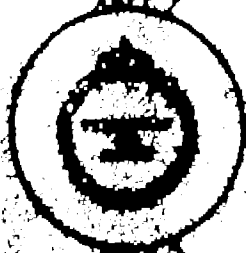
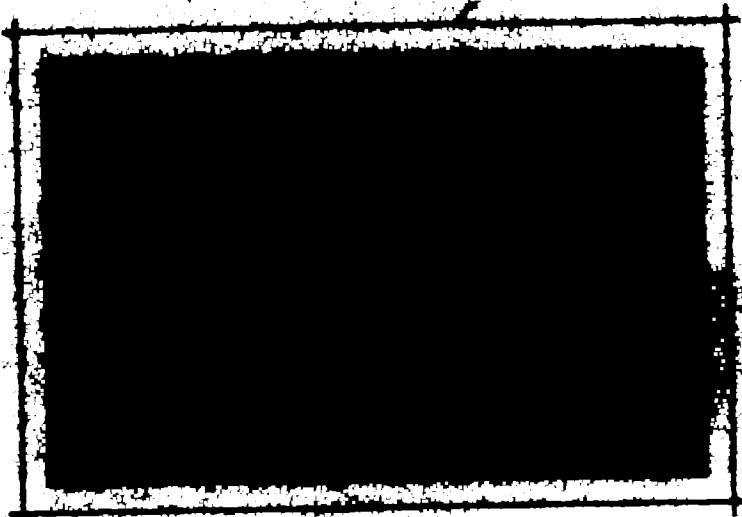


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SHADOW EFFECTS IN THE SATURNIAN
RINGS

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Abstract

The mass distribution in the Saturnian ring system is investigated and compared with predictions from the cosmogonic theory by Alfvén and Arrhenius. According to this theory, the matter in the rings has once been in the form of a magnetized plasma, in which the gravitation is balanced partly by the centrifugal force and partly by the magnetic field. As the plasma is neutralized, the magnetic force disappears and the matter can be shown to fall in to a distance $2/3$ of the original. This gives cause to the so called "cosmogonic shadow effect", which has been demonstrated earlier for the astroidal belt and in the large scale structure of the Saturnian ring system.

The relevance of the comogonic shadow effect is investigated for parts of the finer structures of the Saturnian ring system. It is shown that many structures of the present ring system can be understood as shadows and antishadows of cosmogonic origin. These appear in the form of double rings centered around a position a factor 0.64 (slightly less than $2/3$) closer to Saturn than the causing feature.

1. INTRODUCTION

A theory for the evolutionary history of the Solar System taking account of plasma effects was published ten years ago in two monographs by Alfvén and Arrhenius (1975, 1976). Since then plasma research has produced a drastic change in our views of cosmic plasmas, a summary of which has been given in Alfvén, Cosmic plasma (1981). Further observational results have demonstrated to what extent cosmogony depends on the new in situ measurements in the magnetospheres. A survey of this has recently been published (Alfvén, 1984). According to table I in that paper, the evolution of the solar system passes through three phases: 1) a primeval dusty plasma which condensates to 2) planetesimals, which accrete to 3) planets and satellites.

The transition from 2) to 3) does not take place in the Saturnian rings (inside the Roche limit) or the asteroidal belt (because of extremely low smeared out density). This makes these two regions of special interest to cosmogony, because the plasma-planetesimal transition (PPT) can best be studied in these two regions.

It is expected theoretically that the PPT should be associated with a general contraction by a factor $\Gamma = 2/3$, which because of certain secondary effects should be corrected downwards by a few percent. This transition is clearly visible in four cases in the Saturnian rings and in three cases in the asteroidal belt. With these seven cases the importance of a PPT of the theoretically predicted type seems to be clearly established.

However, as in most early space plasma models, electric fields and electric currents were not taken into account in an appropriate way. The paradigm transition discussed in Alfvén (1984) demonstrates that this is not adequate. The general

breakthrough of electric fields and electric current took place at the Chapman conference on electric currents in the magnetosphere (Potemra, 1983).

Electric field measurements belong now to the standard operations at almost all space missions, and in the magnetospheric theories they are now of decisive importance.

With this as a background, it is obviously unsatisfactory that in the development of the cosmogonic theory, as presented in Alfvén (1984), electric fields are not taken into account. In the present magnetospheres there are a number of phenomena producing electric fields. It is very likely that quite a few similar phenomena existed at cosmogonic times. It is important to try to clarify the electric structure of the cosmogonic magnetosphere. One mechanism which must necessarily produce such fields is the density gradients at the borders between the dusty plasma and the voids produced by the absorption of plasma by satellites.

The recent detailed measurements made by the Pioneer and Voyager missions have shown a wealth of fine structure in the Saturnian ring system. Many of the newly discovered ringlets have been identified as gravitational resonances but a large number remains, which might be of cosmogonic origin. While the bulk structure of the Saturnian rings can be treated without introduction of the effects of density gradients, such effects must be taken into account if the cosmogonic theory is to be extended to this fine structure.

The present paper is therefore written with a dual purpose: on one hand, it is meant to test the cosmogonic theory by an investigation of whether it (in a first-order extrapolation) can explain the newly discovered fine structure, particularly the many isolated ringlets in the C ring. On the other hand, it is an attempt to determine how the theory should be

developed in order to include the effects of density gradients. To this purpose, the fine structure (where one might expect density gradients to play a role) is studied in detail in a search for repeatable patterns, which could indicate in what direction the "homogeneous" model should be developed.

A brief review of the theory, and its application to the bulk structure of the ring system, is given in Sections 2 to 4. In Section 5, the observational material from the C ring is studied in detail, and an attempt is made to determine in what way the predictions of the homogeneous theory are modified by density gradients. The development of the theory to include the inclusion of density gradients is discussed in section 6. Section 7, finally, contains a summary of the results.

2. THEORETICAL BACKGROUND

The transition from the plasma state to planetesimals has been studied by Alfvén (e.g. Alfvén, 1984). His analysis starts with an investigation of the equilibrium of a very thin dusty plasma which rotates around a uniformly magnetized central body with the axis of magnetization and the rotational axis coinciding. The magnetization is supposed to be so strong as to compel the guiding centres of the electrons, ions and charged dust grains to move parallel to the magnetic field. The pressure forces are assumed to be negligible in the force balance. In the direction along the magnetic field a (dusty) plasma element is therefore acted upon only by gravitation and the centrifugal force. Because these forces make different angles with the magnetic field, the case of force balance along the magnetic field gives a situation where only 2/3 of the gravitational force is balanced by the radial component of the centrifugal force. The factor 2/3 follows from the geometry of a dipole field. The remaining third of the gravitational force is balanced by electromagnetic forces.

This state of equilibrium with respect to forces parallel to the magnetic field is called partial corotation.

If the electromagnetic forces in partial corotation are cancelled instantaneously (e.g. by recombination for the case of ions), the centrifugal force cannot keep equilibrium with gravitation. The result is that the matter in the considered plasma element starts to move in an ellipse with an eccentricity $e = 1/3$ and a semi-major axis $a = 3/4 a_0$, where a_0 is the central distance of the place of recombination. The ellipses will intersect the equatorial plane at $a_p = 2a_0/3$. Collisions between the grains and/or with a thin layer of dust which rapidly will be formed in the equatorial plane, will circularize the orbits of the grains by inelastic collisions, so that they all will move in circles at Γa_0 , with $\Gamma = 2/3$.

Hence circularization of the orbits will lead to a contraction of the plasma by a factor $\Gamma = 2/3$ at the transition to neutral matter.

3. PREDICTIONS OF THE THEORY. THE 2/3 ANTICORRELATION.

According to this model, the matter which today exists at a given central distance a_1 in the Saturnian ringlet system once was in the form of a partially corotating plasma at a distance approximately $3a_1/2$. During the formation of the ring system, the matter in the plasma phase would continually be swept up at positions where rings and satellites are under formation, with the following two important consequences:

(1) Since a partially corotating plasma moves with a velocity below the Kepler velocity, the angular velocity of the sweeping-up matter is reduced. It is therefore displaced towards Saturn. This effect has been estimated to reduce the final fall-down factor by a few percent from the value

$$\Gamma = 2/3.$$

(2) There should be some kind of anticorrelation between the present-day density at any central distance a_0 and the density at the distance Γa_0 , in the form of "shadows" and "antishadows" as described below.

