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THE ROLE OF PLASMA IN THE PRIMEVAL NEBULA

H. ALFVEN, G. ARRHENIUS and D. A. MENDIS

The role of plasma and hydromagnetic processes in the primeval solar nebula is evaluated. In the light of the present knowledge of particles and fields in space it is difficult to avoid the conclusion that they must have played a crucial role in the emplacement of the material as well as its subsequent condensation into "planetesimals." Strong evidence in support of these processes in the primeval nebula is provided by the dynamical fine structure of the asteroidal belt and the Saturnian rings. The importance of current planetary magnetospheric as well as cometary research in clarifying certain physical processes believed to have occurred in the primeval nebula is stressed.

INTRODUCTION

Most theories of the origin of the solar system tend either to completely ignore or minimize the role of plasma and hydromagnetic processes in the primeval nebula. However there is a reason to believe that these processes not merely played some role, but rather that they played a fundamental role both in the chemical differentiation and in the dynamical state of the planetary as well as the regular satellite systems.

We are now going back over 4 billion years into the past and there is more uncertainty and speculation about what happened then than what happened subsequently. This is not only because of the time factor but also because plasma physics and hydromagnetics are much more complicated and less developed fields than celestial mechanics which is the basis of the evolution of the later granular phase. Furthermore, the underlying chemistry, at least in the earliest stages, was not equilibrium neutral chemistry but rather non-equilibrium plasma chemistry, which too, despite recent advances with regard to processes in the interstellar medium, is in a less developed state than neutral gas chemistry.

However in the Saturnian ring system and in the asteroidal belt, which have not undergone the final step in the evolutionary process into single consolidated bodies due to different reasons, the solar system has retained two time capsules containing vital clues about the state of the plasma from which they condensed.

Also recent magnetospheric research indicates that the basic hydromagnetic processes believed to be involved in the primeval nebula is operative even today albeit on a much reduced scale.

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THE CRITICAL VELOCITY EFFECT AND THE EMPLACEMENT OF THE PLASMA

Our basic model consists of a spinning central body, be it the sun or a planet or a precursor state of either. It is assumed to have a magnetic field which is dipolar. It is still surrounded by a remanent cloud which is gradually falling in, with a small amount of plasma present at any time.

It is an experimentally observed fact that when the infall energy of a neutral atom is equal (to the first-order) to its ionization energy rapid ionization sets in, even though the collision mean free path is orders of magnitude larger than the size of the plasma region in question. This is the so called "critical velocity effect" observed in the early homopolar experiments (Angerth *et al.* 1962) and later in plasma beam experiments (Danielson 1970). The theoretical justification is not so obvious because the ionization must be produced largely by the electrons and their acceleration processes need to be understood. While there are several theories, an excellent review is provided by Sherman (1973). We will not dwell into the question any further here. We will only add that in the cosmogonic case, it is not necessary that the critical velocity process ionizes all the infalling gas, because large amounts of energy are released when the partially ionized gas is accelerated during the partial corotation process, which we will discuss later. This energy is available for further ionization. So the critical velocity process may be regarded as only the first step in a more involved process.

Once a neutral species is ionized it is stopped by the magnetic field of the central body, while the other species freely fall through. So the consequence of this critical velocity effect is to stop different groups of elements at different distances from the central body and thereby produce a chemical differentiation. This was earlier proposed (Alfven 1954) to explain the observed band structure both in the planetary and in the satellite systems wherein all the planets and all the prograde satellites fall into one of three (or perhaps four) horizontal bands of gravitational potential energy, which are separated by wide gaps almost devoid of matter. See Fig. 1.

However if only atomic species are considered, the observed secondary bodies fall into the wrong bands. For instance the terrestrial planets are observed in the region where H and He are stopped, the large outer planets, Jupiter, Saturn, Uranus and Neptune are located in a region containing C, O and N, but deficient in H, while Pluto is located in the region composed mainly of the metals. If, however, this obviously oversimplified model is made more realistic by allowing for the existence of radicals and molecules as well as refractory dust, these difficulties are largely overcome (Alfvén and Arrhenius 1976). For instance, radicals such as CH can increase the H content in the region where the giant planets are formed, while the ablation of the fast moving refractory grains in the innermost region occupied by H and He can enrich it in metals, silicon, etc., which would ultimately account for the chemical composition of the small terrestrial planets.

