

## NOTICE

THIS DOCUMENT HAS BEEN REPRODUCED FROM  
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT  
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED  
IN THE INTEREST OF MAKING AVAILABLE AS MUCH  
INFORMATION AS POSSIBLE

JPL PUBLICATION 80-80

# Saturn: Origin and Composition of Its Inner Moons and Rings

A. J. R. Prentice

(NASA-CR-163630) SATURN: ORIGIN AND  
COMPOSITION OF ITS INNER MOONS AND RINGS  
(Jet Propulsion Lab.) 20 p HC A02/MF A01

CSSL 03B

N80-34320

Unclas

G3/91 29038

October 15, 1980

National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California



JPL PUBLICATION 80-80

# **Saturn: Origin and Composition of Its Inner Moons and Rings**

**A. J. R. Prentice**

October 15, 1980

National Aeronautics and  
Space Administration

**Jet Propulsion Laboratory**  
California Institute of Technology  
Pasadena, California

The research described in this publication was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100.

## FOREWORD

Part of this report was written at the Department of Mathematics, Monash University, Clayton, Victoria 3168, Australia, and part during tenure of an NRC-NASA research associateship at the Jet Propulsion Laboratory.

A shorter version of this report will be published in Physics Letters.

## ABSTRACT

Theoretical modelling of the contraction of the primitive proto-saturnian cloud, using ideas of supersonic turbulent convection, suggests that each of Saturn's inner moons, excepting Rhea, condensed above the ice-point of water and consists primarily of hydrous magnesium silicates. It is predicted that Voyager 1 may find that the satellite mean densities steadily increase towards the planet and that the rocky moons are irregular in shape.

## CONTENTS

	Page
1. INTRODUCTION .....	1
2. THE MODERN LAPLACIAN THEORY .....	2
3. CALCULATIONS .....	4
4. PREDICTED CHEMISTRY, DENSITIES AND SHAPES OF THE SATELLITES .....	6
5. FORMATION OF SATURN'S RINGS .....	8
6. CONCLUSIONS AND ACKNOWLEDGEMENTS .....	9
REFERENCES .....	10

### Figures

1. Surface temperature of the contracting protosaturnian cloud .....	13
2. Schematic illustration of pre-Voyager predictions of the shapes, sizes, and densities of Saturn's inner satellites .....	14

### Table

1. Physical and chemical properties of the system of gaseous rings shed by the contracting protosaturnian envelope at the present orbital positions of the satellites and rings .....	15
--	----

## 1. INTRODUCTION

The recent spate of sightings [1] of suspected new satellites of Saturn observed during the rare ring-plane crossing of this planet in March 1980 has aroused a fresh interest in the origin of this planet and its inner family of moons and rings. This interest is particularly intense in view of the forthcoming fly-by of Voyager 1, scheduled November 12, 1980. Very little is known about the inner moons. Photometric evidence suggests that they have frost covered surfaces and low mean densities typical of a mostly icy composition [2]. In this report I present the results of detailed calculations of a possible mechanism for the formation of the moons and rings, which is based on ideas of supersonic turbulent convection applied to the original Laplacian hypothesis [3]. The calculations, which are a sequel to the work of Prentice and ter Haar [4], suggest that all of the moons interior to the orbit of Rhea, as well as the particles of the F ring discovered by Pioneer 11 [5] and the E ring [6], consist mostly of hydrated silicates. The A, B, C rings are mostly icy. These results can be reconciled with the existing observational data if the moons are irregular in shape.

The orbital radii  $R_n$  of the inner family of moons (Mimas through Rhea) form a roughly geometric sequence of the form  $R_n/R_{n+1} = 1.30 \pm 0.07$ , where  $R_0$  denotes the orbit of Rhea and  $n = 0, 1, 2, \dots$ . The moon 1979 S 1 discovered by Pioneer 11 [5], as well as the Fountain-Larson object 1966 S 2 [7], lie amongst a suspected faint stream of satellites whose mean orbital radius of  $2.52 R_S$  ( $R_S =$  Saturn's equatorial radius  $\approx 60,000$  km) is close to the next term in the geometric sequence after Mimas. The regular spacings of these orbits, including their near circularity and coplanarity and common sense of motion around Saturn, are features which



are also seen in the regular satellite systems of Jupiter and Uranus and the Sun's own planetary system. It is natural therefore to assume that some common mechanism was responsible for the formation of all systems [8].