3.1 Cosmogonic shadows

If a satellite (or an embryo of a satellite, or a jet stream accreting to a satellite) is located at a central distance a_0 , it will deplete the plasma in a magnetic flux tube with the L-value a_0 . This is a phenomenon which is well known from spacecraft measurements of the Jovian and Saturnian magnetospheres. After the PPT this depleted region will be found at Γa_0 and there produce an empty region in the equatorial disc. We call this depleted region the cosmogonic shadow of the satellite. Also the mini-satellites of which the Saturnian ring consists will produce such shadows. Hence the ring will also produce its own shadow.

3.2 Cosmogonic antishadows

In a similar way, the gaps in the ring system, e.g. the Encke division at $R/R_S = 2.21$ (see Figure 6), should correspond to regions where plasma is not swept out. The fall-down of this plasma with a factor Γ should give rise to rings in an otherwise empty region; we call such rings cosmogonic antishadows.

4. THE BULK STRUCTURE OF THE SATURNIAN RING SYSTEM

The Saturnian ring system, with the inner satellites, is schematically illustrated in Fig. 1. The "homogeneous" theory, as outlined above, gives a good explanation of the bulk structure. This is illustrated in Fig. 2, in which the density

of the rings (actual opacity) is plotted. At the top of the figure the inner satellites are represented but with their Saturnocentric distances reduced by a factor $\Gamma = 0.64$. It is obvious that the Cassini division can be interpreted as the cosmogonic shadow of Mimas, the Holberg minimum at $R/R_S = 1.6$ as the cosmogonic shadow of Janus (with Epimetheus) and the rapid fall in intensity at the border between the B and the C ring as the combined effect of the Shepherds and the A ring. Furthermore, the inner edge of the C ring corresponds to the shadow of the rapid rise in density between Cassini and the B ring. Gravitational disturbances from the satellites produce resonances which are clearly visible (see Holberg, 1982), but small compared to cosmogonic shadow effects.

5. THE FINE STRUCTURE OF THE SATURNIAN RING SYSTEM

For a study of the fine structure of the rings, we have used UVS ring occultation data supplied on magnetic tape by J.B. Holberg, University of Southern California. The Holberg data seem to agree with the curves of Esposito *et al* (1983).

The figures represent plots of the normal optical depth τ versus the radial distance from Saturn.

Some figures contain averaged data, where the averaging has been done in the following way:

$$\tau_{\text{aver}} = \alpha \ln \frac{1}{n} \sum_{i=1}^n w_i \exp(\tau_i / \alpha)$$

where $\alpha = -0.4803$ and w_i is a weighting factor. This weighting factor is computed to weight the points according to a Gaussian distribution around the central point $i = (n+1)/2$. The width of the Gaussian is such that \pm one standard deviation, $\pm 1 \sigma$, corresponds to the radial averaging distance given in each figure. Points beyond $\pm 3 \sigma$ are discarded. The

average is a running average, i.e. there are as many data points in the averaged data sets as in the original data set.

5.1 The effect of density gradients

The fine structures we will discuss here are the shadows of satellites and the antishadows from holes in the ring system. In the plasmaphase, each such structure would necessarily be bordered by density gradients, transverse to the magnetic field. Such gradients are generally associated with electric fields. Both the pressure term ($\text{grad } p$) and the electric fields would influence the force balance in the partial corotation. This would in turn change the fall-down ratio Γ from the value $\Gamma = 2/3$ obtained from the original theory, which neglected density gradients.

Since a theory for the effect of these density gradients is not yet developed, we will in this section analyze the observational material from the simple assumption that the regions with inwards and outwards directed density gradients influence the fall-down factor in opposite senses. In each structure in the plasma phase (a gap swept out by a satellite, or a ring of plasma left by a hole in the ring system) there will be one region where the density gradient is directed inwards, and one where it is directed outwards. Every shadow and antishadow should therefore be expected to split up into some approximately symmetric structure, the shadow profile, around the central Γ value expected in the absence of gradients.

In our analysis of the observational material, we will therefore search for such symmetric structures at the location where we expect shadows and antishadows to fall. This will serve both our purposes with this paper: the aspect of test of the theory lies in the existence of symmetric structures at

the expected locations, while the aspect of development lies in the identification of the shape of the shadows and antishadow profiles, which should be explained by a developed theory.

5.2. Cassinis division and Holbergs minimum

Cassinis division and Holbergs minimum have earlier been proposed to be the shadows of Mimas and Janus (Alfvén, 1983). They are shown in Figures 3 and 4. It is true that there are considerable differences between them, but this is not unexpected because the shadow-producing objects are different; Mimas is one satellite, but Janus (with Ephimetheus) is a double satellite. The Holberg minimum is broader than Cassini, which may have some connection to this. Further, in the B ring there is obviously a population superimposed on the population we study. This is shown by the fact that the density in the Holberg minimum never approaches zero as it does in the Cassini. This unknown population in the B ring -- let us call it the X population -- may also be the reason why the B ring is much more erratic than the A ring.

However, the main impression is the mutual similarity. In both cases there is a central double peak. In Cassini the outer peak is larger than the inner one, for unknown reasons. In Holberg the outer one is also higher, but the inner one is broader. The peaks are in both cases surrounded by voids, which are rather symmetric in Holberg while in Cassini the outer one is somewhat narrower.

Disregarding these smaller differences, both Cassinis division and the Holberg minimum can approximately be represented by the same symmetric structure:

1. Two peaks, centered around $\Gamma = 0.64$, with a separation $D = \pm 0.008 R/R_S$ from the central position.
2. Surrounding voids, with a width $W = 0.03 R/R_S$ in both directions from the central position. We will call these the inner and outer voids.

5.3 The C ring

The outer part of the C ring (outside $R/R_S = 1.40$) is the most complicated region of the ring system. There are sharp gravitational resonance peaks identified by Holberg, and two other peaks, at $R/R_S = 1.311$ and 1.658 , which, to judge from their appearance, are probably due to resonances. Further, there is a remarkable eccentric ring at 1.45 , which has been studied in detail by Esposito et al (1983), but has not been identified. Moreover, there are a large number of well-defined maxima, some of them being remarkably similar.

We will now investigate to what extent the shadow profile we found for Cassinis division and Holbergs minimum can explain also the details in the C ring.

5.4 The shadows of the Shepherds

Fig.5 is the basis for the discussion in sections 5.4 to 5.6. Both the upper and the lower curves show the present-day Saturnian ring system. The upper curve is reversed, and the scale is reduced by a factor 0.64 for convenient identification of shadows and antishadows. The rings which have been identified as resonances by Holberg et al (1982) are marked by R's.

The main impression of the C ring is the absence of matter; this can be understood basically as the shadow of the A ring. However, this shadow would extend only out to $R/R_S = 1.45$, while the inner edge of the B ring is located at $R/R_S = 1.52$. Between these values we expect the shadows of the Shepherd satellites to fall.

From the shape of Cassini's division and Holbergs minimum, we expect the outer Shepherd (Shepherd II) to produce a double ring, at the outside of which there is a void region. It seems reasonable to identify the double ring with the maxima M and N (at $R/R_S = 1.488$ and $R/R_S = 1.499$) and the outer void with the low density region $R/R_S = 1.50-1.52$. This structure is similar to the transition from the Cassini division to the A ring. In fact, this similarity was discovered by Holberg, who pointed it out during a seminar discussion. (see Fig. 7b in Alfvén, 1983). Numerical values for this shadow are $\Gamma = 0.636$, peak separation $D = \pm 0.006 R/R_S$, and outer void width $W = 0.03 R/R_S$.

The inner void of Shepherd II is superimposed on the shadow of Shepherd I. This satellite produces a similar double ring (peaks K and L in Fig. 5, at $R/R_S = 1.465$ and $R/R_S = 1.477$). Numerical values for this shadow are $\Gamma = 0.637$ and $D = \pm 0.006 R/R_S$. The outer void of Shepherd I is overlapped by the Shepherd II shadow; the low density region between $R/R_S = 1.427$ and $R/R_S = 1.488$ may therefore be considered as a combination of the inner void of Shepherd II and the outer void of Shepherd I. In a similar way the inner void of Shepherd I should be the empty region $R/R_S = 1.449-1.465$, which extends in to the outer edge of the expected shadow of the A ring.