THE TRANSFER OF ANGULAR MOMENTUM TO THE SURROUNDING PLASMA

Once the plasma is emplaced at various discrete distances from the central body the next stage consists of its acceleration resulting in the transfer of angular momentum to it from the spinning central body. This is illustrated in Fig. 2, where, as long as the angular velocity (ω) of the plasma is less than the angular velocity of the spinning central body (Ω), a homopolar e.m.f. is induced in the circuit which causes currents to flow in the manner shown. This current causes an I x B body force on the plasma and transfers angular momentum to it from the central body. The current also pinches the plasma, thereby causing high density and low temperature regions, where grain condensation processes would proceed most effectively.

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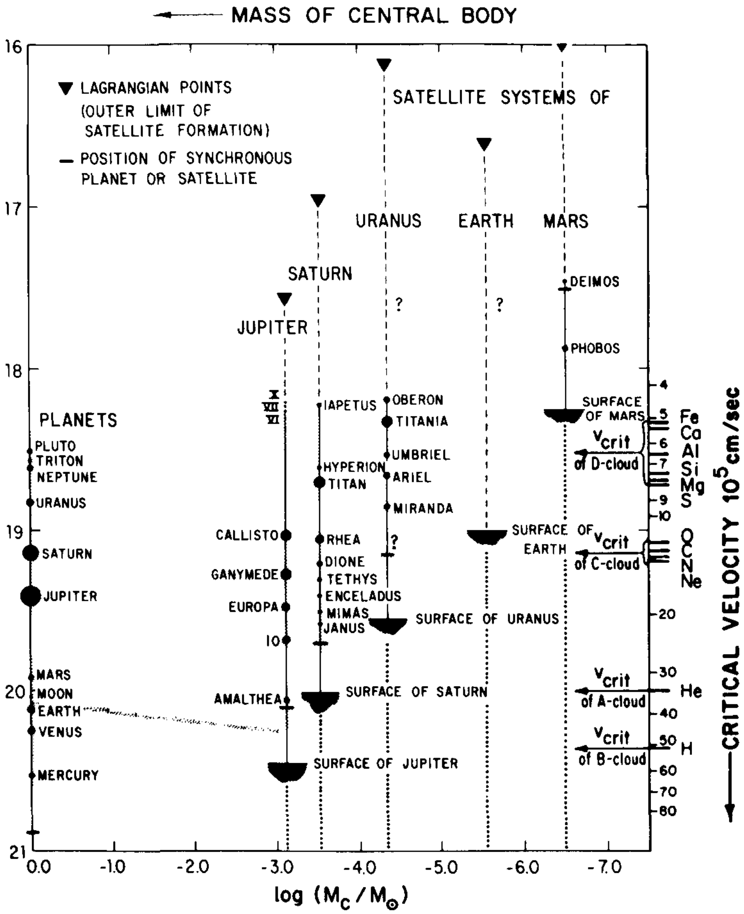

Figure 1. The "band structure" in the planetary and satellite systems.

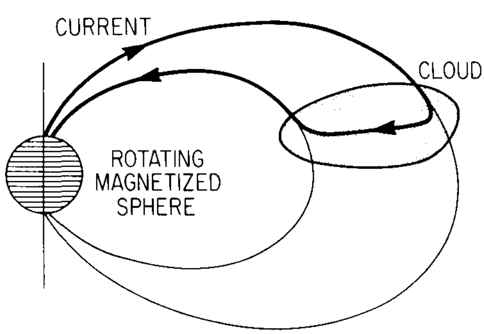

Figure 2. Transfer of angular momentum from the central body to the surrounding plasma.

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This current system is very similar to one part of the present day ionospheric-magnetospheric current system, shown in Fig. 3.

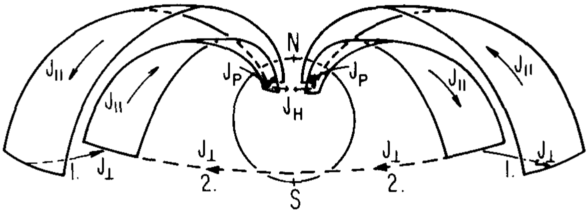

Figure 3. Part of the terrestrial ionospheric-magnetospheric current system.

From a purely hydromagnetic point of view one would expect the process to continue until the angular velocity of the plasma is equal to that of the central body - *i.e.*, until a state of Ferraro corotation is achieved. However, as we know from present day magnetospheric research, the establishment of parallel electric fields and electrostatic double layers by the field aligned currents eventually decouples the outer plasma when it becomes essentially free-wheeling. The situation is depicted in Fig. 4. Here the dynamic plasma equilibrium is maintained by the balance between gravitation, the centrifugal force and the electromagnetic force.

