SOLAR SYSTEM HISTORY AS RECORDED IN THE SATURNIAN RING STRUCTURE

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Abstract. The paper is based on Holberg's analysis of the Voyager photographs in both reflected and transparent light, combined with occultation data of stars seen through the rings.

Besides rapidly varying phenomena (spokes, braided ring, etc.), which according to Mendis are due to gravito-electromagnetic effects, the ring consists of a *bulk structure*, *a fine structure*, and also a *hyperfine structure*, showing more than 10000 ringlets.

The large number of ringlets can be explained by the Baxter-Thompson 'negative diffusion'. This gives the ringlets a stability which makes it possible to interprete them as 'fossils', which originated at cosmogonic times.

It is shown that the *bulk structure* can be explained by the combined 'cosmogonic shadows' of Mimas, the co-orbiting satellites, and the Shepherd satellites. This structure originated at the transition from the plasma phase to the planetesimal phase (which probably took place $4\text{–}5 \times 10^9$ y ago).

Further, Holberg has discovered that the shadows are not simple void region but exhibit a certain characteristic 'signature'. This is not yet understood theoretically.

Parts of the *fine structure* are explained by Holberg as resonances with the satellites. Parts are here interpreted as cosmogonic shadow effects. However, there are a number of ringlets which can neither be explained by cosmogonic nor by resonance effects.

The most important conclusion is that an analysis of the ring data is likely to lead to a *reconstruction of the plasma-planetesimal transition with an accuracy of a few percent.*

1. Introduction and Classification

It is generally recognized that the behavior of dispersed media in space is regulated by a combination of mechanical and electromagnetic forces, often referred to as magneto-hydrodynamics or magnetoplasma physics. A remarkable exception to this view is the evolutionary history of the solar system, where the generally accepted approach takes for granted that electromagnetic effects were of negligible importance. However, space research has, to a large extent, consisted of a clarification of the decisive role of electromagnetic forces in regulating the dynamics of dispersed media in the upper ionospheres, the magnetospheres, the solar photosphere, and corona and in the whole heliosphere. This has caused or is causing a 'paradigm transition', leading to a drastically new view of the properties of dispersed media. Moreover, much progress has been made in the 'translation' of phenomena between one astrophysical or geophysical region and another, connecting also with laboratory investigations (see Alfvén, 1981a).

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All this is now making it possible to depict several of the processes regulating the evolution of the solar system as *extrapolations of more or less well-studied phenomena*. Moreover, the studies of dusty plasmas, which are of decisive importance in the evolutionary history, have led to the new field of 'gravito-electromagnetics' (Mendis *et al.*, 1982).

The result of all this space-research-stimulated development is that it now is necessary to take account of plasma processes in all realistic theories of the origin and evolution of the solar system. The field is now ripe for a change which is at least as drastic as the change in a number of other fields of cosmic-plasma physics (Alfvén, 1981a, 1982). Of paramount importance are the results of the Pioneer/Voyager/Saturn encounters which will be analyzed in this paper.

The conclusion is that it seems possible to *reconstruct some events taking place at cosmogonic times with an accuracy of a few percent.*

The encounters with Saturn have shown that the ring system consists of at least four different structures:

1.1. Transient phenomena

Rapidly changing structures such as the spokes, and some excentric rings like the *F* ring, are likely to consist of micron-sized particles. They are shown to be produced by gravito-electromagnetic effects (Mendis *et al.*, 1982; Alfvén and Mendis, 1983).

1.2. The bulk structure

This is essentially the structure which can be observed from the Earth. This structure has size of $\sim 0.1 R_h$ (*A*, *B*, and *C* rings: 0.2, 0.4, 0.3; Cassini's division: 0.1). It is a controversial question whether this is produced by ordinary celestial mechanical forces working today or *is a fossil from cosmogonic times* when it may have been produced partially by plasma effects. The first alternative is preferred by most people working in the field, but more than half a century of effort has not led to any reasonable explanation of the bulk structure. Concerning the fossil (plasma) theory there has not yet been a serious discussion about its merits, but this seems essentially to be due to the fact that the cosmogonic discussion is traditionally bound to non-plasma theories (see Alfvén and Arrhenius, 1975; 1976). With the recent results of space missions to Saturn as a background, we shall here give a brief review of the fossil (plasma) theory of the bulk structure, thus trying once again to start an unbiased cosmogonic discussion.

1.3. Fine structure

Typical scale 0.01–0.001 $R_h = 600$–60 km. This is essentially the structure which can be seen from photographs of the rings. It includes the *fine structure of the borders* of the rings. The transitions are sometimes abrupt, but are often of the order of $0.001 - 0.005\ R_h$. Further, there are several *resonances* with the satellites which have a breath of 0.001 R_h. These are drastically different from the signatures

