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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 protosaturnian 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

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 $n = 0,1,2,\ldots$. 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 $\simeq$ 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 ρ 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, μ = 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

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

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 7×10^{24} g whilst the rock + H_2O ice component is 1.9×10^{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 $Z_\odot$ 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 1.0×10^{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_{set} for the settling of grains of radius $a = 0.01$ cm and density $\rho_S = 3$ g cm^{-3} is 150 yr whilst the dispersal time scale, based on a simple thermal evaporation argument [4], is

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

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 $t_{set} \propto 1/\rho_S a^2$. At the orbit of Mimas $t_{set} = 2600$ yr if $a = 10^{-3}$ cm, while $t_{evap} = 30$ 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 ρ_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 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 2.5×10^{24} 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 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° 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 β 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 β 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 3×10^6 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 ϕ_{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_2O ice and 11% NH_3.

6. CONCLUSIONS AND ACKNOWLEDGEMENTS

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

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parameter β 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.

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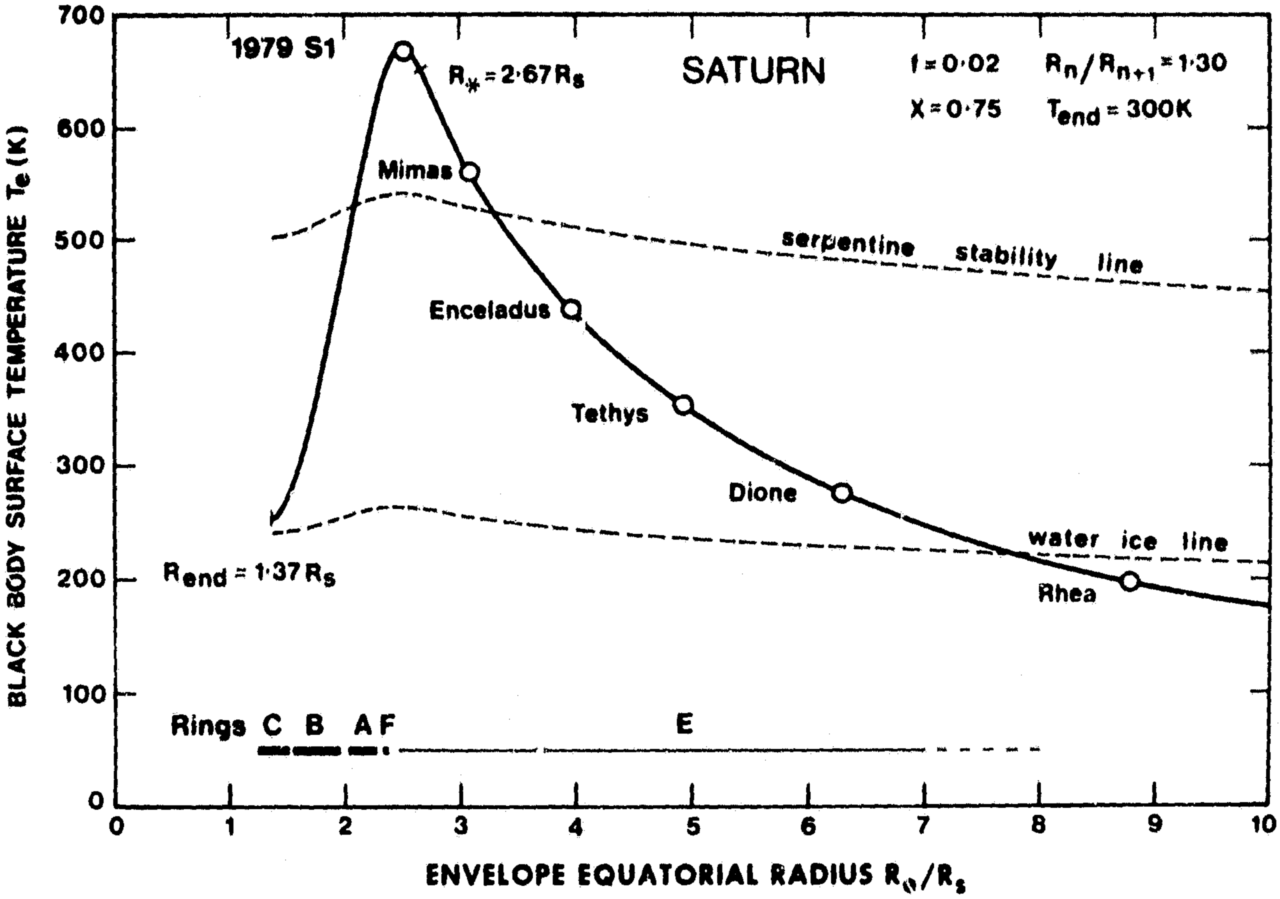