## 2. THE MODERN LAPLACIAN THEORY

One possible mechanism which seems fairly accurately to account for the mass and chemical composition of the Galilean moons and the planetary system is a variant of the original nebula hypothesis due to Laplace [9]. In this modern Laplacian theory [3,4] the satellites and planets condensed from a concentric system of orbiting gaseous rings that were shed by the rotating turbulent gaseous envelope which gravitationally contracted to form the central parent body.

In the case of Saturn, this gaseous envelope was captured by a rock + ice planetary core of mass  $\sim 10 M_{\oplus}$  ( $M_{\oplus}$  = mass of Earth) which had accreted on the mean circular orbit of a protosolar gas ring of mass  $\sim 10^3 M_{\oplus}$  and temperature 60 K. This gas ring had, in turn, been shed by the turbulent protosun at the orbit of Saturn during the Sun's own primordial contraction. Since the temperature of this gas ring is much less than the  $H_2O$  ice point (150 K), one would expect the gas to be very heavily depleted of  $H_2O$ , including admixed rocky condensate. A large fraction of the uncondensed gases, consisting mostly of H and He would thermally escape from the solar system prior to their capture by the core when the protosun passed through its overluminous phase [3,10]. The model of the primitive protosaturnian cloud would thus consist of a central dense planetary core of mass  $\sim 10 M_{\oplus}$  surrounded by a tenuous rotating gaseous envelope of mass 85-90  $M_{\oplus}$ . The heavy element abundance  $Z_S$  of the envelope is expected to be much less than the solar value  $Z_{\odot} = 0.018$  [11] and its spin axis would be parallel to that

of the orbital motion. The present mass of Saturn is  $M_S = 95.2 M_\oplus$ .

It is interesting to note that Anderson et al. [12] have established an entirely similar picture from completely different considerations. These authors have computed the present structure of Saturn using gravitational moment data returned by Pioneer 11. They have concluded that  $H_2O$  and possibly  $NH_3$  and  $CH_4$  are primarily confined to the vicinity of a 15 - 20  $M_\oplus$  core, if they are present in solar proportions to rock.

Consider now the evolution of a tenuous protosaturnian envelope whose size initially exceeds the orbital radius of Rhea. Pollack et al. [13] showed that such a cloud would be fully convective, but unable to exist in a state of hydrostatic equilibrium since its internal energy requirement exceeds the available gravitational energy. Instead the cloud would collapse hydrodynamically over a period of a few days to about the orbit of Mimas, allowing no time to dispose of its excess spin angular momentum efficiently through the orderly process of mass extrusion and shedding [14]. To overcome this problem, which also manifests itself in the study of both the protosolar and protojovian envelopes, Prentice [3] has suggested that a supersonic turbulent stress arising from the motions of overshooting convective elements may help stabilize the envelope against free collapse.

The turbulent convective stress is buoyancy driven and in a non-rotating cloud has the form  $\langle \rho_t v_t^2 \rangle = \beta \rho GM(r)/r$  where  $\rho$  is the gas density,  $M(r)$  the mass interior to radius  $r$  and  $G$  is the gravitation constant [15]. The turbulence parameter  $\beta \sim 0.1$  is assumed to be a constant throughout the cloud. The turbulent stress equals some 10 times the normal gas pressure  $\rho RT/\mu$  ( $R$  = gas constant,  $T$  = temperature,  $\mu$  = molecular weight) in the outer