Close to the shadows of the Shepherds are also two resonances, which we disregard here. The satellite Atlas (at $R/R_S = 2.276$) with a volume of only a few percent of the Shepherds is considered to be too small to be included. It may contribute

to making K different from L .

5.5. Shadows of the A ring (inside $R/R_S = 1.45$): Antishadows

The A ring is dense enough to give a shadow inside $R/R_S = 1.45$ which makes the density of the C ring in the shadow region close to zero. However, there are "holes" in the A ring, which should give rise to antishadows. The extremely void Encke division (at $R/R_S = 2.214$) is the outer of these (compare Fig. 6). Inside $R/R_S = 1.40$ the density curve in the C ring is very smooth (except for gravitational resonance peaks), which it should be since the A ring, which casts its shadow here, has no "hole" inside the Encke division. The density is close to zero. The reason why it is not exactly zero may be that the A ring during the early stages of ring formation was somewhat "leaky" (but this is only a speculation). When we reach the Cassini division we note that there are two regions where the density is close to zero, viz., at $R/R_S = 1.953$ (which is named the Maxwell gap) and at $R/R_S = 1.980$. Following the arguments in these notes we should expect these minima, and Enckes division, to produce antishadows in the inner C ring.

The good fit for the shadows of Shepherd I and Shepherd II gives us a clue to what kind of structure to look for in order to logically extend the discussion to antishadows. The main difference between shadows and antishadows is that the density gradients (in the plasma phase) are directed outwards (away from the hole swept out by the satellite) in the former case, and inwards in the second. From the spacing of the double peaks produced by the shadows, we conclude that the presence of density gradients can change the Γ value so that the matter is displaced typically a distance $\pm 0.008 R/R_S$ from the central position. We therefore to a first approximation search for such double peaks also for the antishadows.

The three expected antishadows, from the Encke division and the two minima in the Cassini division, are all easily found, as illustrated in Fig. 5. The double rings are all remarkably symmetrical and also centered very well around $\Gamma = 0.64$. No expected ring is missing. Numerical values of the Γ values and the rings separations are given in Table I.

If we take away the identified resonances, and the rings identified above, only a few small rings remain. These are possibly yet unidentified gravitational resonances. We will here briefly discuss the alternative possibility that some of them are antishadows from earlier gaps in the ring system which have later been filled out.

Close to the antishadow peaks D and G from the Encke division lie four small peaks (E, F, H and I in Fig. 5). If these are antishadow doublets, one should expect the same ring separation D as in the neighbouring Encke antishadow. This means that E and H would be the antishadow of one gap, and F and I the antishadow of another. These gaps would have to lie in the outer A ring, between the Encke division and the Roche limit. Figure 6 shows the details of this region; indeed, there are two places where the density does go down to zero, in the Keeler division at $R/R_S = 2.26$ and in a "leaky region" around $R/R_S = 2.24$ where some readings go down to close to zero. It is possible that these minima were more pronounced in the early stages of the formation of the Saturnian rings, and that the four peaks are antishadows from that period. However, this is still only a speculation.

5.6. Peak at $R/R_S = 1.449$

Inside the region of shadows produced by the Shepherds but outside the antishadows produced by the holes in the A ring there is a very strong peak at $R/R_S = 1.449$. A detailed analysis by Esposito et al (1983) has shown that this derives from an eccentric ringlet. Although there are other eccentric ringlets, this is unique due to its strong eccentricity. Its position does not agree with any identified resonance. If we look for a signature which might cause a cosmogonic shadow effect at this location, the only possible choice seems to be the Roche limit, which gives a Γ value of 0.640.

There is not yet any theoretical motivation why the Roche limit should cause a shadow consisting of an eccentric ringlet, but a value so close to the other Γ values indicates that this might be the case. (According to Holberg the fall in intensity at $R/R_S = 2.265$ may be sharpened by a resonance effect, but this does not mean that the ringlet at $R/R_S = 1.449$ is a direct resonance effect).

6. THEORY: THE EFFECT OF POLARIZATION ELECTRIC FIELDS

In the preceding section, we have started with the very general assumption that the effect of density gradients is to give rise to symmetric shadow and antishadow profiles; the observational material then shows that these must be double peaks, surrounded by voids.

We will now make a tentative theoretical analysis of the processes which give rise to these structures. We will first consider the shadows, i.e. the structures produced by Mimas, Janus, Shepherd I and Shepherd II.

At the border between the dusty plasma and the void swept out by a satellite we expect electric fields. It is well known that at every border between a plasma and a void region there are electric fields which in a non-magnetized plasma prevent

the electrons from escaping too rapidly and which accelerates the ions in the direction of the void, hence causing ambipolar diffusion.

In a magnetized plasma the same phenomenon occurs, but if the electron Larmor radius is smaller than the ion mean free path the ions may escape more easily than the electrons, with the result that the electric field is reversed.

In a dusty plasma of the kind we consider -- with positively or negatively charged dust -- the situation is complicated by that the mass of a dust grain is much larger than the ionic mass. Their gyroradii may therefore be comparable to the scale length of the density gradients. This would call for a consideration of the Rosseland field (see Alfvén, 1984), but we will not discuss this here. Another problem is that the process of depletion of plasma might act differently on the grains than on the much lighter ions and electrons. During the Pioneer mission, Fillius and McIlwain (1980) actually observed this kind of phenomenon. The counting rate for high energy (>80 MeV) protons went down orders of magnitude at the distances of Mimas and Janus, while the "shadows" at lower energies were much less pronounced, or absent.

Close to the equatorial plane the force $F = qE$ must be essentially radial, for reasons of symmetry. At some distance from the equatorial plane it may have somewhat different direction, but this is difficult to calculate, especially, as mentioned above, because there are other effects producing additional electric fields. Moreover, in order to transfer momentum between the central body and the partially corotating dusty plasma there are currents along the magnetic field lines. This current system is similar to the auroral current system or the Jupiter-Io current system. The best way to determine the direction of the electric field in the cosmogonic case is to study the electric field in the auroral

and Jupiter-Io case, again treating cosmogony as an extrapolation of magnetospheric research.

This directs the attention to an important magnetospheric problem, viz., the electric field not too far from the equatorial plane. Not until this is clarified can we treat the cosmogonic problem in an adequate way. Before this is done it is reasonable to make the simple tentative assumption that the field everywhere is perpendicular to the axis of rotation.

The electric force on the grain $F = q E$ should be added or subtracted from the centrifugal force (see Figure 8). Without electric fields the angular velocity of the plasma element adjusts itself so that the centrifugal force keeps equilibrium with the gravitational force, both projected on the magnetic field vector. In a region with density gradients, an electric force is added, which makes it necessary for the plasma to rotate faster (or slower, depending on the direction of the density gradient) because the centrifugal force has to compensate also the electric force. Hence, after de-ionization, the element will have a larger (or smaller) velocity so that the after circularization the contraction ratio becomes different than 2/3.

The result is that matter outside the direct shadow will be displaced so that outside the direct shadow there will be a void region. As the transition between the primary plasma and the shadow is not abrupt, some matter is left just outside the primary plasma, forming a small peak. The double rings found on the analysis of the observational material could be such peaks, one from the region with outwards directed gradient, and one from the region with inwards directed gradient.

A similar mechanism should operate in the case of antishadows; also in this case one should expect double peaks, originating in the regions with oppositely directed density gradients.

6.1 Development of the model

We find that there is a qualitative agreement between our model and the observations. However, there may be other models which give the same result, although it seems unlikely that the same agreement can be obtained by a completely different basic mechanism. It is quite possible that, for example, the electric field pattern of the model can be modified to some extent.

We will conclude the theory section by outlining some problems that should be studied further.

(a) In the theory outlined above, the voids of the shadows are due to a change in the Γ value. The missing matter from these regions should therefore be expected to appear somewhere else. An inspection of Cassinis division (Fig. 3) and Holbergs minimum (Fig. 4) shows that this matter seems to be piled up in banks around the inner and outer voids.

