

## THE PLASMA PHASE OF THE EVOLUTION OF THE SOLAR SYSTEM

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## ABSTRACT

Sophisticated magnetospheric measurements have drastically changed our views of the magnetospheric plasma which earlier were based on theories without sufficient empirical support. Also the theory how to translate laboratory plasma results to space has been important. The result is a paradigm change of the theory of cosmic plasma. A new unified plasma theory, valid both for laboratory and space plasma is emerging. The new paradigm to the evolution of the solar system shows that plasma dominated processes were essential for the early phases, viz. the evolution of interstellar clouds and later the evolution of the circumsolar cloud up to the transition from the plasma to the planetesimal phase. Later phases are not affected by plasma phenomena.

Keywords: Cosmic Plasma, Origin of Solar System, Magnetospheric Results, Formation of Planetesimals.

- (1) Formation and evolution of interstellar clouds
- (2) The "collapse" of certain types of such clouds into protostars
- (3a) Formation of planets around some of these stars
- (4a) Formation of satellites around some of the planets
- (5a) Formation of small bodies, like asteroids, comets and meteoroids

If we accept that satellites were formed by essentially the same kind of processes as the planets (the hetegonic principles, see ESS 1.2) and that these processes were of the planetesimal type, we should substitute 3a, 4a and 5a by

- (3b) Formation of planetesimals and other small bodies (asteroids, comets, and meteoroids) around a central body
- (4b) Accretion of planetesimals to planets and satellites (and to asteroids, perhaps also to comets)

The pros and cons for the scenarios 3, 4a, 5a on one hand and 3b, 4b on the other shall be discussed below.

## 1. HISTORIAL SURVEY

The problem how the solar system originated and got its present shape is a classical problem. From the early mythological discussions of it, it began to approach a scientific treatment through Kant. Laplace formulated a qualitative theory of it, which of course was based on mechanical effects. As we know today, not the least through the space research during the last few years, plasma phenomena are of decisive importance for practically all phenomena associated with the evolution of disperse cosmic clouds. It is not remarkable that Laplace knew nothing about this, but it is very remarkable that most cosmogonists of today still deny that electromagnetic forces were of decisive importance for some important phases of the formation of the solar system. We shall refer to all the theories based on exclusively mechanical forces as "Laplacian".

In some respects there is a general agreement about how the solar system originated. It derived from an interstellar cloud about 4-5 billion years ago and the formation included the following phases.

Of the fields we have listed, (1), (2) and partially (3a), (4a) and (5a) in the first alternative and (3b) in the second are applications of the physics of diffuse cosmic media. This field of research is characterized by a drastic change in our views of the basic properties of such media, which has resulted from the exploration of the magnetospheres (including the heliosphere = solar magnetosphere) and the ionospheres by spacecraft measurements. As has been pointed out by Fälthammar, Akasofu and Alfvén 1978 (Ref. 1) and by Alfvén 1981 (Ref. 2) it is unavoidable that these results will change our views of the basic properties of diffuse media (plasmas) on many fields of astrophysics, because it is impossible to claim that the basic properties of diffuse media are different outside the present limit of the reach of spacecrafts than what we know they are inside this limit. Similarly it is not very likely that their properties at the time of formation of the solar system were basically different from what they are now.

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## 2. PROPERTIES OF DIFFUSE MEDIA EXPLORED BY IN SITU MEASUREMENTS IN THE MAGNETOSPHERE

### 2.1 The new magnetospheric paradigm och astrophysics

As some of the lectures during the following will show that magnetospheric research together with laboratory plasma investigations have given us a fair understanding of some basic properties of diffuse media within very large range of parameters, in some cases nine orders of magnitude or more. The linear size of the studied regions varies from less than 1 m (in the laboratory) up to more than 1 Tm (distance to Saturn), time periods between less than a nsec and several years, magnetisations between picoteslas and about one tesla, and densities between less than  $10^6$  and more than  $10^{16}$  particles  $m^{-3}$ .