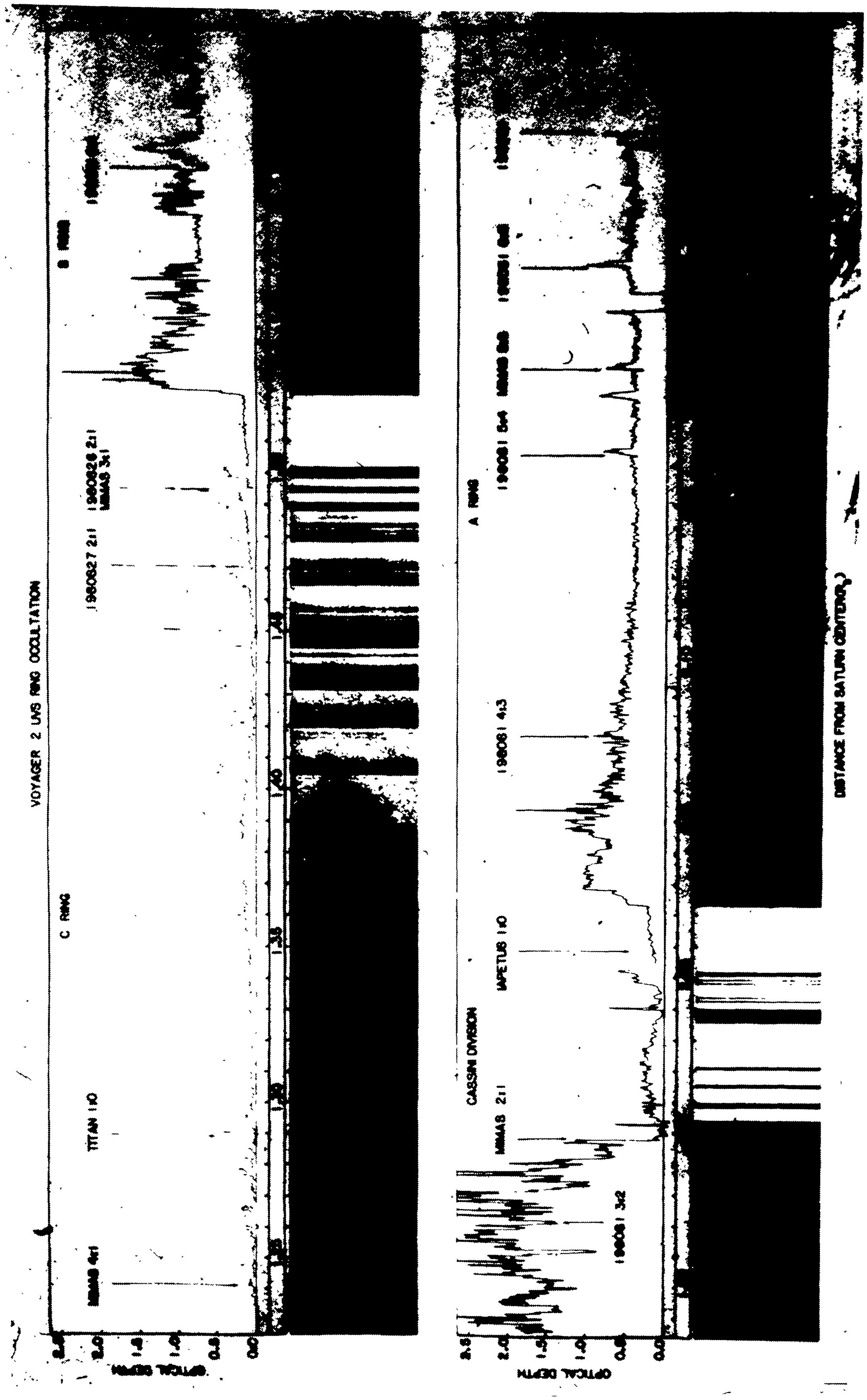

Fig. 1. The normal optical depth of the rings from Voyager 2 UVS ring occultation data. Below is the brightness of the rings in transparent light (Holberg *et al.*, 1982, 1983).

associated with the bulk structure. There are also a number of unidentified structures, especially in outer parts of the C ring, with breadth of $0.005R_h$ (cf. Figure 1).

1.4. Hyperfine structures

Typical scale $0.0001R_h$ (6 km) can only be seen by occultation measurements. They help to make sure identifications of the larger features. However, there are also other signatures which are usually identified as gravitational waves, excited by resonances. We shall postpone a discussion of these very interesting phenomena until (a), (b), and (c) have been more clarified.

2. Can the Bulk Structure be a Fossil?

The main mass of the Saturnian ring system is believed to be in the form of particles of a size of mm–several m. This means that they are 10^{10}–10^{20} times more massive than the micron-sized particles which are responsible for the gravito-electromagnetic effects. It is reasonable that they obey other laws than the micron-sized particles; and, hence, it is possible that they are more permanent. A discussion whether these particles now may move in essentially the same orbits as they were put in at cosmogonic times has been given by Alfvén and Arrhenius (1975, 1976; Chapter 18.6.2, 6.6, 6.7). The answer is clearly affirmative. One of the factors is that (as shown by Baxter and Thompson, 1971, 1973) collisions between particles in Kepler orbits produce *negative diffusion* (under certain conditions which seem to be satisfied). *This explains the large number of separate ringlets* in the rings. It also makes it *possible that the bulk structure of the rings is a fossil.*

The resistance against the idea of negative diffusion seems now to be weakening. This is shown by a recent paper by Lin and Bodenheimer (1981), who give what is essentially the hydrodynamic analog of the Baxter and Thompson approach, without mentioning their ten-years-older work. They want to call it 'viscous instability'. To associate a phenomenon which may make the ring system stable over billions of years with 'instability' seems not to be appropriate, so the original term 'negative diffusion' seems preferable.

3. Fossil Theory of the Bulk Structure

As has been shown in detail by Alfvén and Arrhenius (1975, 1976), the bulk structure of both the asteroidal belt and the Saturnian rings should represent an *intermediate state* in the formation of planets and satellites. It should contain essential information which is lost when the planetesimals aggregate to big bodies. The bulk structure of both these regions can be explained as a result of the *transition from the plasma state to the planetesimal state* in the evolutionary history of the solar system.