For the case of the Shepherds, a combined outer bank could be the high-density region at the inner edge of the B ring, at $R/R_S = 1.52 - 1.54$. The combined inner bank of the Shepherds would then, for symmetry reasons, fall in the region $R/R_S = 1.42 - 1.44$. This bank seems to be missing; the reason for this discrepancy might be connected to the fact that this position is unique in the sense that the inner Shepherd satellite lies close to the main ring system. In fact, the "missing bank" would fall in the shadow of the A ring.

(b) The deviation of Cassinis division and Holbergs minimum from symmetry should be investigated. One possibility is that the orbits of Mimas and Janus have changed during the cosmogonic period. As both are now trapped in resonances with other satellites, the evolution of the trapping may be a reason. Further, Janus (with Epimetheus) is a double satellite, which probably has been formed during the cosmogonic evolution. This may have affected the fine structure of Holbergs minimum. When cosmogony matures it is likely that other explanations of the deviation from the ideal structure will appear.

(c) It is evident from the diagrams that the cosmogonic ringlets of the C ring have a certain characteristic inner structure. An attempt to account for this might be rewarding.

(d) In order to explain the X population, which partly fills Holbergs minimum (the shadow expected from Janus), we only have two logical alternatives: The first alternative is that the matter in Holbergs minimum has arrived there by some other mechanism than the "2/3 fall-down". One would then have to explain why such matter is not present in the Cassini division and in the C ring. A possible answer to this question is that a superimposed population could be centered around the Saturnocentric distance of the synchronous satellite, as suggested by Mendis.

The other alternative is that Janus has appeared at a later stage in the formation of the Saturnian rings; the X population would then be due to the usual "2/3 fall-down" before Janus's appearance. After the appearance of Janus, the Holberg minimum would be created by the continued fall-down in the regions $R/R_S = 1.52-1.56$ and $R/R_S = 1.64-1.94$ (see Fig. 4).

(e) Above, we have discussed the effects of the electric fields produced by density gradients. An obvious problem which should be treated in future work is the effect of pressure terms in the force balance along the magnetic field. This might influence the state of partial corotation considerably, since the angular velocity in partial corotation is essentially obtained from the force balance along the magnetic field. In the original theory, only the centrifugal and gravitational forces are considered. The pressure gradient might have an even larger effect than the electric field in this force balance.

(f) Another problem relates to the inner edge of the C ring. If the electromagnetic forces are suddenly cancelled in the state of partial corotation, the matter starts to move in ellipses with the eccentricity $e = 1/3$, and finally ends up in circular orbits with the same angular momentum as the ellips. The distance of closest approach of the ellipses is a factor $3/4$ closer to Saturn than the radius of the final circular orbits. Matter which hits the surface of Saturn before completing one ellipse would be lost. As a consequence one would expect very little matter inside a radius $R/R_S = 1.33$. Final (circular) orbits inside this limit would correspond to ellipses that pass inside the surface of Saturn. (If the Γ value is reduced from $2/3$ to 0.64 after the circularization of the orbits, this inner limit would be displaced from $R/R_S = 1.33$ to $R/R_S = 1.28$).

The antishadows from the two empty regions in the Cassini division fall in this region (peaks A, B and C in Figs. 5 and 7). If these rings shall be seen as evidence of the $2/3$ -falldown, we must assume that the matter has been stopped in the equatorial plane at the first pass, after completing only one quarter of the elliptical orbit. Whether this is a realistic assumption or not depends on the density in the equatorial plane. The continued accretion of the rings A, B

and C might be understood if some rudimentary rings are already there to stop at least part of the infalling matter at the first pass. The origin of these first rudimentary rings seems more difficult to explain. This is a problem which remains to be investigated.

7. DISCUSSION

The theory for the PPT is not yet developed enough to give detailed predictions in a case like the Saturnian ring system. In order to explain the ring system, it has to be supplemented with a few ad hoc hypotheses (e.g. the reduction of Γ by a few percent from $2/3$ to 0.64 , and the splitting of the shadows and the antishadows into double rings). These hypotheses might be motivated qualitatively, but are not yet proven.

Seen as a test of the cosmogonic theory, the result of this work is therefore "semi-statistical": the number of features that are explained should in some sense be compared to the number of assumptions that are needed to explain them:

1. The sweeping-up of corotating plasma reduces the Γ value from $2/3$ to $\Gamma = 0.64$.
2. Density gradients influence the the shape of shadows and the antishadows in such a way that they are split up into the structures described in section 5 (symmetric double rings, for the case of shadows surrounded by voids).
3. There is a "X population" in the B ring superimposed on the population we study here.

The most crucial test of the theory lies in the possible absence of rings. From the present structure of the Saturnian ring system we expect two shadows and three antishadows to fall in the C ring. The symmetric structure have looked for is

approximately symmetric double rings centered around the position corresponding to $\Gamma = 0.64$. If any of these $2 \times 5 = 10$ rings were missing, the theory would have to fall.

The presence of rings that are not explained by the theory is not so crucial. Such rings could either be unidentified resonances, or antishadows from gaps in the early Saturnian ring system, which have later been filled in.

From the assumptions listed above follow definite predictions about the ring system. Taking the ring and the satellite systems as they exist today, there are four cases of expected shadows, and three (or perhaps five) of expected antishadows. The most striking feature around their expected "shadow location" at $\Gamma = 0.64$ is that in all seven cases we find a central void flanked by two peaks. The central position between the peaks is at $\Gamma = 0.64 \pm 1\%$ (in the five cases in the outer C ring, $\pm 0.5\%$). The two peaks are in many cases surprisingly equal.

The good agreement between the Γ values is difficult to ascribe to arbitrary selection. Indeed, the shadows of every satellite in the relevant region are identified. Also, the antishadows of every zero value in the A ring and Cassini are identified. Further, excepting the resonance peaks identified by Holberg and the peaks at $R/R_S = 1.312$ and $R/R_S = 1.358$, which are sharp maxima similar to the resonance peaks (see especially Fig. 7), every pronounced peak in the C ring is identified with a cosmogonic effect.

The symmetry between the double peaks in the C ring is also encouraging (see Fig.5). Of the seven proposed ring pairs (A-left hump of B, right hump of B - C, D-G, E-H, F-I, K-M, L-N) all except the pair K-M are virtually identical, both in height and width.

This agreement between theory and observation seems too remarkable to be a coincidence, particularly since the existence of a fall-down factor a few percent below $2/3$ was proposed before the detailed measurements of the Pioneer and Voyager missions were made.

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TABLE I. COSMOGONIC SHADOWS AND ANTISHADOWS

Peak separations and saturnocentric distances in units R/R_S

STRUCTURE (ANTISHADOW DOUBLETS OR SHADOW CENTRAL PEAKS)	PEAK SEPARATION $2 D$	CAUSE (GAPS OR SATELLITES)	Γ VALUE
A 1.240 B 1.262	0.022	Maxwell Gap 1.953	0.640
B 1.262 C 1.276	0.014	Zero point in Cassini 1.980	0.641
D 1.405 G 1.432	0.027	Encke 2.214	0.641
E 1.419 H 1.443	0.024	Leaky Region 2.240	0.639
F 1.423 I 1.445	0.022	Keeler 2.262	0.634
Excentric ringlet J 1.449		Roche 2.265	0.640
K 1.465 L 1.477	0.012	Shepherd I 2.310	0.637
M 1.488 N 1.499	0.011	Shepherd II 2.349	0.636

SATURN WITH MASSIVE RINGS AND INNERMOST SATELLITES.

