explaining the Encke division as produced by an adiabatic circularization of the initial orbits of the grains are being studied. In this way it may be possible to reconstruct the state of the Saturnian environment at cosmogonic times.

With a similar analysis of the asteroidal region, we will have the possibility of reconstructing how the planetesimal state developed into planets/satellites.

Further, we can conclude:

Since the PPT, the structure of the Saturnian rings and the asteroid belt cannot have undergone any violent large-scale disruptions. A slow evolution, resulting in concentration of mass in a few bodies, is indicated. In the equatorial region there could have been no "solar gale" strong enough to disrupt the basic pattern. However, there could very well be a solar wind (or solar gale) in the polar regions. Indeed the transfer of angular momentum from the sun to the solar nebula must be accompanied by a large release of energy (rotational energy of the sun) which must produce an intense heating particularly in the close neighbourhood of the sun, resulting in a solar wind emission (see Alfvén and Arrhenius 1976 Chapter 5.5 p.78). There will be little to prevent this in the axial directions, but the infall of matter accreting in the equatorial plane will make it difficult to proceed very far. This is in agreement with the results of Axon and Taylor (1984), who give a model of a biconical protostellar wind for a star in the Orion nebula.

Further during the PPT and later there could not have been any strong, large-scale turbulence.

Violent events before the PPT cannot be excluded, but so far there seems to be no decisive arguments in favor of such phenomena. On the contrary, what has been said in Section 3 speaks against it. The large-scale evolution of the solar system, from an interplanetary cloud to the present structure, could very well have been a slow, quiet process (but consisting of rapid, consecutive processing of cloudlets) which, during many millions of years, built up the present structure.

6.0 SUMMARY OF THE PROCESSES NECESSARY TO UNDERSTAND THE EVOLUTION OF THE SOLAR SYSTEM

As we stated in Table II, a cosmogony taking account of electromagnetic effects requires these processes:

- (a) Electromagnetic transfer of angular momentum
- (b) The existence of a phenomenon later called "critical velocity"
- (c) A plasma-planetesimal transition associated with a 2:3 contraction which produced "cosmogonic shadows".

The existence of all three predicted processes has been confirmed. When elaborating the theory in different respects it was found necessary to introduce one more process:

- (d) Local pinch effects in the interstellar source cloud is required to form a non-Laplacian solar nebula of a kind which could give the required initial condition for the cosmogonic processes.

Of these, (b) and (c) have been discovered after being predicted from the cosmogonic theory, whereas (a) has been discovered independently.

Our claim that our result could not be uncertain by more than a few percent seems to be legitimate.

The usefulness of a theory is often judged by the number of earlier unknown phenomena it predicts. If we apply this criterion to the introduction of electromagnetic effects in the cosmogonic processes, the electromagnetic approach seems to be not too bad.

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7.0 FIGURE CAPTIONS

- Fig. 1 Opacity of Earth's atmosphere to incoming radiation. The curve shows the altitude below which the radiation is invisible.
- Fig. 2 X-ray picture of the Sun. Dark features called "coronal holes" are one of the largest and one of the most important features of the Sun.
- Fig. 3 X-ray picture of the Orion nebula. What is seen is cosmic plasma. Its emission dominates in this wavelength region.
- Fig. 4 Typical emission in a gamma-ray burst. Total duration 50 s.
- Fig. 5 When a cosmic plasma invades the atmosphere aurorae are observed. They show the true nature of a cosmic plasma. It is very inhomogeneous and the aurora changes its shape within a timescale of down to minutes.
- Fig. 6 Magnetospheric research has matured to such an extent that it is possible to treat essential parts of the evolutionary history of the solar system as an extrapolation of magnetospheric research. Laboratory experiments also form an important basis for this. Further, extrapolation from both magnetospheric and laboratory results contribute to a revision of our view of interstellar clouds, and hence influence also the way in which we approach cosmogony. The transfer of information from one field to another is shown in the figure. The thickness of the arrows is proportional to the flow of information.

Fig. 7 Three special cases of stationary and cylindrically symmetric current (i) and magnetic field (B) configurations. (a) A toroidal current and an axial magnetic field leading to a force opposing contraction. (b) A force-free configuration with i and B parallel. (c) The Bennet pinch with an axial current and a toroidal magnetic field. Electromagnetic effects aid and even start contraction. (d) If $\text{curl } B_{\perp} \neq 0$ at any point on surface of the cloud its evolution depends on the total circuit. (Magnetic merging theories not applicable.) e) The behavior of plasma in a tube depends not only on local plasma parameters but also on the total circuit, including R and L . Energy transfer cannot be calculated by magnetic merging.

Fig. 8 After the formation of the sun and its magnetic field, remnants of the (non-Laplacian) solar nebula (formed according to 3.3 and 3.4) fall towards the sun in cloudlets of dust and gas. When a falling cloudlet reaches its critical velocity, it is stopped. Currents from the spinning sun support the cloudlet for a short period of time and transfer angular momentum to it. At the plasma-planetesimal transition, grains in Kepler orbit are produced and plasma processes are then no longer important.