The first phase of the evolution of an interstellar cloud to a star or a solar

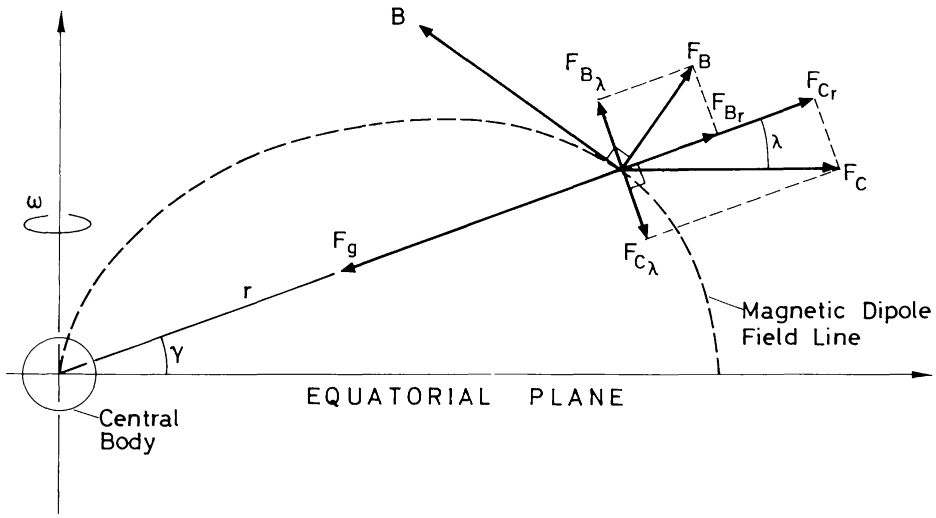

Fig. 2. Charged particles (charged dust, or perhaps also plasma elements) in an axisymmetric magnetic dipole field around a gravitating rotating body. If their motion is magnetic-field dominated, a quasi-stationary motion requires that the projections of gravitation and centrifugal force on the magnetic field line are equal. As shown by Alfvén and Arrhenius (1975, 1976), this means $v_0(\frac{2}{3})^{1/2}\, v_K$, where v_θ is the rotational velocity and v_K the Kepler velocity.

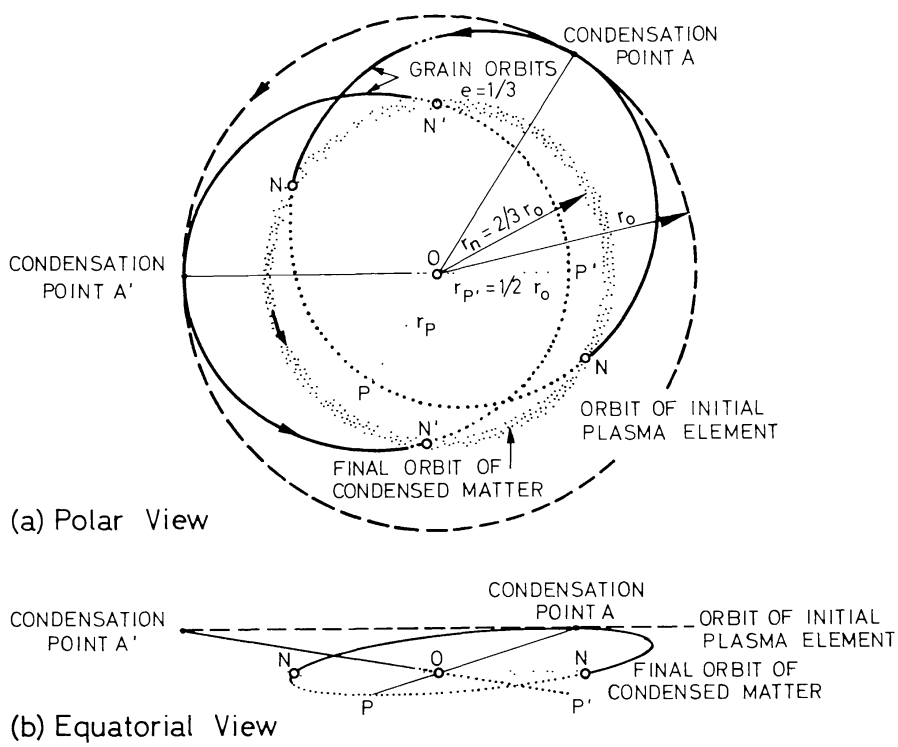

Fig. 3. Vanishing magnetic forces give a transfer into elliptic orbits. If the magnetic field or the particle charge suddenly disappears, the particles at the central distance a_0 will orbit in ellipses with semi-major axis $a = \frac{3}{4}a_0$, and eccentricity $e = \frac{1}{3}$. They will collide mutually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

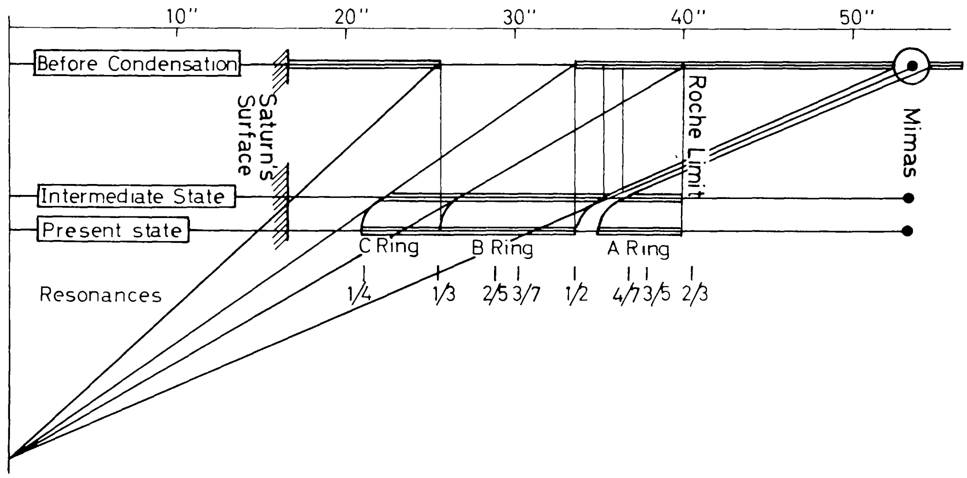

Fig. 4. Correction of the fall-down ratio. The upper line, marked 'Before Condensation', shows the plasma density in the equatorial plane of Saturn, the center of which is at the left end. Next line, marked 'Intermediate State', represents the density of the grains produced by condensation of the gas. 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).

system was strongly influenced by plasma forces, particularly gravito-electromagnetic effects in a dusty cloud (see Alfvén and Carlqvist, 1978; Alfvén, 1981b; Alfvén and Mendis, 1983).