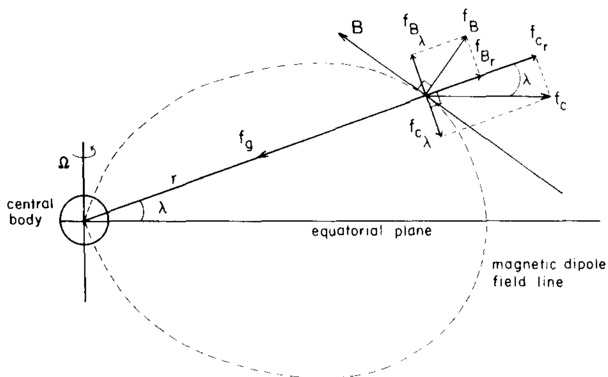

Figure 4. The "free-wheeling plasma" model.

CONDENSATION OF THE PLASMA: "THE 2/3 FALL DOWN RATIO

A consequence of the dipolar field we assume (which we believe is not sufficiently distorted by the current system) is that a plasma element at a given distance from the central body has 2/3 the K.E. of circular Kepler motion at that distance. Consequently if condensation takes place and the grain decouples from the magnetic field, it will fall through the equatorial plane of the central body in an ellipse of eccentricity 1/3 and always intersect it at a distance of 2/3 the original distance at which it formed. Consequently due to inelastic collisions with material already existing there, the grains will tend to collect in that region. The eccentricity and inclination will gradually reduce and the grain will be incorporated into an almost circular "jet stream"

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from which planets and satellites eventually grow. We will not discuss that final phase of evolution here - it has been done elsewhere (Alfven and Arrhenius 1976). What we wish to know is if there is any evidence present today for the aforementioned processes having taken place in the past. The answer is in the affirmative and is provided by the earlier mentioned time capsules - the asteroidal belt and the Saturnian rings.

THE TIME CAPSULES

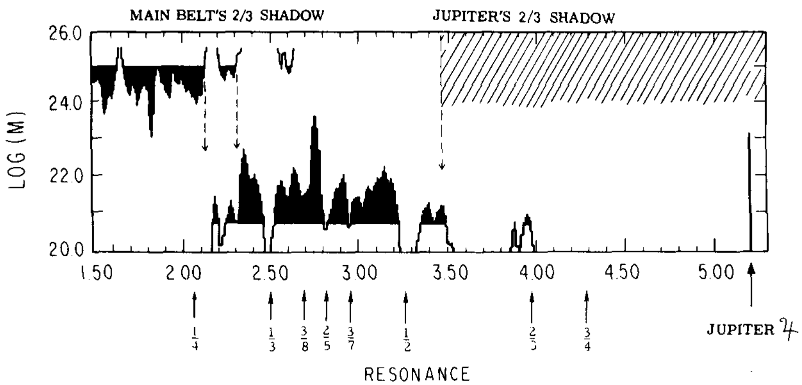

Figure 5. Mass distribution of the main belt asteroids showing "shadow" effects.

The Asteroidal Belt

The mass distribution in the main belt asteroids is shown in Fig. 5 where mass (m) vs. semimajor axis (a) is plotted, assuming constant albedo and density as a first approximation. It is seen that the structure is very regular, with sharp cutoffs at 2.2 AU and 3.5 AU. In between these limits lie 99.9% of the total mass. The only notable exception is the Hilda group at 3.95 AU, which correspond to a 2/3 resonance with Jupiter. There are no known processes operating at the present time which can account for these sharp cutoffs. On the other hand, an immediate explanation is provided by the aforementioned cosmogonic process which predicts a 2/3 fall down ratio for the condensed matter. The outer limit of the asteroid belt is almost exactly 2/3 the orbital radius of Jupiter. This is clearly because the grains falling into the asteroidal region from outside Jupiter or its parent jet stream would be perturbed or captured, and consequently the asteroidal region must derive from material condensing inside the orbit of Jupiter. Furthermore, because material in the asteroidal belt will itself sweep up yet uncondensed plasma, there should be a sharp fall at 2/3 its outer limit. In other words, the inner limit of the asteroidal belt is its own cosmogonic shadow.

It is also significant that there are hardly any asteroids with eccentricity, $e \gtrsim 1/3$.

The Saturnian Ring System

The Saturnian rings form another excellent example of arrested development. While the asteroid belt did not progress any further due to the lack of mater-

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ial in its source region, the Saturnian rings did not do so because they are inside Saturn's modified Roche limit.

The Cassini division between the A and B rings is normally attributed to the 1/2 resonance of Mimas. However it is substantially displaced inwards. Moreover there does not exist the striking fine structure as in the asteroidal belt, where resonances are expected. This is because the ratio of the masses of Mimas to Saturn is 10^{-7}, whereas the ratio of masses of Jupiter to the Sun is 10^{-3}. So the perturbing forces in the former case are 10^4 smaller than in the case of the asteroidal belt. The Cassini division, however, is almost exactly at 2/3 the distance of Mimas and may be explained directly as the cosmogonic shadow of Mimas as is clearly apparent from Fig. 6.