convective layers. It drastically lowers the cloud's moment-of-inertia coefficient  $f$  [16], thereby increasing the absolute store of gravitational potential energy. The stress also leads to the development of a very dense shell of non-turbulent gas above the photosurface. When rotation is included, this outer shell evolves into a belt-like structure of mass  $m$  at the equator, which is discontinuously abandoned by the contracting cloud when the centrifugal force overcomes the gravitational force. The net result is that the rotating cloud of mass  $M$  sheds a concentric system of orbiting gaseous rings whose mean orbital radii  $R_n$  satisfy the equation

$$R_n/R_{n+1} = [1 + m/Mf]^2 . \quad (1)$$

If the contraction is uniform, meaning that both  $m/M$  and  $f$  are constant, then the sequence is geometric. Eq. (1) can be inverted to estimate empirically the masses of the gaseous rings and hence compute the expected masses of the condensing system of moons, given the value of  $f$  and the envelope composition. In the case of the Galilean moon system, a best fit to the observed masses occurs with the choice  $f = 0.02$ , for a gas of solar composition [4].

### 3. CALCULATIONS

Applying eq. (1) to the protosaturnian cloud, with  $M = M_S$ ,  $f = 0.02$  and  $R_n/R_{n+1} = 1.3$ , we obtain a mean ring mass  $m = 1.6 \times 10^{27}$  g. If this gas is of solar composition the mass of rock condensate per ring is  $7 \times 10^{24}$  g whilst the rock + H<sub>2</sub>O ice component is  $1.9 \times 10^{25}$  g, using Cameron's abundances [11]. We see from Table 1, however, that both these masses are much larger than the observed values of any of the regular moons. If Rhea is mostly icy, the shortfall in expected mass corresponds to a factor of 9. This suggests that the heavy element abundance  $Z_S$  of the saturnian envelope

was depleted relative to the solar value  $Z_0$  by the same factor, yielding  $Z_S = 0.002$ .

Now applying eq. (1) specifically to Dione's orbit with  $Z_S = 0.002$  and  $R_0/R_1 = 1.40$  we obtain a rock mass of  $1.0 \times 10^{24}$  g. This precisely coincides with the observed mass of this moon suggesting that Dione is, in fact, rocky. The steady decline in the masses of the moons interior to Dione can also be accommodated in terms of a rocky composition if much of the rock remains suspended in the gas ring as a fine dust unable to settle onto the mean orbit before the ring dispersed, taking with it the finer material [4]. The presence of the gas ring is essential both for focusing grains onto the mean circular Keplerian orbit of the gas ring [3,17] as well as for the efficient accretion of the settled material by the growing satellite embryo [18].

At Dione's orbit the time scale  $t_{\text{set}}$  for the settling of grains of radius  $a = 0.01$  cm and density  $\rho_S = 3 \text{ g cm}^{-3}$  is 150 yr whilst the dispersal time scale, based on a simple thermal evaporation argument [4], is

$$t_{\text{evap}} = 2.73 R_n \left( \frac{\mu}{RT_n} \right)^{1/2} \exp \left( \frac{5\mu GM}{64RT_n R_n} \right) \sim 80 \text{ yr} . \quad (2)$$

Here  $T_n = 275$  K is the gaseous ring temperature (see table 1). Moving inwards from Dione, the rings are warmer ( $T_n \propto R_n^{-1}$ ) so the grains may be dustier and smaller with a correspondingly longer settling time  $t_{\text{set}} \propto 1/\rho_S a^2$ . At the orbit of Mimas  $t_{\text{set}} = 2600$  yr if  $a = 10^{-3}$  cm, while  $t_{\text{evap}} = 30$  yr. Hence, only a very small fraction of the rocky condensate may have settled out onto the mean orbit  $R_n$  by the time the gas had dispersed. Thermal stirring of the dense inner gas rings, whose density  $\rho_n$  is shown in table 1,

would also destroy the orbital angular velocity structure in the ring, causing the gas and its imprisoned dust to spread away from the mean accretional orbit  $R_n$ . We suggest, therefore, that Feibelman's E ring formed from the slowly settling dust which failed to become incorporated into the rocky moons [19].