At a certain evolutionary state there was a transition from the plasma state to the planetesimal state, from which later the present planets and satellites were formed. This transition was a slow process with a time constant of 10^7–10^8 yr (Alfvén and Arrhenius, 1975, 1976). During a period of such a duration there was a presumably rather slow injection of matter from distant remnants of the proto-solar cloud. The transition resulted in a *contraction by a factor* $\Gamma = 2:3$, a factor derived from the geometry of a magnetic dipole field (see Figures 2 and 3).

Satellites moving in the condensing plasma will produce 'holes' in it by absorption. This produces a *cosmogonic shadow effect* (see Figure 4). The forming ring itself absorbs plasma, and this produces a change in the angular momentum of the ring particles (Figure 4). The result is that the fall-down ratio Γ should be corrected downward by a few percent (from 0.67 to 0.63–0.65). For particulars, see Alfvén (1954).

4. Comparison with Pre-Voyager Observation

4.1. Asteroidal belt

A statistical study of the orbits of asteroids showed that, together with the resonance effects producing the Kirkwood gaps, it is the cosmogonic shadow effect that determines the bulk structure. There are *three clear identifications of the shadow effect*. The value of Γ *agrees with the theoretical value within* 1 *or* 2% (see

Alfvén, 1981b; Alfvén and Mendis, 1983). The value $\Gamma = 2:3$ should not be corrected as in the Saturnian rings.

4.2. Saturnian rings

Concerning the Saturnian rings, the best terrestrial observations (due to the French school) demonstrated that Cassini's division should be identified as the cosmogonic shadow of Mimas, and the inner edge of the B ring as the shadow of the outer edge of the *A* ring (see Alfvén and Arrhenius, 1975, 1976). Objections to the generally accepted resonance interpretation were presented. As is evident from Holberg's curves, these objections were correct, but because of the general reluctance to accept the introduction of electromagnetic effects, these arguments were never even mentioned in the general discussion of the evolution of the solar system.

When the remarkable photographs from Voyager were obtained, it was officially reported that the observed structure was 'contrary to all known laws of physics'. As there were three monographs and at least 20 papers in which the general character of the observed features was described, this was not a completely adequate statement.

5. The Early Voyager Results

The preliminary Voyager I results confirmed the earlier plasma approach identifications (Alfvén, 1981b; Alfvén and Mendis, 1983). The agreement with the theoretical predictions was unexpectedly good. The two earlier identifications were supplemented by a third identification, viz., the inner limit of the *C* ring as caused by the shadow of the outer limit of the *B* ring; hence, bringing up the total number of identifications from five to six. Further, the discovery of the *F*-ring-Shepherd-satellite complex made it possible to identify the edge between the *B* and *C* ring as caused either by this complex or by the outer edge of the *A* ring.

6. Present Day Plasma Distribution in the Saturnian Magnetosphere

Following our principle of trying to *consider cosmogonic phenomena as extrapolations of present observations*, it is of interest to see how at present the plasma is distributed in the Saturnian magnetosphere. Observations have been made by the Pioneer 11, Voyager 1, and Voyager 2 spacecrafts. (See the special issues of *Science*; respectively, Vol. 207, pp. 400–453, Vol. 212, pp. 159–244, and Vol. 215, pp. 499–594.) From these observations it is clear that the satellites of Saturn sweep holes in the plasma whereover it moves relative to them (see, e.g., Krimigis and Armstrong, 1982). The innermost region is of greatest interest to

TABLE I

Cosmogonic shadows

Saturnian ring from Holberg's data

	a	Γ
Mimas	3.075	
Co-orbitals	2.510	0.646
Shepherds	2.349	
	2.310	0.63
Cassini Center	1.984	
Outer B	1.945	0.655 (0.650–0.660)
Holberg min	1.58	0.635
Inner B	1.525	
Inner C	1.235	

Average $0.642 \pm 2\%$

Asteroidal region

	a	Γ
Jupiter	5.18	
Main belt		0.676
outer limit	3.50	
High density		0.674
outer limit	3.22	
High density		0.683
inner limit	2.36	
Main belt		
inner limit	2.20	
Theoretical value		0.667

(Alfvén, 1981b)

cosmogonic studies, and in this region the only available measurements are by the high energy particle detectors on Pioneer 11. The sweeping phenomenon is conspicuous in the upper part of Figure 5, taken, from Fillius and McIlwain (1980). *All satellites in the relevant region* produce very pronounced minima; viz., Mimas, the co-orbital satellites S1 and S3, and the shepherding satellites S26, 27.

We should expect that under cosmogonic conditions the dusty plasma was orders of magnitude denser and orders of magnitude cooler than the particles measured by Fillius and McIlwain (1980). Furthermore, the satellites were not in their present state. At least to a certain extent, their mass was distributed as jet streams. Still it is reasonable that a somewhat similar sweeping took place. The Larmour radii of the measured protons and the cosmogonic charged grains may be comparable.

If we assume that the Fillius–McIlwain curves are somewhat similar to the plasma distribution under cosmogonic conditions, we should expect that the present bulk distribution of mass in the Saturnian ring system should show some similarity with these curves reduced by the fall-down ratio Γ. Figure 5 shows that such a rough similarity indeed exists.