Further, we can now - to some extent - "translate" the observed phenomena over large parameter ranges (Fig. 1) so that we can predict the properties of plasmas from studies made at a different range of parameters. This means that we can transfer knowledge from magnetospheric and laboratory studies to the investigations of e.g. interstellar clouds. Magnetospheric research has demonstrated that much of the earlier theories of diffuse media were misleading. As stated already a new paradigm has emerged, and this is likely to penetrate more or less rapidly into many other fields of astrophysics, including our field of research (Ref. 2-4).

### 2.2 Dualism in the theory of cosmic plasmas

1. The usual description of the hydromagnetic state of a space medium by magnetic field models can only account for some of the phenomena (Fig. 2). It is

necessary to "translate" magnetic field models into electric current model in order to understand a number of phenomena which are decisive for understanding the properties and the evolution of the medium. This dualism is analogous to the general field-particle dualism in physics.

2. Diffuse media in space are penetrated by thin filaments in which electric currents flow, and also by discontinuity surfaces (surface currents) which gives space a cellular structure. Adjacent cells often have different densities, temperatures, magnetisations and chemical compositions.

3. The space medium can exist in two different states:

- Active regions carrying field-aligned currents and neutral line currents. These produce heating, transfer of energy and often generate double layers, which accelerate particles to high energies (sometimes very high energies).
- Passive regions, in which such currents are small. Passive regions can transmit waves and high energy particles, but these are energized by phenomena in the active regions.

Although often the active regions are small compared to the passive regions, they are decisive for the evolution of cosmic clouds.

4. The properties of a cosmic cloud through which an electric currents flows are not determined only by the parameters (like density, temperature, magnetisation, state of ionisation) in the cloud, but depend in an often decisive way on the whole circuit in which the current flows. Hence, if the magnetisation of a cloud is non-curlfree (i.e.