Fig. 9 Simplified picture of the auroral circuit transferring angular momentum between a magnetized rotating body A and a surrounding plasma cloud C. Current I may produce double layers D.

Fig. 10 (a) Charged particles (plasma, charged dust, or cloudlets) in an axisymmetric magnetic dipole field around a gravitating rotating body. If their motion is magnetic-field dominated, a quasistationary motion requires that the vector sum of gravitation and centrifugal force be perpendicular to the magnetic field line. As shown by Alfvén and Arrhenius (1975,

1976), this means $v = (\frac{2}{3})^{1/2} v_K$, where v is the rotational velocity and v_K is the Kepler velocity.

(b) Vanishing magnetic forces give a transfer into elliptic orbits. If the magnetic field or the particle charge suddenly disappears, the particles at the central distance a_0 will orbit in ellipses with semimajor axis $a = \frac{3}{4} a_0$, and eccentricity $e = \frac{1}{3}$. They will collide mutually when they reach the nodes in the equatorial plane with $a = \frac{2}{3} a_0$, and after collisions move in a circle at $a = \frac{2}{3} a_0$ with $\Gamma = 2:3$.

Fig. 11 Interaction of a large number of particles in Kepler orbits. In the discussion of collisions between particles in interplanetary space (e.g. evolution of the asteroidal belt or meteor streams) it is usually taken for granted that state a will evolve into state b (positive diffusion). This is usually not correct. Collisions between the particles will not spread the orbits since the diffusion coefficient is negative (Baxter and Thompson, 1971, 1973). Instead, collisions will lead to equalization of the orbital elements, leading from state b to state c so that a jet stream is formed.

Fig. 12 This photo of the Saturnian Ring shows some of its fine structure. In order to maintain a large number of ringlets, a negative diffusion process is indicated.

Fig. 13 Comparison between present magnetospheric plasma distribution and mass distribution in the rings. Present-day charged particle distribution in the Saturnian magnetosphere often shows void regions produced by absorption by the satellites. The upper curves are obtained by Fillius and McIlwain (1980). It is argued that the plasma distribution was qualitatively the same in cosmogonic times. The contraction by a factor $\Gamma = 2:3$ at the transition from plasma to planetesimal should result in a somewhat

similar mass distribution at a Saturnian distance of 2:3 of the plasma distribution. The lower curve shows the present mass distribution in the Saturnian rings (Holberg, 1983). It is compared with the Fillius-McIlwain curve reduced by a factor $\Gamma = 0.64$. The "cosmogonic shadows" of Mimas, the co-orbital satellites and the Shepherds are identified with Cassini's division, the deepest minimum in the B ring, and the inner limit of the B ring.

Fig. 14 Correction of the fall-down ratio. The upper line, marked "Before Condensation", shows the plasma density in the equatorial plane of Saturn, the center of which is at the left end. Next line, marked "Intermediate State" represents the density of the grains produced by condensation of the gas. As these move at 2:3 of the distance of the gas out of which they are produced, the density distribution is obtained by a geometrical construction reducing the central distances to 2:3. The lower line, marked "Present State", represents the density distribution into which the "Intermediate State" is transformed by the "shadow reaction", or "shadow load" (see Alfvén, 1954).

Fig. 15 The normal optical depth of the rings from Voyager 2 UVS ring occultation data. Below is the brightness of the rings in transparent light (Holberg et al., 1982).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

IMPORTANT FIELDS OF PLASMA PHYSICS

Fig. 6

a.

b.

c.

Fig. 7

COSMIC CIRCUIT

Fig. 7d

LABORATORY

Fig. 7e

Fig. 8

Fig. 10a

(a) Polar View

(b) Equatorial View

Fig. 10b

EVOLUTION OF BODIES MOVING IN KEPLER ORBITS AND INTERACTING

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

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SPACE RESEARCH AND THE NEW APPROACH TO THE MECHANICS OF FLUID
MEDIA IN COSMOS

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Space research has increased our knowledge of fluid media in
space in two ways.

1. It has made it possible to SEE our cosmic environment
not only in visual light and radio waves but also in
infrared, ultraviolet, X-rays and gamma rays. The picture
we get in these now accessible wavelengths is drastically
different from the pre-space-age view.

One of the results is that (at least by volume) our cosmic
environment consists to more than 99% of magnetized, often
dusty, plasma.

2. In situ measurements in the magnetospheres - including
heliosphere - combined with laboratory experiments have
given us new information about the properties of cosmic
plasmas. This makes it possible to UNDERSTAND what we see.
It turns out that a drastic revision of the classical
theory of plasmas is necessary.

3. The new results are APPLIED to cosmogony (origin and
evolutionary history of the solar system). Magnetospheric
physics has matured to such an extent that it is possible
to treat certain aspects of cosmogony as an extrapolation
of magnetospheric physics. It is shown that certain events
4-5 billion years ago can be reconstructed with an accuracy
of a few percent.

Key words: Cosmic plasma physics, Dusty plasma, Paradigm
transition, Cosmogony, Evolution of the solar system,
Saturnian rings, Cosmogonic shadow.