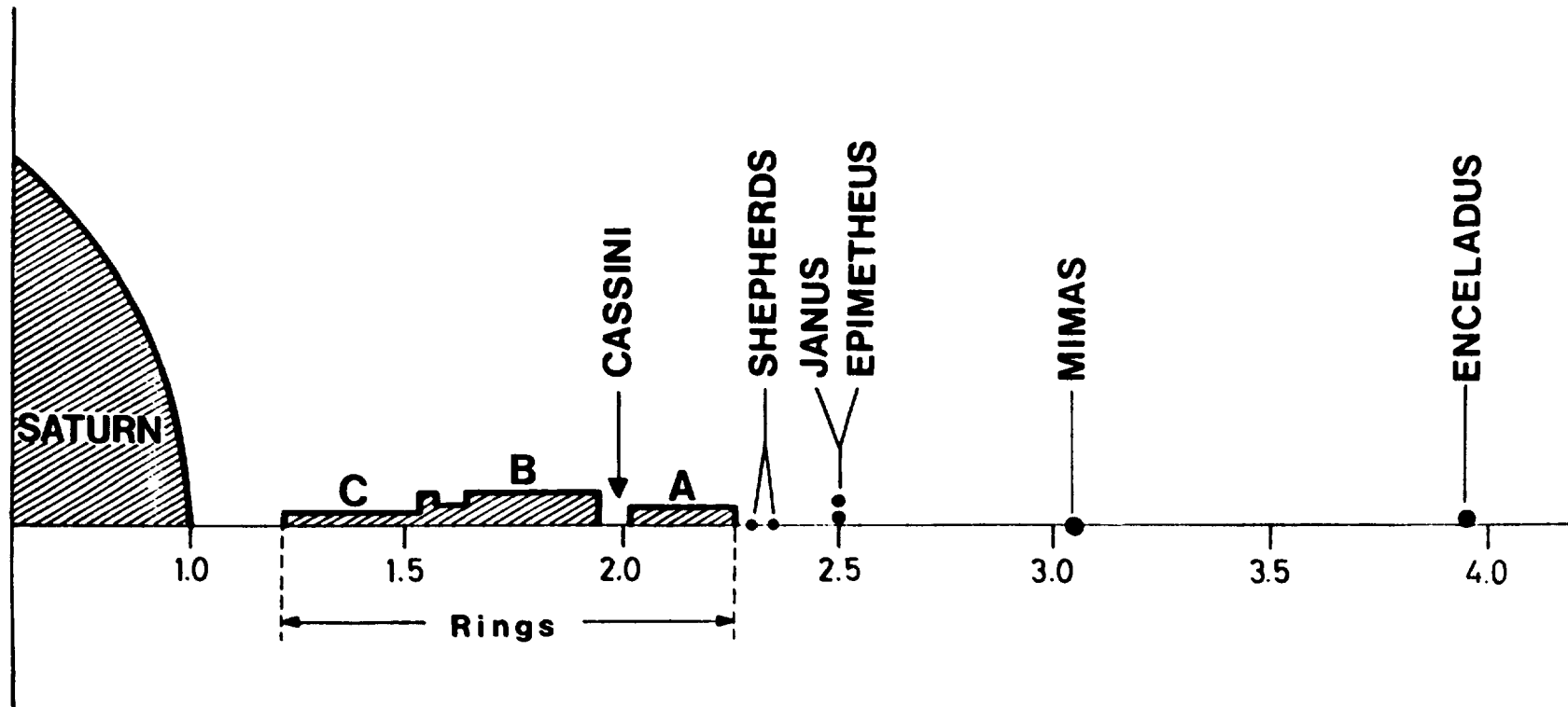


Fig.1 Saturnian rings and the innermost satellites.

VOYAGER 2 UVS - SATURNIAN RING OCCULTATION

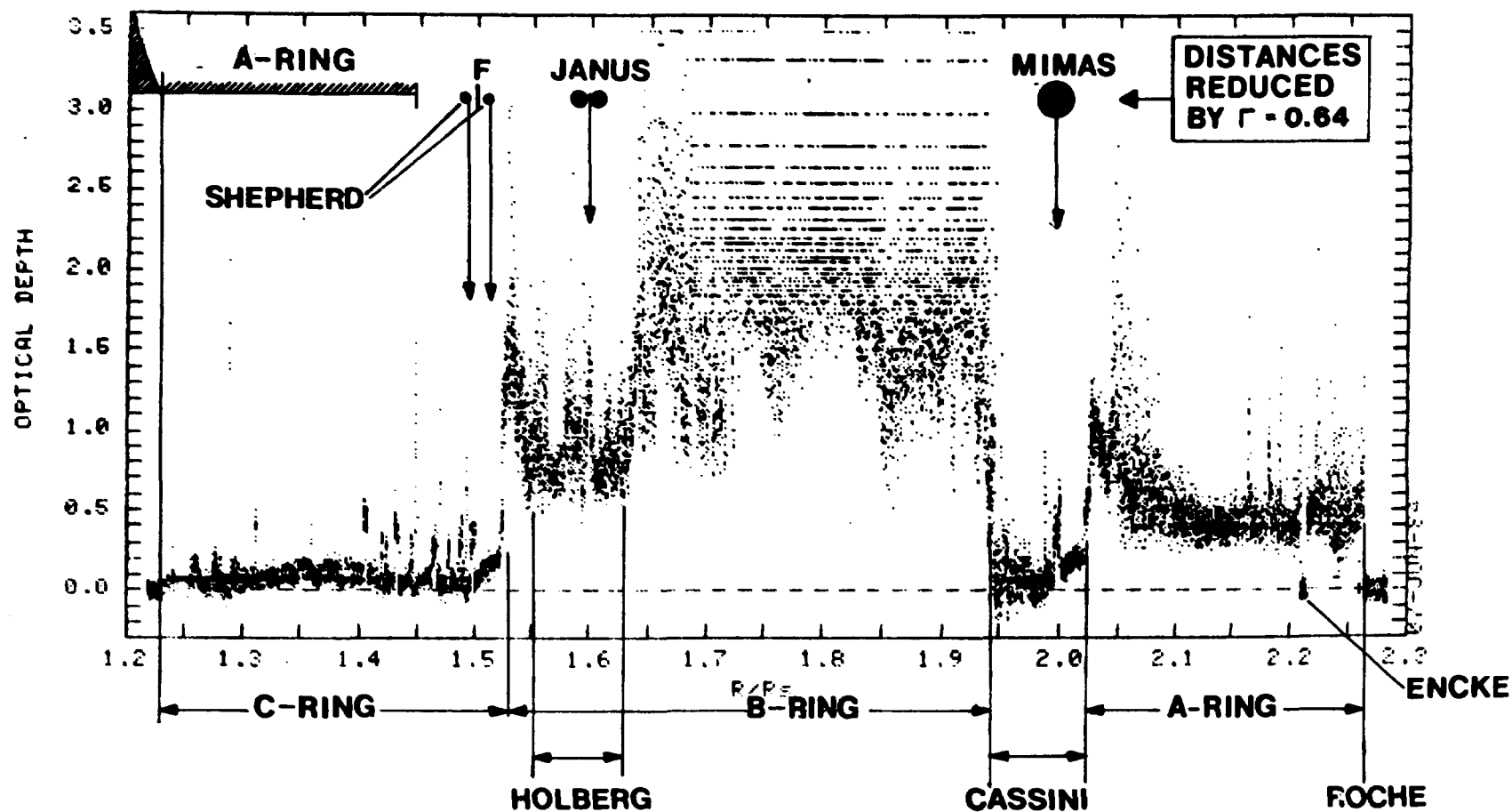


Fig.2 All measurements of opacity plotted as a function of the saturnocentric distance. At the top: the innermost Saturnian satellites and the A ring with saturnocentric distance scaled down by a factor $\Gamma = 0.64$, one point average.