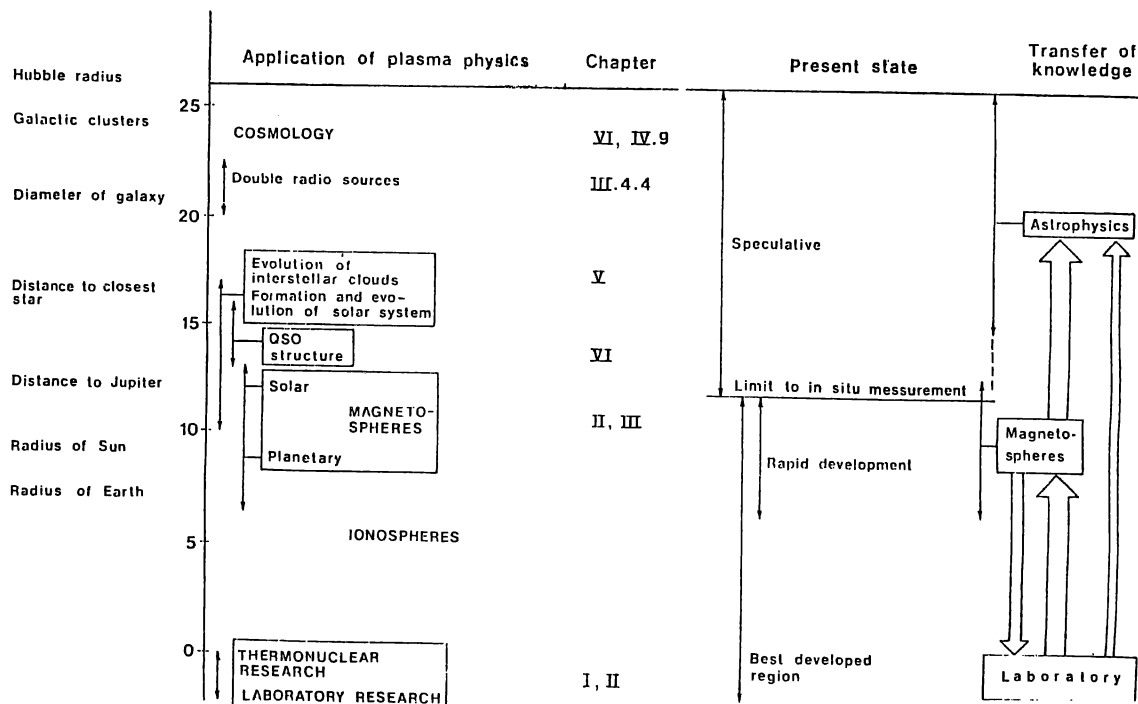


Fig. 1 Plasmas in laboratory and in cosmos. The diagram gives a survey of the regions which are of interest, and the chapters in the monograph Cosmic Plasma in which they are treated. It also indicates the limit between the regions which can be explored by high class diagnostics and those which cannot. Hence, the latter must necessarily be regarded as speculative.

## DUALISM IN PLASMA PHYSICS

## TRANSLATION FORMULA

$$\nabla \times \vec{B} = \mu_0 \vec{i}$$

## MAGNETIC FIELD DESCRIPTION

Magnetic fields are:

Measured rather easily,  
Basic for plasma anisotropy  
including high energy particle motion,  
Giving a good description of some waves in plasmas

## ELECTRIC CURRENT DESCRIPTION

Electric currents are:

Difficult to measure directly but  
Essential for understanding:  
Double layers  
Transfer of energy from one region to another  
Current sheet discontinuities  
Cellular structure of space  
Magnetic substorms, solar flares

Applicable in

Passive plasma regions

Active plasma regions

Fig. 2 The plasma dualism is somewhat analogous to the general particle-field dualism in physics. The current description requires a new formalism with ELECTRIC CIRCUITS as an important ingredient.

an electric current flows there) the properties of the cloud may be determined by phenomena taking place very far away. In other words, the boundary conditions are essential. If the current through the cloud is part of a general galactic current system (as it is likely to be in many cases) the cloud may be energized by an e.m.f. located in another part of the galaxy, and its evolution determined by the conditions far away.

5. Magnetic fields do not necessarily counteract the contraction of cosmic clouds. They may just as well assist a contraction or even cause a contraction. This is easily seen if the magnetic field description is translated into a current description (see CE 5.5 and Ref. 5).

In the simple case of a cylinder in which the magnetic field has a constant curl ( $\nabla \times \vec{B} = \mu_0 \vec{i}$ ) and the number of particles with temperature  $T$  is  $N$  per  $m$  length, the electromagnetic forces cause a compression ("pinch effect") if the Bennet relation

$$I^2 > \frac{4\pi}{\mu_0} \sum N_v kT_v$$

(where  $I$  is the total current and the sum is taken over the different plasma components) is satisfied. If  $I = 10^{13} A$ , a reasonable value for an interstellar current (Ref. 5), and  $T = 100^\circ$ , we have

$$N_n < 10^{40} m^{-1}$$

If the current region has a cross-section of  $10^{15} m$  ( $\approx 0.1$  ly) the requirement for compression is  $n < 10^{10} m^{-3}$  which is a value which is larger than the average value in interstellar space, and also larger than in many clouds. This numerical example shows that electromagnetic compression may be a dominating factor in the pressure balance in a cosmical cloud.

6. A cosmic medium has a general tendency to differentiate chemically. The well-known phenomenon of condensation of dust grains consisting of the least volatile components of the medium, leads to a chemical differentiation because dust grains

above a certain size (often  $\approx 1\mu$ ) are not appreciably affected by electromagnetic forces and hence their motion differs from the motion of the diffuse medium (which generally is at least partially ionized) (Ref. 6). Moreover, as is well-known from magnetospheric and solar physics, electric currents produce differentiation between elements with different ionization potentials (Refs. 7-8). Pronounced isotope separation effects are also observed in the interstellar cloud medium, and are understood in principle on the basis of the high reactivity of the partially ionized medium even at low kinetic temperature.