The temperatures  $T_n$  of the gaseous rings at their time of detachment  $t_n$  from the contracting globe can be computed by evolving a turbulent polytropic model of mass  $M = M_S$  through the dimensions of the regular satellite system [20]. The results of these computations for a cloud having H mass fraction  $X = 0.75$  and  $Z_S = 0.002$  are shown in fig. 1. This figure shows the variation of the black-body surface temperature  $T_e$  of the cloud with equatorial size  $R_e$ . During uniform contraction,  $T_e = 2^{-1/4} T_{ph}(R_i) R_i / R_e$  where  $T_{ph}(R_i)$  is the photosurface temperature at the initial cloud radius  $R_i = 10 R_S$ . The values  $T_n = T_e(R_n)$  at the orbital positions of the satellites and mid-point positions of the A, B, F rings, including Cassini's division, are shown in table 1, along with the expected composition of the condensate that would form, derived from the equilibrium condensation sequence data of Lewis [21].

#### 4. PREDICTED CHEMISTRY, DENSITIES AND SHAPES OF THE SATELLITES

The simplified polytropic calculations indicate that Rhea condensed below the water vapour ice point. This moon should therefore consist of 36% by weight rock and 64% ice, with a mean density close to  $1.3 \text{ g cm}^{-3}$  [22]. The gravitational energy released during the accretion of Rhea's outer mantle would be sufficient to melt the icy mix if this moon's mass exceeds  $2.5 \times 10^{24} \text{ g}$ . It follows that the surface of Rhea may be nearly spherical. Closer to Saturn the moons are predicted to be increasingly rockier with a mean density of order  $2.4 \text{ g cm}^{-3}$ , similar to that of asteroidal rock [21]. Peale et al. [23],

using tidal considerations, have also predicted that Mimas and probably Dione may be rocky. Thermodynamic data of hydrous silicates [24] suggest that the masses of the moons are just sufficient to liberate some of the water of hydration from the outer mantles during accretion. This steam would form a torus around the circular orbit of the satellite which would subsequently recondense on its surface to give it a frosty appearance, when the temperatures everywhere began to drop. In this connection 1979 S1 and Mimas should be darker and denser than the other moons since the mineral phase tremolite is less hydrous than serpentine.

The masses of the rocky moons are far too small for them to have melted during accretion and assumed a spherical form. We cannot, therefore, overlook the possibility that they may be irregular in shape. There is an apparent discrepancy between the radiometric estimate of Dione's diameter [2] and the lunar occultation value [25], taken when the satellite was at a different orbital phase, namely  $68^\circ$  before eastern elongation [26]. Dione also has a non-sinusoidal light curve [27]. These data suggest that this moon is a rocky elongated body, having a semi-major axis of about 575 km directed towards Saturn and minor axes of 425 km perpendicular to this. Tethys has a larger visual magnitude than Dione, despite its smaller mass. Combining this fact with Elliot's uniform disk measurements [25] and Tethys' uniform light curve, we deduce that this moon, if rocky, is a bright oblate spheroid having semi-major axes of about 450 km in the orbital plane and a minor axis of 300 km normal to this. Enceladus has a much lower photometric density than Mimas. It also has an unusual light curve [28]. This moon may therefore be elongated like Dione, but of higher visual albedo and having a longest semi-axis of 300 km. A schematic illustration of the predicted satellite shapes and sizes is shown in Fig. 2.

## 5. FORMATION OF SATURN'S RINGS

During the slow final stages of the cloud's contraction, the degree of turbulence measured by the parameter  $\beta$  is progressively reduced, commencing at radius  $R_* = 2.67 R_S$ , in a manner such that the surface temperature  $T_e$  follows the locus shown in fig. 1.  $T_{end} = 300$  K is the final chosen photosurface temperature at radius  $R_e = 1.37 R_S$ , corresponding to a fully rotating cloud having polar radius equal to the present value  $0.912 R_S$  [5]. As  $\beta$  declines, the mass of the shed rings and their spacing  $R_n - R_{n+1}$  rapidly decreases. With  $R_* = 2.67 R_S$  the cloud sheds one final ring at orbital radius  $2.52 R_S$ , equal to that of 1979 S 1, then remains rotationally stable until the radius  $2.42 R_S$  is reached. Below this point the cloud can remain stable only if  $f$  starts to increase. The outer non-turbulent layers, however, cannot be braked during contraction and will be stripped away creating a gaseous Keplerian disc in the equatorial plane. In our model it is the material which condenses from this disc which forms Saturn's rings [29].