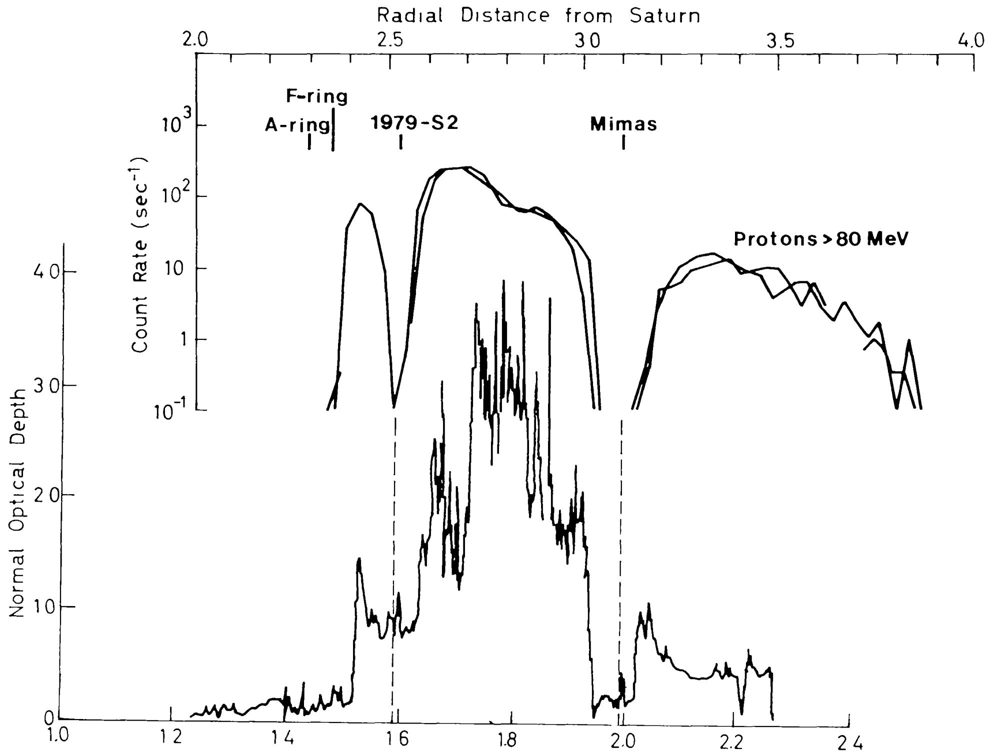

Fig. 5. Comparison between present magnetospheric plasma distribution and mass distribution in the rings. Present-day charged particle distribution in the Saturnian magnetosphere often shows void regions produced by absorption by the satellites. The upper curves are obtained by Fillius and McIlwain (1980). 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 (S_1 and S_3) and the Shepherds are identified with Cassini's division, the deepest minimum in the *B* ring, and the inner limit of the *B* ring.

7. Analysis of the Holberg diagrams

The detailed analysis of the ring structure by Holberg *et al.* (1982) now makes it possible to check the earlier results. We conclude from his data:

A. *All* the satellites in the relevant regions produce clearly identifiable structure (Figure 6): compare also Figure 8.

(1) Mimas produces Cassini's division. Taking 1.984 as the center of the Cassini division we obtain $\Gamma = 1.984/3.075 = 0.646$.

(2) The co-orbital satellites ('Janus') produce a very strong minimum in the *B* ring, which Holberg has discovered. This gives a *seventh identification* with $\Gamma = 1.58/2.51 = 0.63$.

(3) In Section 5 it was said that either the *F*-ring-Shepherding-satellite complex or the outer limit of the *A* ring produces the inner edge of the *B* ring. From the following discussion it will appear that the first alternative seems to be preferable.

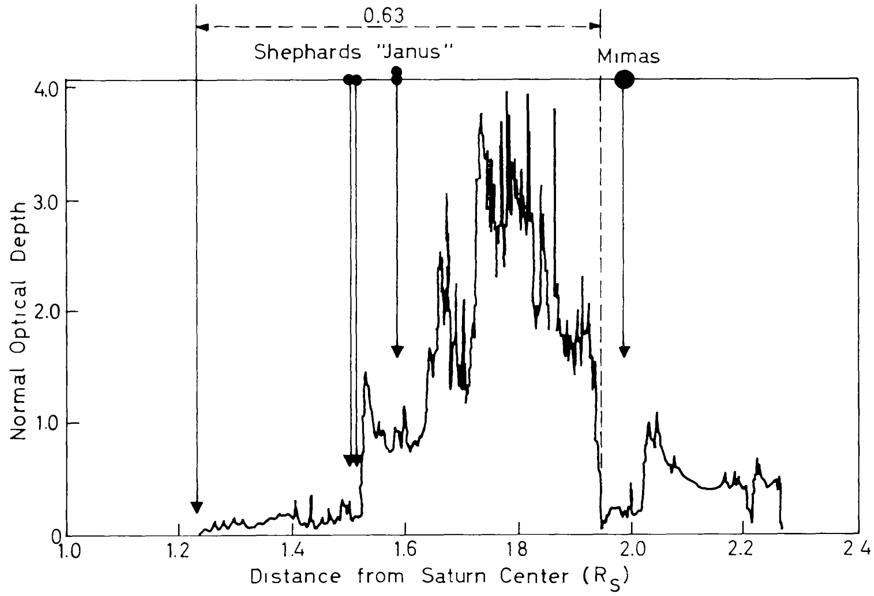

Fig. 6. Shadow production by Mimas, co-orbitals, and the Shepherds. The present orbital distances of Mimas, co-orbitals and the Shepherds, reduced by a factor $\Gamma = 0.64$ are supposed to produce the Cassini division, the deepest minimum in the *B* ring, and the border between the *B* and *C* rings. The inner limit of the *C* ring is identified as the shadow of the outer edge of the *B* ring (cf. Alfvén, 1981b; Alfvén and Mendis, 1983).

With the average of the Shepherds we obtain $\Gamma = 1.525 : 2.330 = 0.655$. The outer Shepherd alone gives $\Gamma = 0.650$, the inner $\Gamma = 0.660$.

Furthermore, the earlier identification of the inner edge of the *C* ring as the shadow of the outer edge of the *B* ring is confirmed. Holberg gives for the inner limit of *C* the figure 1.235. Hence, $\Gamma = 1.235 : 1.945 = 0.635$. Table I gives the Γ values from Holberg's data. They agree with earlier value (Alfvén 1981b; Alfvén and Mendis, 1983) but are probably more accurate.