7. A chemical differentiation should be counteracted by turbulence. However, in the magnetospheres there is no certain indication anywhere of the existence of (large scale) turbulence (Ref. 2). Certainly a spacecraft penetrating the "shock front" ahead of the magnetopause measures wildly fluctuating plasma parameters, but this may be due to a filamentary structure. Similarly, a spacecraft moving through the solar corona would measure rapidly varying parameters, but the filamentary structure of the corona demonstrates the absence of at least large-scale turbulence.

### 3. APPLICATION TO THE FORMATION AND EVOLUTION OF INTERSTELLAR CLOUDS

From these general properties of space media which the last few years of magnetospheric investigations have clarified we can draw the following conclusions about the properties of interstellar clouds.

1. An interstellar cloud may very well be formed by electromagnetic forces producing a contraction ("pinch effect") in a region in which initially the density is very low. When the cloud is formed, its density may be increased by the same effect up to the limit at which a Jeans collapse sets in, either in the whole cloud or in a small part of it. Hence, there is no need for a "triggering mechanism" (like shock waves etc) to produce a gravitational collapse. This does not rule out that in certain cases triggering mechanism may be im-

portant, but they have to be treated according to the new formalism (Ref. 2).

2. Chemical differentiation is observed to be a common process in cosmic clouds and may be essential for the chemical differentiation observed in the solar system. Certainly a chemical differentiation would be counteracted by turbulence. However, as we have seen above there is no certain indication that turbulent mixing is of any importance in the magnetospheres. Wildly varying values of plasma parameters and broadening of spectral lines may be due to waves or to filamentary structures. There seems to be no certain indication that turbulence is of major importance anywhere in cosmic plasmas.

3. Filamentary structure. There are both theoretical and observational evidence for the view that filamentary structures are a characteristic feature of cosmic clouds. Theoretically it is difficult to imagine that the properties of diffuse media change drastically at the outer limit of the reach of spacecrafts. Hence because current-carrying filaments and surfaces play such an important role in the magnetospheres, we should expect similar phenomena in cosmic clouds.

Observationally there are quite a few examples of filamentary structures (Fig. 3). In some cases the filaments are believed to be associated with shock fronts from supernovae. As magnetohydrodynamic shock fronts always are characterized by electric currents this supports our interpretation. Further, if photographs of nebulae which show no filamentary structure are subjected to contrast enhancement they show in many cases a pronounced filamentary structure. Hence one is tempted to conclude that many clouds - perhaps all - have a filamentary structure, demonstrating the existence of thin current filaments or layers. From what we know from the magnetosphere these may govern the evolution of the clouds.

What has been said eliminates the possibility that the evolution of a cosmic cloud can be treated with neglect of electromagnetic effects. This seems to be in agreement with what many authors have found in different ways (Ref. 9). However, most of these authors treat the evolution without paying attention to the new results from magnetospheric research.

4. As currents produce regions with much higher densities than the average, the condensation into dust grains and their increase in size may proceed orders of magnitudes more rapidly than is indicated by calculations based on average plasma densities.

I think that I have given a fair review of some recent results of magnetospheric research and the possible extrapolation to the conditions in cosmic clouds. (For a more detailed review see Alfvén, Refs. 2 and 4). I hope that this will be useful as a background for our discussions of the formation and evolution of cosmic clouds.

#### 4. FORMATION OF PROTOSTARS

The generally accepted view is that protostars are formed by gravitational collapse. This is probably correct at least in part. However, there are at least two effects which may assist the collapse so that also small clouds (one solar mass or less) can collapse. This makes trigger actions (by shock waves

etc) and fragmentation in the collapsing cloud unnecessary (but it does not rule out such mechanisms).

1. The first of these is the electromagnetic contraction we have discussed in the previous chapter. This may increase the density of a cloud - even a small cloud - and bring it up to the limit of gravitational collapse.