Initially the condensate in the disc is rock. After a time  $t_{H_2O}$ , typically about  $3 \times 10^6$  yr, the temperature at each point falls below the  $H_2O$  ice-point and ice begins to precipitate out of the gas. Owing to the thermal evaporation, however, the fraction of gas  $\phi_{H_2O}$ , shown in table 1, which survives to time  $t_{H_2O}$  decreases rapidly with distance from Saturn. The calculations thus show that whilst the B and C rings may be mostly icy, the fraction of ice to rock rapidly decreases through the region of the A ring. The particles of the F ring and other suspected nearby moonlets should therefore all be rocky [30]. Finally, according to this theory Titan and

the outer moons of Saturn are captured bodies which originally condensed at the same orbit as Saturn but failed to be accreted into its central core. As such, they should consist of 32% by weight rock, 57% H<sub>2</sub>O ice and 11% NH<sub>3</sub>.

#### 6. CONCLUSIONS AND ACKNOWLEDGEMENTS

Voyager 1 will test the predictions of this theory in November, 1980.

I thank J. D. Anderson, M.S. Bloom, R.A. Gingold, K. Hourigan, P.D. Nicholson and D. ter Haar for useful discussions.



## REFERENCES

- [1] B.G. Marsden, I.A.U. Circular Nos. 3456, 3457, 3463, 3466, 3470, 3474, 3483, 3486 (1980).
- [2] D. Morrison, *Icarus* 22 (1974) 51; D.P. Cruikshank, *Rev. Geophys. Space Phys.* 17 (1979) 165.
- [3] A.J.R. Prentice, in: *The Origin of the Solar System*, ed. S.F. Dermott (J. Wiley & Sons, London, 1978) p. 111; A.J.R. Prentice, *The Moon and the Planets*, 19 (1978) 341.
- [4] A.J.R. Prentice and D. ter Haar, *Nature* 280 (1979) 300; *ibid.* *The Moon and the Planets* 21 (1979) 43.
- [5] T. Gehrels et al., *Science* 207 (1980) 434.
- [6] W.A. Feibelman, *Nature* 214 (1967) 793; B.G. Marsden, I.A.U. Circular Nos. 3454, 3457, 3476 (1980).
- [7] J.W. Fountain and S.M. Larson, *Icarus* 36 (1978) 92; K. Aksnes and F.A. Franklin, *ibid.* p. 107.
- [8] H. Alfvén and G. Arrhenius, *Structure and Evolutionary History of the Solar System* (D. Reidel, Boston, U.S.A., 1975) p. 3.
- [9] P.S. Laplace, *Exposition du Système du Monde* (Courcier, Paris, 1796) p. 387.
- [10] F. Hoyle and N.C. Wickramasinghe, *Nature* 217 (1968) 415.
- [11] A.G.W. Cameron, *Space Sci. Rev.* 15 (1973) 121.