CASSINI A-RING

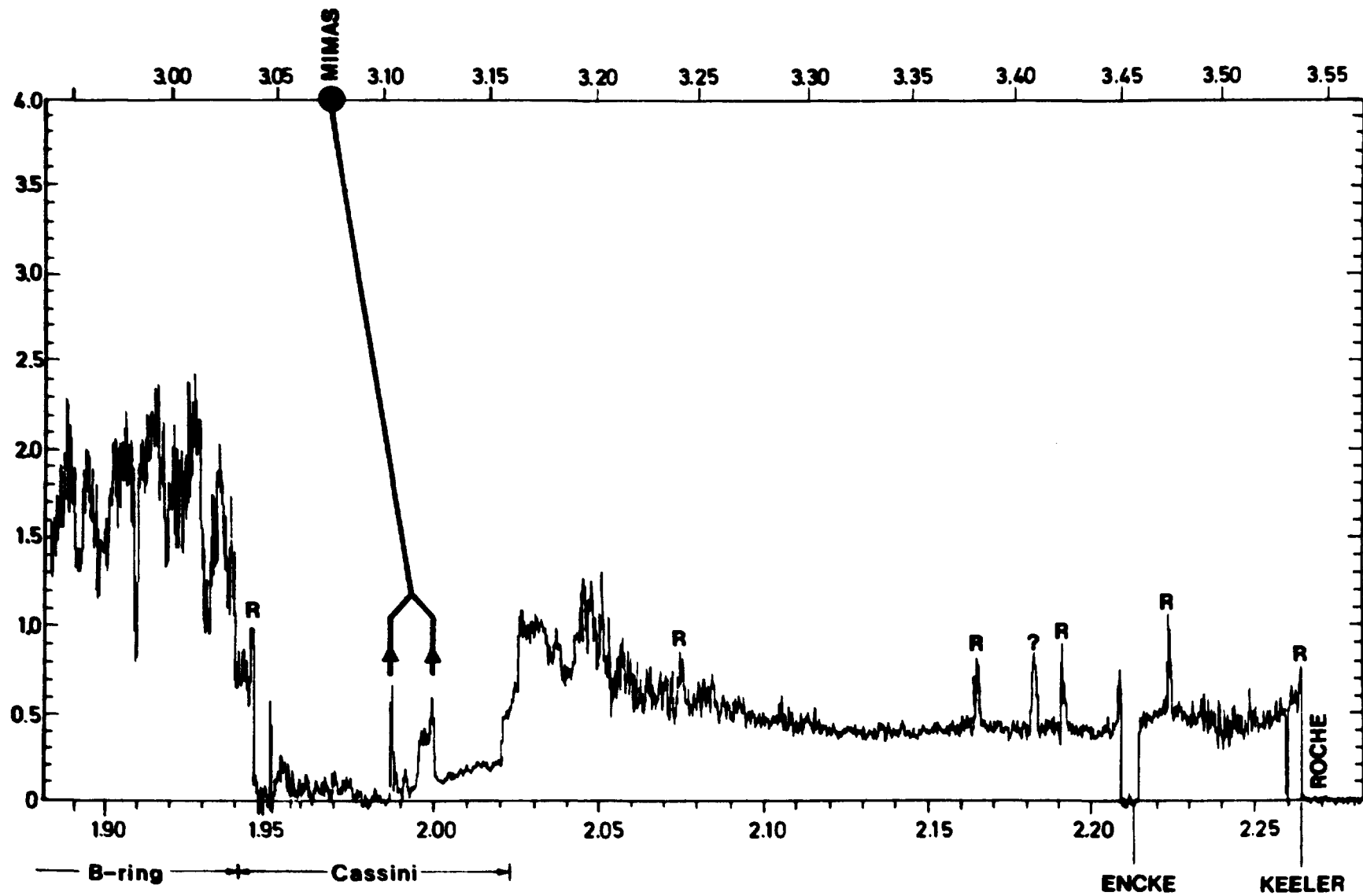


Fig.3 The opacity of the A ring and Cassini's division. Ten point average.

B-RING

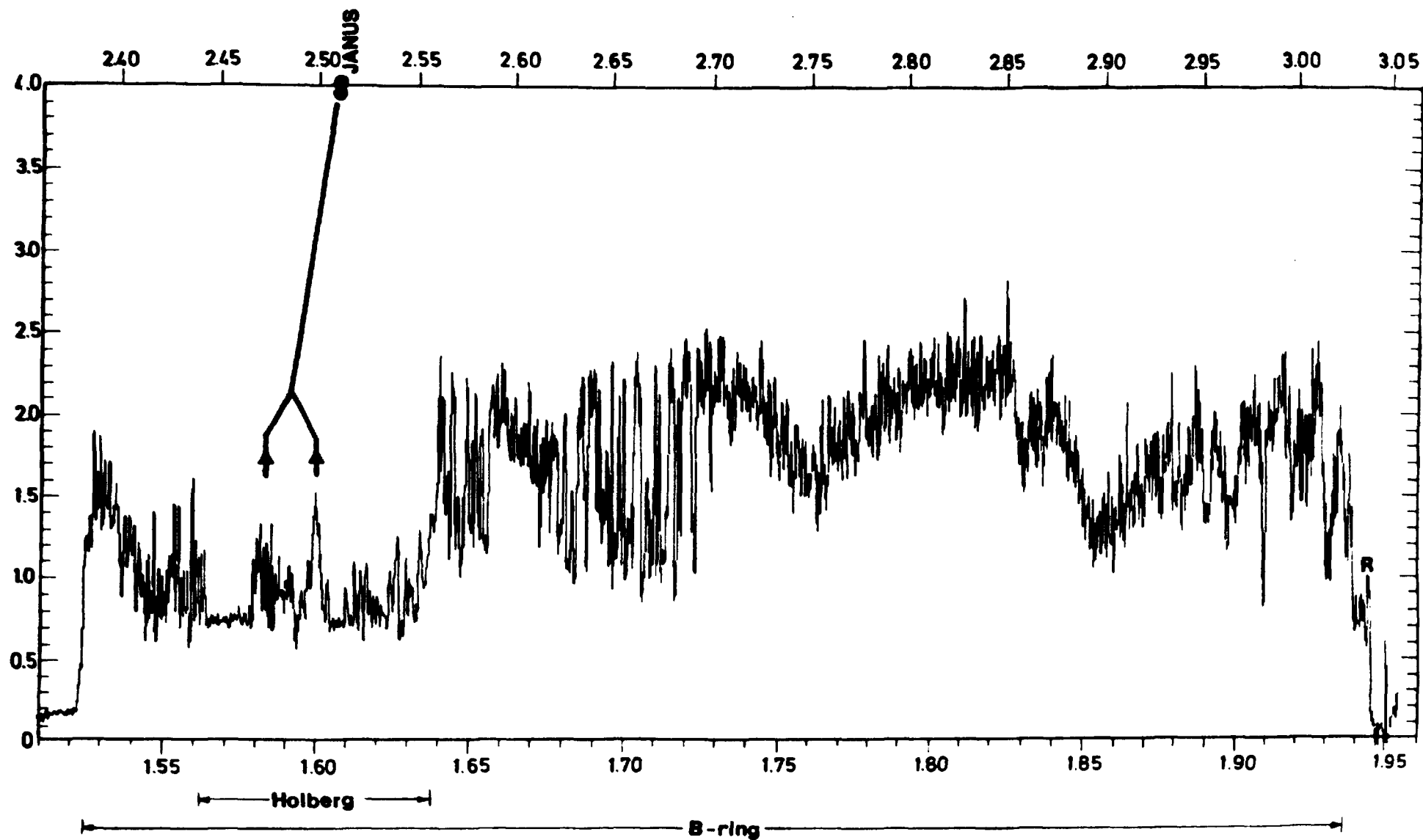


Fig.4 The opacity of the B ring with Holberg's minimum. Ten point average.