2. The other mechanism should take place in a cloud consisting of a dusty plasma (Ref. 10). (There are good reasons to suppose that many interstellar clouds consist of dusty plasma.) If the dust at least partially consists of particles which are so large that their motion is not determined by electromagnetic effects, these will accrete to a dust ball, which serves as a core around which the gaseous components of the cloud can collapse. (For details see Alfvén and Carlqvist (Ref. 5) and Horedt (Ref. 10).)

Neither one of these mechanisms does necessarily produce an immediate collapse of the whole cloud. If the current density in the cloud is inhomogeneous - as is normal in cosmic plasmas - it may cause a contraction of a number of cloudlets to the Jeans limit, and hence make the cloud fragment into a number of "stellessimals" which later form a protostar by essentially the mechanism by which planets accrete from planetesimals (we need not specify this mechanism here). Similarly, if a dusty cloud is inhomogeneous (as most clouds are likely to be) so that the gravitational potential in it has a number of local maxima, a number of cores for local condensations are produced. Also in this way stellessimals may be formed which later accrete to a protostar. Hence the fragmentation of a cloud may take place before the contraction, not necessarily during it. This mechanism which has been studied in detail by Horedt, leads to the same mechanism for the formation of stars, planets and satellites. (It should be observed that one of the difficulties which Horedt is concerned with, viz. the low density of the interstellar clouds, is not very serious if the current produced inhomogeneity is taken into account.)

#### 5. PLANET-SATELLITE FORMATION

If a protostar is formed in this way it seems likely from a theoretical point of view that it is surrounded by an almost void region which separates it from the rest of the "primeval cloud" out of which the protostar has formed (Refs. 10 and 5). Also at this stage electromagnetic effects are decisive. In fact we have basically two different types of models.

A If we accept that a part of the "primeval cloud" from which the protostar is formed, is "hung up" - perhaps essentially by electromagnetic effects outside the void region around the protostar - and the matter of this cloud rains down towards the protostar during a long time, the planets may be formed by a semi-stationary process during a long period. This leads to the situation which is analysed in details in ESS. Basically the same process takes place around the planets leading to the formation of satellites. The main processes are:

1. Chemically differentiated small clouds of neutral gas and dust fall down to the central body through a region where the gas (plasma) density is low

(typically coronal densities). When it reaches the critical velocity the gas is stopped and ionized. This explains the band structure of the solar system.

2. There is a transfer of angular momentum from the central body to the plasma by a current system of the type which is well-known from magnetospheric studies. This transfer decelerates the angular velocity of the central body and gives the plasma the angular momentum which is later possessed as orbital momentum of the secondary bodies.

3. There is a condensation from the partially co-rotating plasma, and from infalling grains trapped by it, with results in dust particles. These accrete to form planetesimals which eventually coalesce to secondary bodies. Their masses grow slowly during the whole period during which matter falls in from the primeval cloud. When the mass of the primeval cloud is exhausted - or dissipated - the growth of the secondary bodies stops. They have reached essentially their present state.

4. This sequence of processes leads to the formation of the planets orbiting around the sun and is later repeated in miniature around the planets where it leads to the formation of (regular) satellites.

The state at an arbitrary time during the formative period is characterized by a plasma which is penetrated by prominence-like filaments from the central body and at the same time a cold cloud of dust containing planetesimals forming from the dust. These are formed from the infalling matter after being processed by electromagnetic effects. They accrete to secondary bodies. Hence when seen from a large distance the formative process would be characterized by a protostar, perhaps invisible because of absorbing dust grains around it. At the same time the plasma would exhibit rapidly varying chromospheric and coronal phenomena. The whole region of planet formation should be surrounded by the rests of the primeval cloud, which should be an HII region, containing appreciable quantities of dust. The possibility to identify the state of formation with observable celestial objects has been discussed by Alfvén (Ref. 13).