- [12] J.D. Anderson, G.W. Null, E.D. Biller, S.K. Wong, W.B. Hubbard and J.J. MacFarlane, *Science* 207 (1980) 449.
- [13] J.B. Pollack, A.S. Grossman, R. Moore, H.C. Graboske Jr., *Icarus* 30 (1977) 111; P. Bodenheimer, A.S. Grossman, W.M. De Campli, G. Marcy, J.B. Pollack, *Icarus* 41 (1980) 293.
- [14] In the present study we assume that the orbit of Rhea marks the radius where the contracting cloud first became rotationally unstable, meaning the outward centrifugal force at the equator balances the inward gravitational force.
- [15] A.J. R. Prentice, *Astron. Astrophys.* 27 (1973) 237; *ibid.* 50 (1976) 59.
- [16] This quantity is defined by the equation  $f = I/MR_e^2$  where  $I$  is the axial moment-of-inertia,  $M$  is the cloud mass, and  $R_e$  the equatorial radius.
- [17] K. Hourigan, *Proc. Astron. Soc. Australia* 3 (1977) 169.
- [18] A.J.R. Prentice, *Austral. J. Phys.* (to appear).
- [19] Observationally the E ring extends from the outer edge of the A ring to more than  $7 R_S$  [6]. The model for its origin proposed here accounts for the fact that the visual intensity varies directly with the observed shortfall in satellite mass [W.A. Baum, private communication]. Also, B.A. Smith [*Sky and Telescope* 59 (1980) 296] reports that the ring does seem dusty.
- [20] These models, described in more detail elsewhere [3,4], are characterized by a surface temperature factor  $\theta_{ph}$  and turbulence

parameter  $\beta$  which are adjusted to yield an envelope moment-of-inertia factor  $f = 0.02$  and mean ring spacing factor  $R_n/R_{n+1} = 1.3$ . We obtain  $\Theta_{ph} = 0.0069$ ,  $\beta = 0.0814$  in the present study.

- [21] J.S. Lewis, *Icarus* 16 (1972) 241; *ibid.* *Science* 186 (1974) 440; W.D. Metz, *ibid.* p. 817. Since  $Z_S = Z_0/9$ , the partial pressures of the heavy elements are reduced by a factor 9 compared with Lewis' values.
- [22] M.J. Lupo and J.S. Lewis, *Icarus* 40 (1979) 157.
- [23] S.J. Peale, P. Cassen, R.T. Reynolds, *Icarus* (to appear). I thank these authors for providing a copy of their paper prior to publication.
- [24] R.A. Robie, B.S. Hemingway, J.R. Fisher, in: *Thermodynamic Properties of Minerals and Related Substances at 298.15 K and 1 Bar ( $10^5$  Pascals) Pressure and at Higher Temperatures* (U.S. Govt. Printing Office, Washington, D.C., 1978) p. 421.
- [25] J.L. Elliot, J. Veverka, J. Goguen, *Icarus* 26 (1975) 387.
- [26] Tidal effects would cause the inner moons to keep a constant face towards Saturn [S.J. Peale, in: *Planetary Satellites*, ed. J.A. Burns (Univ. of Arizona Press, Tucson, Arizona, 1977) p. 87].
- [27] M. Noland et al. *Icarus* 23 (1974) 334.
- [28] O.G. Franz and R.L. Millis, *Icarus* 24 (1975) 433.
- [29] This model for the origin of the rings is similar to that of J.B. Pollack, A.S. Grossman, R. Moore, H.C. Graboske, Jr., *Icarus* 29 (1976) 35.
- [30] A.J.R. Prentice, *Proc. Astron. Soc. Australia* 3 (1977) 172.