Fig. 1. Surface temperature of the contracting protosaturnian cloud of mass $M_S = 5.69 \times 10^{29}$ g plotted against equatorial size R_e, which is measured in units of the present value $R_S = 6 \times 10^9$ cm. The cloud is assumed to be in a state of supersonic turbulent convective equilibrium 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.

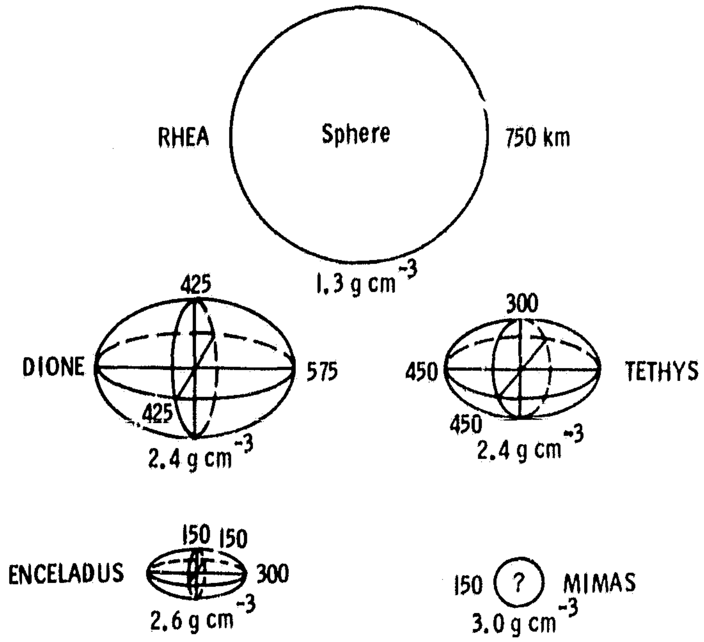

Fig. 2. Schematic illustration of pre-Voyager predictions of the shapes, sizes, and densities of Saturn's inner satellites; sizes refer to semi-axes (km).

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]

$Rock_1$ = $CaTiO_3$, Ni, $(Na,K)AlSi_3O_8$, FeO, serpentine.

$Rock_2$ = $CaTiO_3$, Ni, $(Na,K)AlSi_3O_8$, 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 ρ_n(g cm^{-3})	t_n (10^6 yr)	t_{evap} (yr)	ϕ_{H_2O}	Final chemical composition of condensate
Rhea	8.79	2.2 ± 0.7	200	3.4×10^{-5}	0.3	120	0	$Rock_1$, H_2O ice
Dione	6.30	1.05 ± 0.03	275	9.3×10^{-5}	1.1	80	0	$Rock_1$
Tethys	4.92	0.63 ± 0.02	355	2.0×10^{-4}	1.6	55	0	$Rock_1$
Enceladus	3.97	0.074 ± 0.034	440	3.7×10^{-4}	1.9	40	0	$Rock_1$
Mimas	3.10	0.038 ± 0.001	560	7.9×10^{-4}	2.2	30	0	$Rock_2$
1979 S 1	2.52	<0.01	670	1.2×10^{-3}	2.4	25	0	$Rock_2$
F ring	2.33	?	640	1.2×10^{-3}	2.5	70	0	$Rock_2$
A ring	2.15	?	570	1.0×10^{-3}	2.6	500	0.006	$Rock_1$, H_2O ice
Cassini div.	2.00	?	490	0.8×10^{-3}	2.7	8×10^3	0.915	$Rock_1$, H_2O ice
B ring	1.75	?	355	0.5×10^{-3}	3.9	2×10^7	1.000	$Rock_1$, H_2O ice