B The other model is the well-known basically Laplacean model which is based on non-hydromagnetic processes of solar system formation. This approach is now differentiated into the Kuiper-Cameron collapse models and the planetesimal model. For reasons summarized by Larsson (Ref. 9) there are serious objections to the collapse model (see also ESS). The planetesimal models are in some - but certainly not all - respects similar to the last phase of the hydromagnetic model, which basically is a model of the processes leading from the cloud-protostar state to the formation of planetesimals. This means that we can divide the general cosmogonic controversy into two controversies: one about the creation of the planetesimal state and the other about the evolution of this state to planets or satellites. To some extent we can discuss these two controversies independently.

So far I have tried to present what I believe is the general state of the basic physics which I think must constitute the background of all serious discussions about the formation of interstellar clouds and their development into solar (or stellar)

systems. Although this might reveal what approach to the problem I personally favour, I am not going to give a detailed argumentation here for the views which Gustaf Arrhenius and I have presented in three monographs and a large number of papers. As far as we know there has been no serious objections to these views presented in the literature, although some of the proposed component processes have been criticized or questioned. All modern workers in this field seem to accept the importance of hydromagnetic processes in the low density stages of development but most of them believe that the developing solar nebula passed a stage when hydromagnetic effects were negligible. As has been shown above, the change from homogeneous to inhomogeneous models makes this conclusion doubtful.

## 6. IMPORTANT BASIC QUESTIONS

### 6.1 The hetegonic principle

In three monographs and a large number of papers Arrhenius and I have outlined the reasons why the satellite systems and the planetary system would be formed by essentially the same processes. This is also the basic assumption favored by a number of other scientists, e.g. Horedt. (This is of course not a new idea. When Galilei discovered the Galilean satellites 370 years ago he claimed that they were a planetary system in miniature - we have argued the same thing for only 37 years.) If this premise is accepted, the analysis of the formative processes gets at least four well-developed systems to use for our studies. To our knowledge there has been no objection forwarded against this "hetegonic principle". Few theories - except ours and Horedt's - of the origin of the planets are applicable to the formation of satellites. There are even theories of the formation of terrestrial planets which are not applicable to the formation of the giant planets.

### 6.2 The band structure of solar system

From the time of Laplace, it has been believed that the solar system must have formed with a homogeneous disc as an intermediate state. There has never been any good argument in favour of this view. In fact if we plot the smeared-out density distribution in the planetary and satellite systems, we find that this varies drastically. Indeed, there are intermediate regions with densities of  $< 10^{-6}$  of that in the most dense regions, and even in the latter, there are variations of orders of magnitude (see Fig. 4; ESS 2.5.1, 2.5.2, 2.5.3, 2.5.4). It is evident that homogeneous models are as misleading in this field as they are in so many others. The extremely large variations in the mass accumulated at different distances from a central body is an important fact which must be taken into consideration when accounting for the evolution of the solar system.

Since the matter out of which the secondary bodies (satellites or planets) are formed is likely to derive from matter falling in towards the central body, it is natural to plot the secondary bodies with their gravitational potential, equivalent to the velocity they attain if falling from infinity (see ESS, chapter 21). When this was done (1942) it was discovered that the solar system has a pronounced band structure which, if not due to coincidence, must be of basic importance for the understanding of how the solar system was once