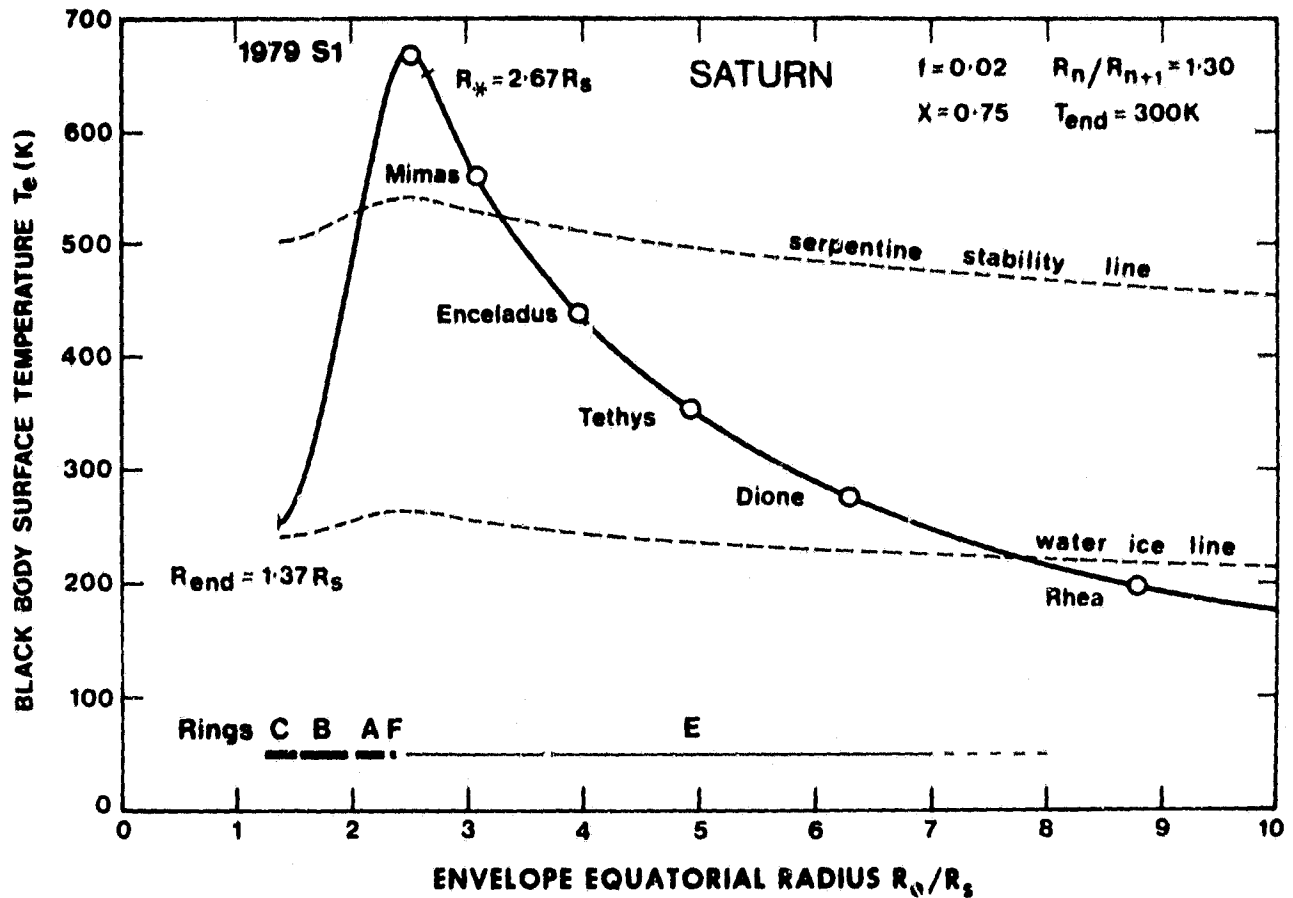


Fig. 1. Surface temperature of the contracting protosaturnian cloud of mass  $M_S = 5.69 \times 10^{29}$  g plotted against equatorial size  $R_e$ , which is measured in units of the present value  $R_S = 6 \times 10^9$  cm. The cloud is assumed to be in a state of supersonic turbulent convective equilibrium and uniform internal rotation, with centrifugal force balancing the gravitational force at the equator. The broken lines show the vapour condensation temperatures of  $H_2O$  ice and the hydrous mineral serpentine  $Mg_3 [Si_2O_5] (OH)_4$  at the cloud's equator. These lines were computed using the equilibrium condensation data of Lewis [22] applied to a gas of heavily depleted metal abundance  $Z_S = 0.002$ . The positions of Saturn's rings are shown at the foot of the diagram.