C-RING

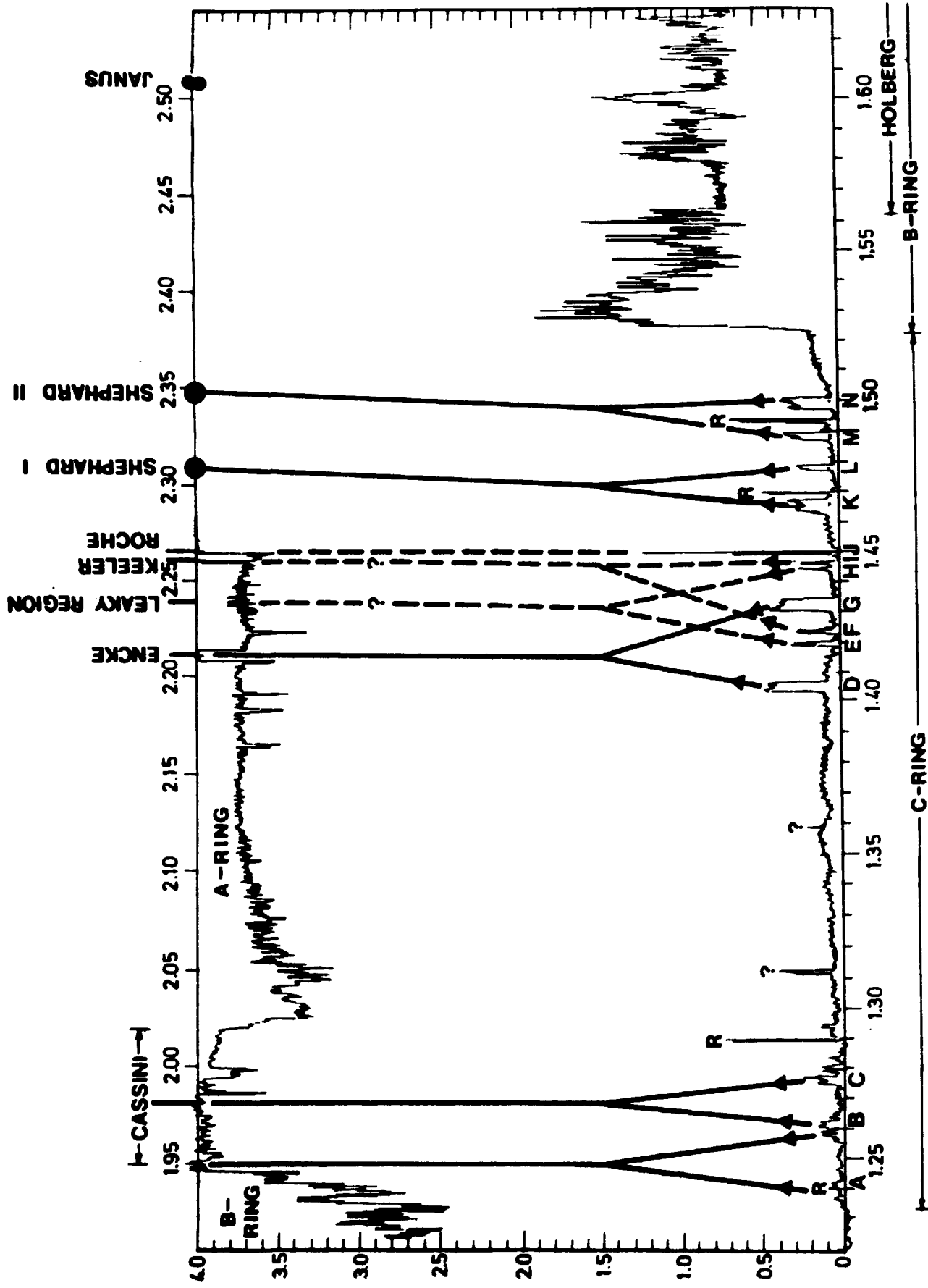


Fig.5 The opacity of the C ring and the inner part of the B ring. Ten point average.

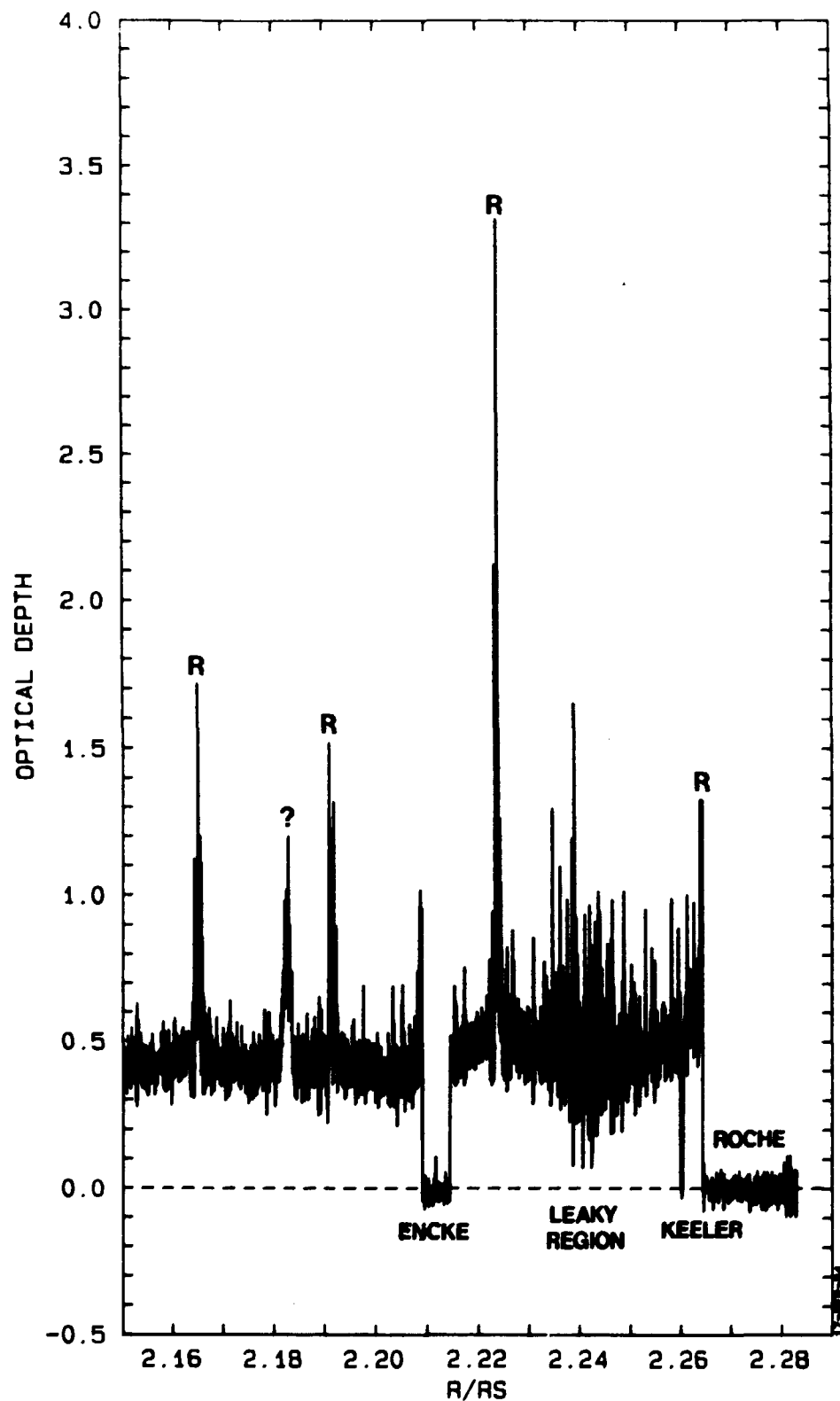


Fig.6 Outermost part of the A ring in high resolution. It shows the Roche limit at 1.212, and the dramatically sharp Encke division. Further there is the Kieler gap at 2.260 where the density also goes down to zero, although it is much thinner than Encke. One point average.

Between the two gaps there is a region around 2.24 where the density at some points goes down to very low values (although never to zero). This region may be "leaky", so that plasma from it may fall down.