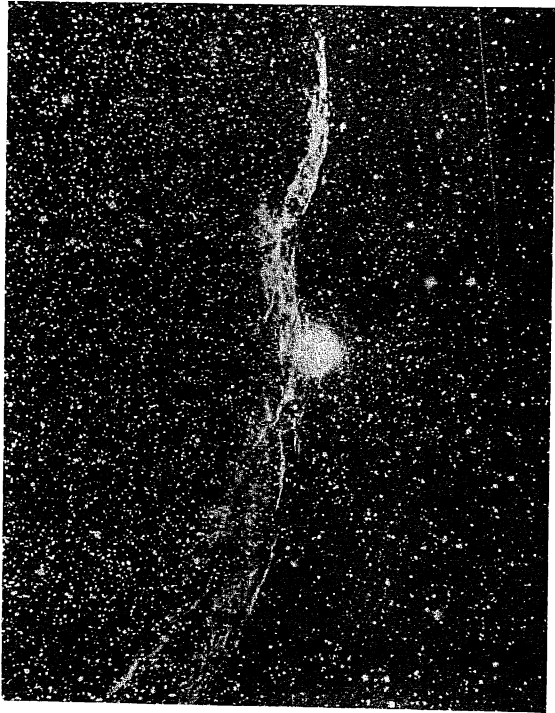


Fig. 3a Detail of the Veil nebula

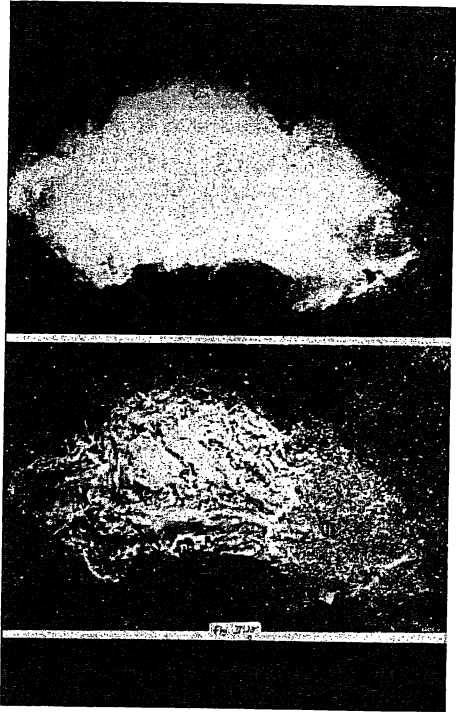


Fig. 3b Filamentary structures are much more common than usually thought as shown by comparing the ordinary photograph of the Lagoon nebula in Sagittarius (upper picture) with the same photograph subjected to contrast enhancement (lower picture)

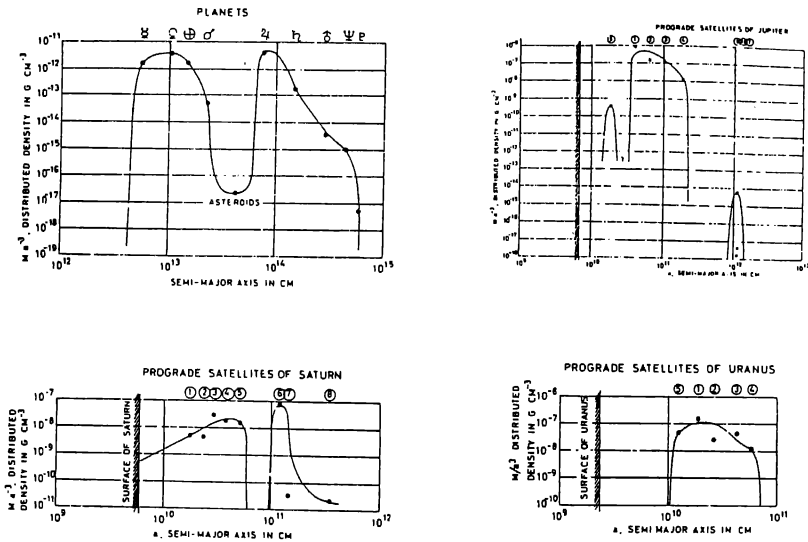


Fig. 4 Distributed density versus semimajor axis for the planets the prograde satellites of Jupiter, Saturn and Uranus

formed (see Fig. 5).

The band structure of the solar system can be understood if there is a mechanism which stops matter falling in from large distances when its velocity has reached certain critical values,  $v_c$ . From the band structure diagram it was evident that these values for the most common elements corresponded to the relation

$$\frac{mv^2}{2} = eV_{ion}$$

( $m$  mass of atom,  $V_{ion}$  ionization potential). A natural explanation would be that when a falling non-ionized gas has obtained the same energy as is necessary for ionization, it will be ionized.