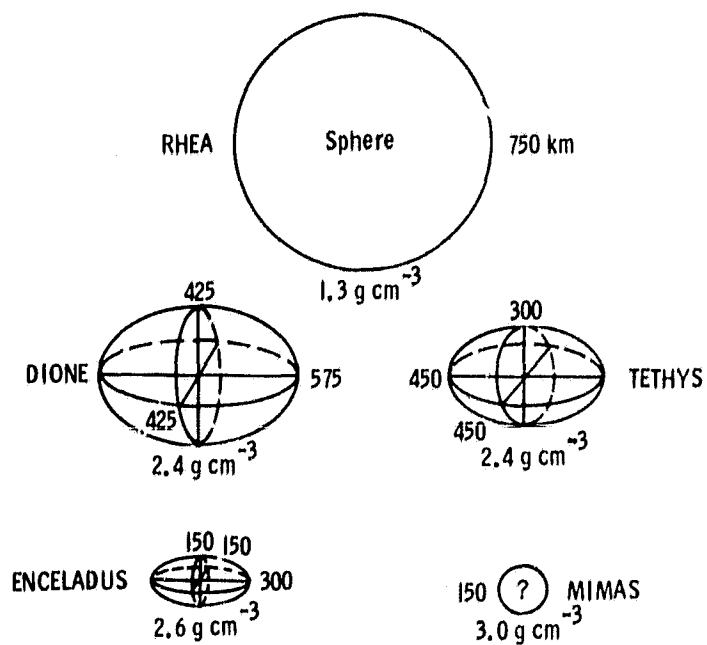


Fig. 2. Schematic illustration of pre-Voyager predictions of the shapes, sizes, and densities of Saturn's inner satellites; sizes refer to semi-axes (km).

Table 1. Physical and chemical properties of the system of gaseous rings shed by the contracting protosaturnian envelope at the present orbital positions of the satellites and rings. Satellite masses are from Anderson et al. [12]

Rock<sub>1</sub> = CaTiO<sub>3</sub>, Ni, (Na,K)AlSi<sub>3</sub>O<sub>8</sub>, FeO, serpentine.

Rock<sub>2</sub> = CaTiO<sub>3</sub>, Ni, (Na,K)AlSi<sub>3</sub>O<sub>8</sub>, FeS, tremolite.

Properties for Saturn's rings apply to the mid-positions.

Object	Orbital radius $R_n/R_S$	Observed mass ( $10^{24}$ g)	Initial gas temperature $T_n$ (K)	Initial gas density $\rho_n$ ( $g\ cm^{-3}$ )	$t_n$ ( $10^6$ yr)	$t_{evap}$ (yr)	$\phi_{H_2O}$	Final chemical composition of condensate
Rhea	8.79	$2.2 \pm 0.7$	200	$3.4 \times 10^{-5}$	0.3	120	0	Rock <sub>1</sub> , H <sub>2</sub> O ice
Dione	6.30	$1.05 \pm 0.03$	275	$9.3 \times 10^{-5}$	1.1	80	0	Rock <sub>1</sub>
Tethys	4.92	$0.63 \pm 0.02$	355	$2.0 \times 10^{-4}$	1.6	55	0	Rock <sub>1</sub>
Enceladus	3.97	$0.074 \pm 0.034$	440	$3.7 \times 10^{-4}$	1.9	40	0	Rock <sub>1</sub>
Mimas	3.10	$0.038 \pm 0.001$	560	$7.9 \times 10^{-4}$	2.2	30	0	Rock <sub>2</sub>
1979 S 1	2.52	<0.01	670	$1.2 \times 10^{-3}$	2.4	25	0	Rock <sub>2</sub>
F ring	2.33	?	640	$1.2 \times 10^{-3}$	2.5	70	0	Rock <sub>2</sub>
A ring	2.15	?	570	$1.0 \times 10^{-3}$	2.6	500	0.006	Rock <sub>1</sub> , H <sub>2</sub> O ice
Cassini div.	2.00	?	490	$0.8 \times 10^{-3}$	2.7	$8 \times 10^3$	0.915	Rock <sub>1</sub> , H <sub>2</sub> O ice
B ring	1.75	?	355	$0.5 \times 10^{-3}$	3.9	$2 \times 10^7$	1.000	Rock <sub>1</sub> , H <sub>2</sub> O ice