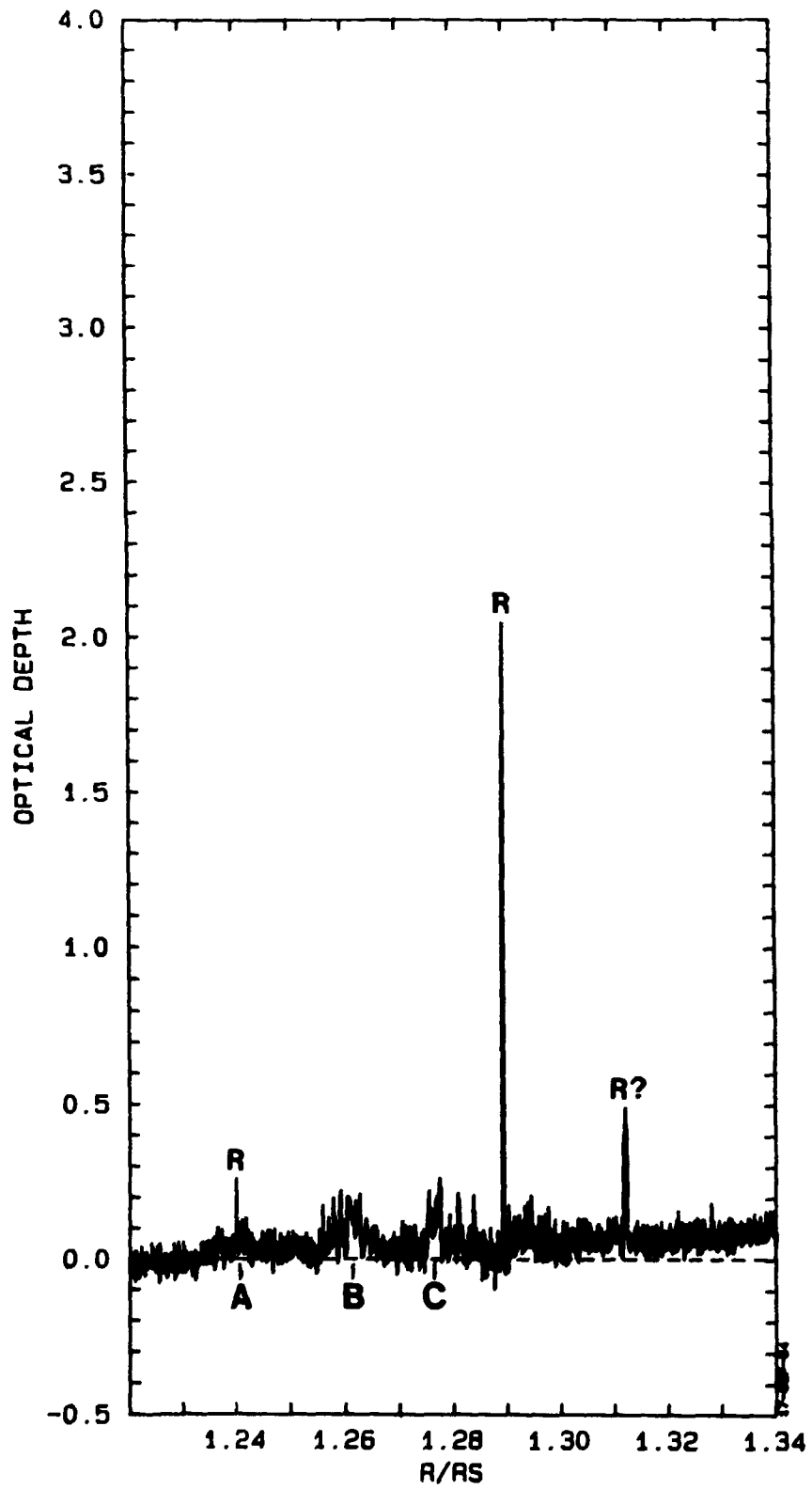


Fig.7 The innermost part of the C ring in high resolution. Note that the unidentified peak at 1.31 is similar to the identified resonances. One point average.

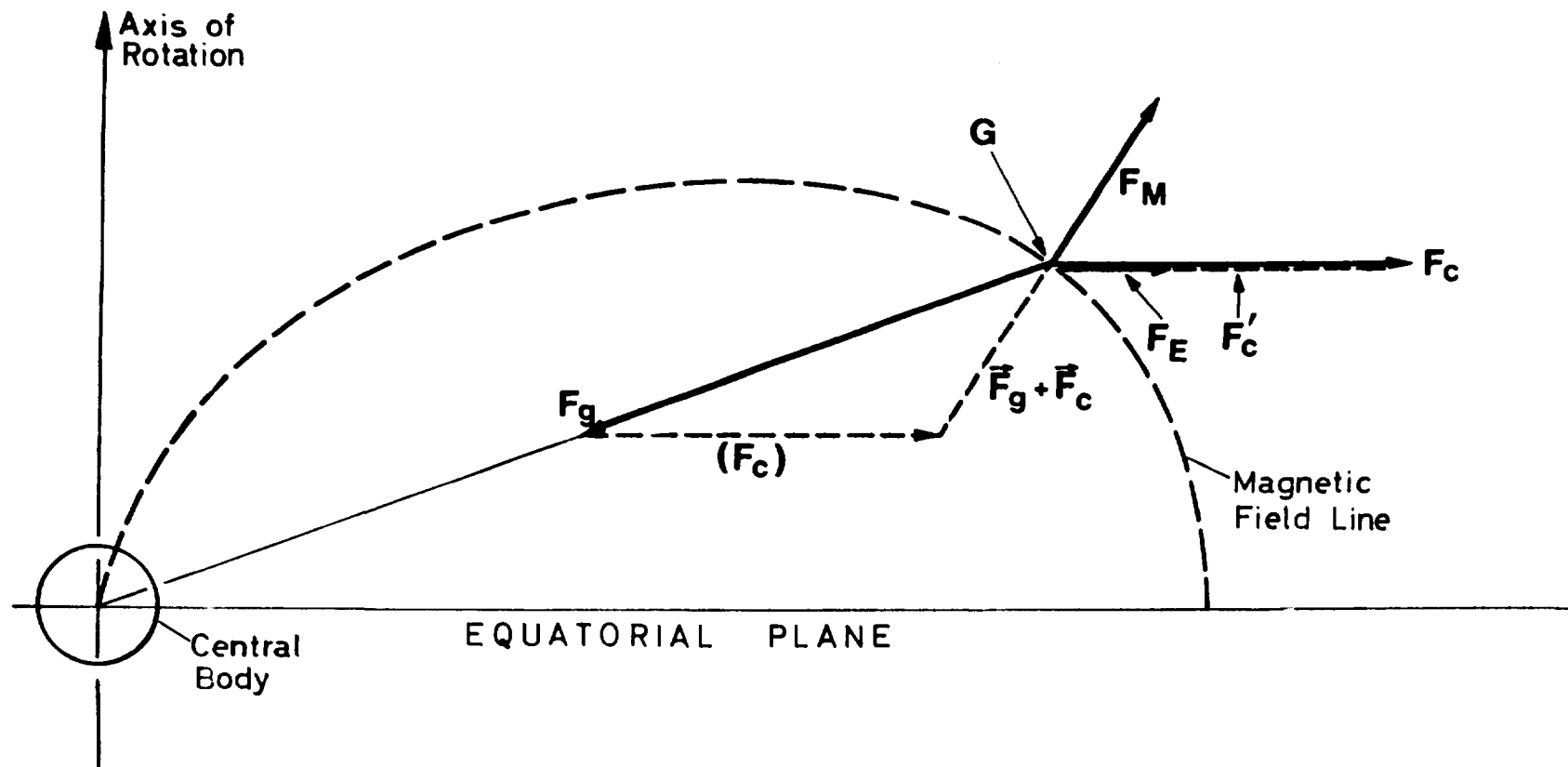


Fig.8 A grain at G is acted upon by gravitation \vec{F}_g , centrifugal force \vec{F}_c and magnetic forces F_M . The rotational velocity adjusts itself so that $\vec{F}_g + \vec{F}_c$ becomes perpendicular to the magnetic field at G. This determines \vec{F}_M so that $\vec{F}_g + \vec{F}_c + \vec{F}_M = 0$. If a radial electrostatic polarization force F_E is added, the centrifugal force must decrease to $\vec{F}'_c = \vec{F}_c - \vec{F}_E$. Hence the rotational velocity becomes smaller, the orbital ellipse after condensation more eccentric, and the Γ smaller.

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FURTHER EXPLORATIONS OF COSMOGONIC SHADOW EFFECTS IN THE
SATURNIAN RINGS

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The mass distribution in the Saturnian ring system is investigated and compared with predictions from the cosmogonic theory by Alfvén and Arrhenius. According to this theory, the matter in the rings has once been in the form of a magnetized plasma, in which the gravitation is balanced partly by the centrifugal force and partly by the magnetic field. As the plasma is neutralized, the magnetic force disappears and the matter can be shown to fall in to a distance $2/3$ of the original. This gives cause to the so called "cosmogonic shadow effect", which has been demonstrated earlier for the astroidal belt and in the large scale structure of the Saturnian ring system.

The relevance of the cosmogonic shadow effect is investigated for parts of the finer structures of the Saturnian ring system. It is shown that many structures of the present ring system can be understood as shadows and antishadows of cosmogonic origin. These appear in the form of double rings centered around a position a factor 0.64 (slightly less than $2/3$) closer to Saturn than the causing feature.

Key words: Cosmogony, Magnetospheres, Planetesimals, Saturnian rings, Solar system history.