It is important to discuss whether the agreements between the Γ values could be falsified by an arbitrary and biassed choice of the values. This is possible only to a very small extent. For example in Figure 1 the transition between *A* and Cassini occurs in two steps. At the present state of the analysis we could choose either step (and also and intermediate value). However, the distance between the steps is only 0.005 which is 0.2 %. It produces a similar change in the Γ value. As we have never claimed the accuracy to be better than 1 or 2 % an uncertainty of 0.2 % is negligible.

Hence, the Holberg material confirms the earlier conclusion that the transition from the plasma to the planetesimal was associated with a contraction by a factor $\sim 2:3$. The remarkably good agreement between the fall-down ratios in four different cases and the agreement with the theoretical prediction $\Gamma = 0.63$–0.65 indicate that the transition was a regular and reproducible process. This result is irreconcilable with the generally accepted view that the solar system originated through highly turbulent processes. However, it fits well into the scenario of a formation through a slow process, lasting 10–100 million years, during which there was a falling in of matter from the surrounding of a newly formed central body (planet or the Sun) (Alfvén and Arrhenius, 1975, 1976).

In this connection it should be observed that there does not exist any decisive support for the general view that cosmic plasmas usually are highly turbulent (see *Cosmic Plasma*, Chapter IV, 4).

8. Signatures of the Shadows

Holberg (1983) has pointed out that the cosmogonic shadows are not simple void regions but show detailed 'signatures'. Figure 7(a) shows the details of the transition from the *B* ring to the *C* ring, which we have identified as the shadow of the Shephards. Figure 7(b) shows also the transition between the *A* ring and the Cassini, which similarly is identified with the shadow of Mimas.

As Holberg pointed out the *A* Cassini transition region shows a detailed structure which is remarkably similar to that of the *B*–*C* transition region, This is evident already from Figure 1 where the outermost part of the *C* ring shows maxima at 1.49 and 1.50 which are analogous to the maxima at 1.992 and 2.001 in the outermost part of Cassini's division.

This similarity is more clearly shown in Figure 7a and b, which show Holberg's records with a higher resolution. Since according to Holberg, the double peak at

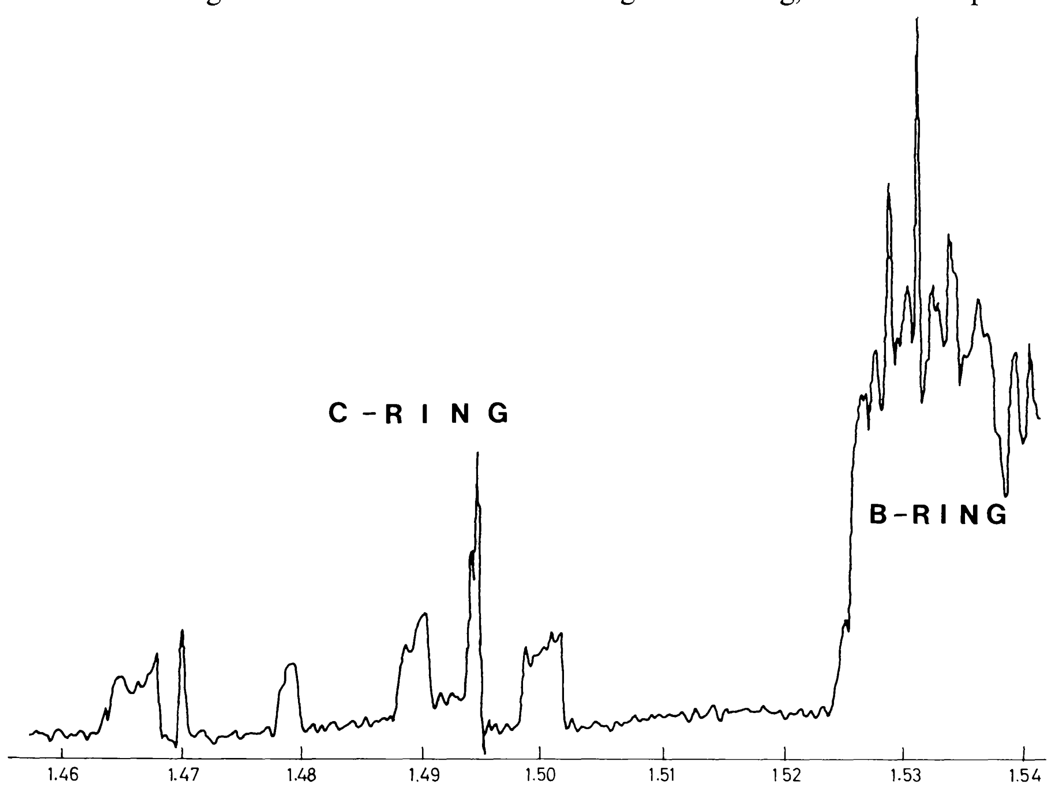

Fig. 7a. Density diagrams according to Holberg. Transition between *B*- and *C*-ring. The sharp double peak is identified by Holberg as resonances Mimas 3 : 1 and S26 2 : 1.