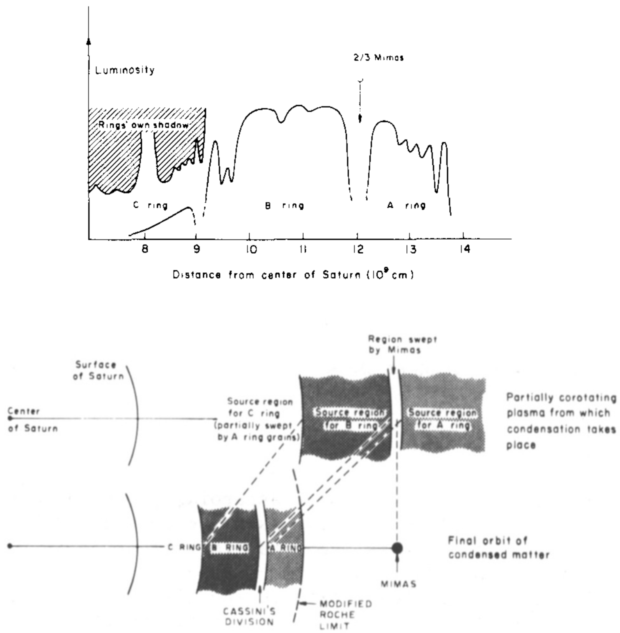

Figure 6. "Shadow" effects in the Saturnian ring system.

It is also interesting to note that a brightness drop observed in the B-ring corresponded exactly to 2/3 the distance of the innermost satellite (Janus) of Saturn subsequently discovered by Dollfus in 1967.

So we see that the hydromagnetic model can explain not only the basic band structure and chemical differentiation in the planetary and satellite systems, but also the dynamical fine structure of those regions which have not undergone the evolutionary process to its completion, and are therefore most likely to retain evidences of the early plasma processes.

In conclusion we note once again that the underlying chemistry in the early nebular stage is clearly non-equilibrium plasma chemistry, as is believed to be the case in the interstellar medium, and not equilibrium neutral chemistry, which is the basis of most cosmochemical theories of the origin and evolution of the solar system.

Clearly much work remains to be done in the laboratory along these lines.

ACKNOWLEDGEMENTS

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DISCUSSION

CHAPMAN: I think it is healthy for science to have alternative models, such as the one you have summarized, to explain the observational data. But you often assert that the Alfven-Arrhenius model accounts for features of the solar system that are not accounted for by the more popular models, whereas that is often not the case. For instance, you said there was no other explanation for the location of the boundaries of the asteroid belt, whereas these are fully understood in terms of current dynamical processes, as described yesterday by J. G. Williams.

MENDIS: Surely any particular feature of the solar system can be explained by more than one plausible theory, on a one to one basis. It is the fact that the Alfven-Arrhenius model explains the dynamical fine structure of the solar system everywhere so naturally that makes it compelling. As regards the location of the boundaries of the asteroid belt; i.e., *why the outer boundary is at exactly 2/3 the Jupiter distance, while at the same time the inner boundary is exactly 2/3 the outer boundary is certainly not explained in any other way. I do not believe that Williams answered that question.*

DELSEMME: Alfven and Arrhenius' ideas are sound when both the density and the temperature are very low. The chemistry can be changed then by reshuffling the chemical species by charge-exchange reactions. But at those high pressures that we speak about for the solar nebula, it is difficult to visualize how the plasma could not be pressure quenched and could therefore still change the whole scenario.

MENDIS: The temperature need not be low. In fact during the acceleration of the plasma a large amount of energy is liberated which is available for heating the plasma. As regards the high pressures you talk about, it is not clear to me that they are really necessary. In any case only a very small degree of ionization is required for the hydromagnetic treatment to be applicable.

ANDERS: In fairness to Alfven, I must note that he requires only a small degree of ionization ($\sim 10^{-6}$) for the magnetohydrodynamic effects. I know of no reason why the gas should not have been ionized to this extent. Such differences of opinion as remain, concern the chemical *effects predicted by Arrhenius and Alfven in 1970, which require higher degrees of ionization. Such plasma-*

chemical effects have been looked for by various authors in the last 6 years, but to my knowledge, none were found that could be uniquely attributed to plasma.

MENDIS: It seems to me that much more work on the plasma chemistry is required before definite conclusion can be drawn.

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