However, then the theory of ionization of a falling gas (in relation to e.g. a thin plasma resting in the magnetic field of the central body) was developed according to the classical theory, it was found that no strong effect should be expected when  $v_c$  was reached. As the classical theory could not be considered as sacrosanct, an experimental investigation was started as soon as the thermonuclear technique had made this possible. The experiments demonstrated that as soon as the relative velocity between a non-ionized gas and a magnetized plasma exceeded  $v_c$ , a very strong interaction is observed. This is now called the "critical velocity" phenomenon, and has been extensively investigated both experimentally and theoretically. The critical velocity is the only physical phenomenon discovered after being predicted by a theory of solar system formation. Further, based on the band structure, B. De (Ref. 11) predicted the existence of a ring around Uranus in 1972 which was discovered several years later. This is the only time an essential new feature of the solar system has been predicted by a theory of solar system formation.

The Jovian ring was not predicted explicitly, but it is located in one of the bands of the band structure diagram which was constructed decades before its discovery.

Further, since the construction of the band structure diagram, the following new celestial bodies have been discovered: a number of Saturnian satellites inside Mimas, the Uranian satellite Miranda and one Jovian satellite. All of the newly discovered regular satellites fall in the bands of the diagram. Hence we can state generally that all the planets and all the regular satellites fall within the bands. A possible exception is the Marian satellites. According to some authors (Ref. 12) they are captured asteroids. Even if the arguments for this are not very convincing, it is likely that they are connected with the asteroid belt.

A large number of new asteroids have also been discovered. They do not change the mass-distance diagram of the asteroids. They do not contradict the earlier results, but neither do they add support to the band structure picture.

We conclude that the band structure cannot be due to coincidence. It is obvious that its reality and significance are very well confirmed.

We have seen how an interplay between gravitational and electromagnetic forces is likely to have formed

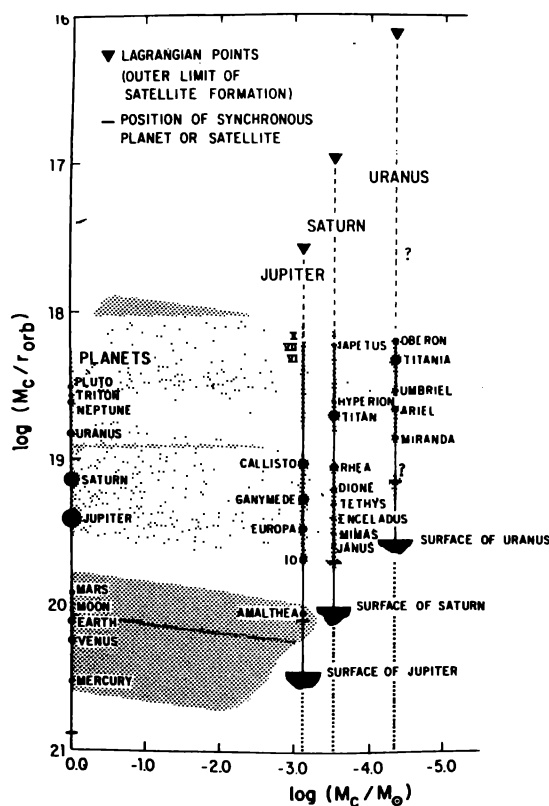


Fig. 5 Gravitational potential energy, which is proportional to the square of the critical velocity, as a function of the mass of the central body for the planetary and satellite systems. The diagram shows that all the regular bodies of the solar system are found in regions which correspond to certain values of the velocity of free fall. These values agree with the critical velocity for the most abundant elements.

interstellar clouds, and formed stars in them. The band structure is also a result of such an interplay. The transfer of angular momentum is almost exclusively due to electromagnetic effects. There now remains two types of processes in the sequence leading to the formation of planets and satellites: the transition from the plasma phase to the planetesimal phase and the accretion of planetesimals to planets and satellites. We shall discuss these in a following lecture.

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