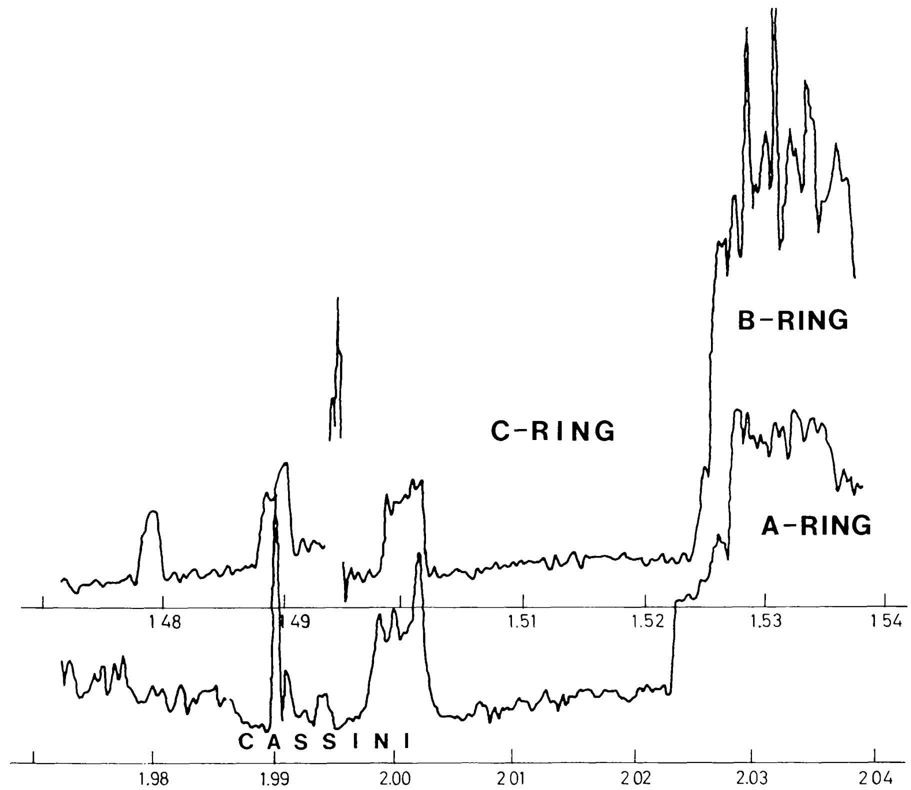

Fig. 7b. *Lower curve*: transition between A and Cassini. *Upper curve*: the same as 7a, but with the resonance peak eliminated. The curves are remarkably similar. However, the *B–C* transition is steeper and the plateau less well-marked than the A-Cassini transition.

1.495 should be identified with the Mimas 3 : 1 resonance and the S26 2 : 1 resonance, we should take away this in order to find what we may call the 'cosmogonic signature'. This is remarkably similar to the signature of the Mimas' shadow, as shown in Figure 7b. Indeed at about the same distances from the steep *B–C* ring and the *A*-Cassini transitions, there are two maxima (at 1.488 and 1.500) and at 1.990 and 2.001). The main difference is that the *B–C* transition is steeper than the *A*-Cassini transition, which has a more marked plateau. The similarity of the patterns remains down to 1.478, where the *C* ring shows a maximum which is absent in the Cassini division.

By analogy we should expect to find a similar signature at the 'Holberg minimum' produced by Co-orbiting satellites. The whole minimum is not included in Figure 1, but the diagram of Figure 6 seems to show a similarity viz. a double maximum around 1.60, a little outside the centre of the Holberg minimum. To try to make a comparison with curves of higher resolution is not very rewarding because these curves are highly disturbed by violent small-scale oscillations.

As a summary we may state that there is clear indication that the cosmogonic shadows are not simply void regions as anticipated but have a more complex structure. They exhibit a 'Holberg signature' consisting of two maxima at some distance to the left of the outer edge of the shadow. A study of such signatures will no doubt be of basic importance for an understanding of the cosmogonic transition from the plasma phase to the plantesimal phase.

9. Conclusions About the Bulk Structure

It is evident that the cosmogonic shadow effect explains essential parts of the bulk structure. It is also evident that it does not explain the structure completely.

We expect the *B* ring to be brighter than the *A* ring because the particles forming the *A* ring must passs the orbit of Mimas at the 2 : 3 contraction. However we do not expect it to be so massive as shown in Figure 1 and most clearly in Figure 6. This must be due to the existence of another population. This is also indicated by the fact that the Holberg minimum does not go down to zero.

Mendis (1983) has suggested that this *B* ring population may be due to gravito-electrodynamic effects at cosmogonic times. Such an effect can be expected to concentrate grains in the neighborhood of the synchronous orbit which is located at 1.8 R_h. It is premature to discuss this possibility in this paper.

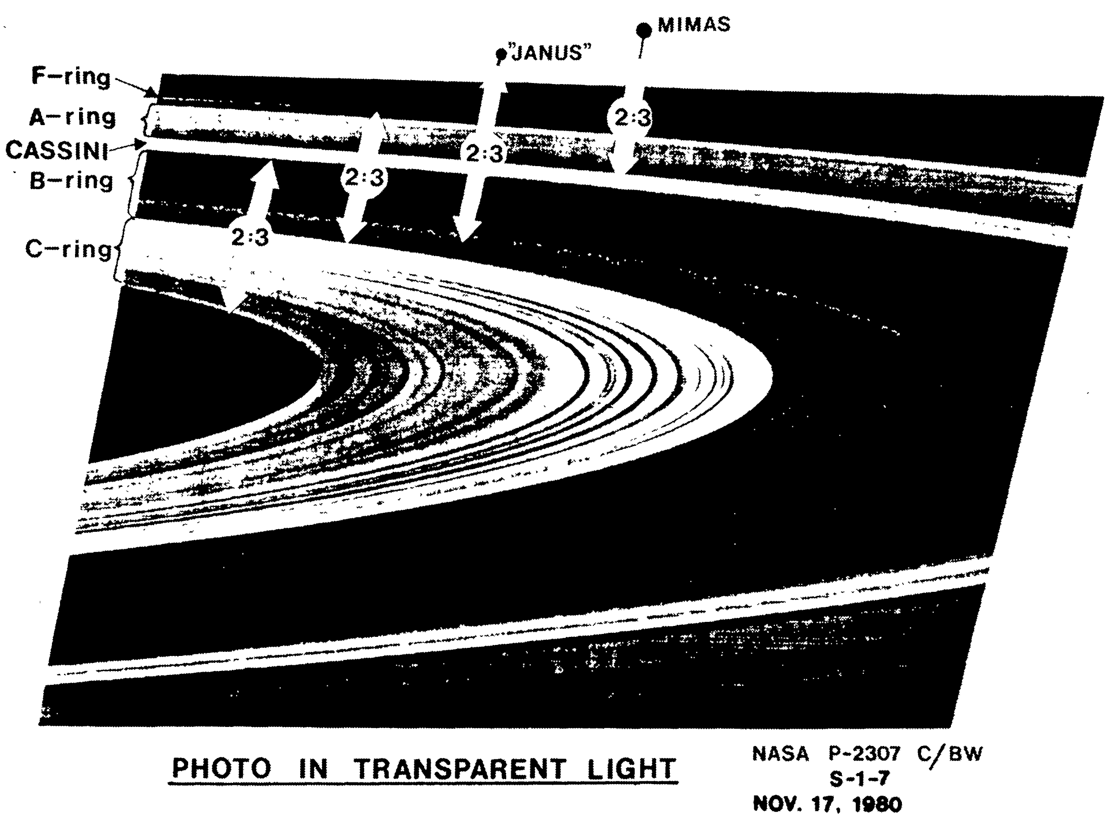

Fig. 8. Saturnian ring in transparent light with theoretical interpretation. Cosmogonic shadows of Mimas produces the Cassini division. Co-orbital satellites produce low density region ('Holberg minimum') in inner part of the *B* ring. *F* ring and Shepherd satellites produces the drop in intensity between *B* and *C* rings. Outer edge of *B* ring produces inner limit of *C* ring.

It has earlier been claimed (by Franklin and Colombo, 1970; and many others) that the bulk structure could be explained as a result of resonances. Strong objections against this interpretation was raised again and again (see, e.g., Alfvén and Arrhenius, 1975, 1976). This criticism was never answered, nor even mentioned in the discussion of the Saturnian rings.

In the asteroidal belt, Jupiter resonances produce the Kirkwood gaps. For example the 2 : 1 resonance produces a very pronounced gap. However, a similar phenomenon *should not be expected* in the Saturnian ring, because the Mimas-Saturn mass ratio is only 10^{-4} of the Jupiter-Sun mass ratio (see Alfvén and Arrhenius, 1976, Chapter 18.6.1).

From Holberg's diagrams it is evident that the criticism was correct. The Mimas 2 : 1 resonance is identified with a small narrow peak at 1.948. It is unreasonable to claim that this could explain the whole Cassini's division which has a breadth almost two orders of magnitude as large as the peak. The resonance seems to make the Cassini-B transition a little more complicated, but whether it steepens it or makes it softer is not quite clear.

The Mimas 3 : 1 resonance gives a somewhat similar sharp maximum at 1.495, also not all affecting the bulk structure. The only resonance which *may* affect the bulk structure seems to be the 1980-S11 : 7 : 6 resonance, which coincides with the outer limit of the *A* ring. It may sharpen this limit, perhaps also affect its location, but only by very small amount.

An noticeable feature of the ring system is that the *B-C* transition is so much sharper than the A Cassini transition, which has a much larger plateau. Northrop (1982) has proposed an interesting mechanism which should make the transition very sharp. It seems reasonable that his mechanism could explain the sharpness.

10. Conclusions About the Fine Structure

We have already discussed the resonance effects, The general impression is that resonances are responsible for some clearly recognisible fine structure signatures, but remarkably few, only about 10. Cosmogonic shadow effect – including the Holberg signatures – explain about the same number. However most of the fine structure remains unexplained.

The Encke and the Keeler divisions are not yet explained. Further there are at least nine maxima in the outermost C ring (from 1.40 to 1.48) in Figure 1 which have not yet any explanation. According to Holberg, they cannot be identified with resonance. We may ask whether they might be due to cosmogonic shadow effects. If so, the shadow-producing region should be located between $1.40 : 0.64 = 2.19$ and $1.48 : 0.64 = 2.31$.

This is the outermost region of the *A* ring out to the Shepherd satellites and the *F* ring. It includes the Encke and Keeler gaps and the Roche limit. We should expect that not only both the Shepherd satellites but also the *F* ring should produce shadow effects. The own shadow of the *A* ring enters also, producing alone the shadow which keeps the intensity of the main part of the *C* ring so low. This combination of four different shadows makes this region the most complicated one of the whole ring system. Its evolutionary history can be expected to be of key importance to the problem of formation of secondary bodies. The complicated and so far unexplained fine structure in the 1.40–1.48 region, and the origin of the Encke and Keeler gaps are certainly great challenges.

11. Comparison With the Asteroid Belt

The other region in the solar system where the products formed at the plasma-planetesimal transition have not accreted to large bodies is the asteroidal belt. Hence, we may expect to find information from the plasma-planetesimal transition stored in this region. As has been shown by Alfvén and Arrhenius (1975, 1976) and more recently summarized by Alfvén (1981b), Alfvén and Mendis (1983) the fall-down ratio 2 : 3 is found in at least three cases. The value should not be corrected in the same way as in the Saturnian rings, so we expect – and actually find – a fall-down ratio of $\Gamma \approx 0.667$ (see Table I).

12. General Considerations

The Holberg diagrams show a certain similarity to the spectrograms which a hundred years ago were puzzling the physicists. It turned out that the deciphering of these gave the solution to one of the great problems of science: the structure of the atom. The present 'spectrograms' show a similar bewildering multitude of 'lines' (or ringlets), of which only a few have yet been identified. It is possible that a detailed analysis of this very rich material will give us the solution to – or in any case a better understanding of – another of the great problems in science: the origin and evolution of the solar system. Indeed, this problem is as fundamental in astrophysics, geology, and paleobiology as the structure of the atom is in physics, chemistry, and biology.

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