COMPOSITION, STRUCTURE AND EVOLUTION OF URANIAN AND NEPTUNIAN SATELLITES*

David J. Stevenson

Division of Geological and Planetary Sciences
California Institute of Technology
Pasadena, California 91125

Abstract

Large uncertainties in the current estimated densities of all of these satellites prevent detailed modeling or predictions. Nevertheless, current evidence suggests that at least Titania and Oberon might have ''anomalously'' high densities (2-3 g cm^{-3}), possibly requiring almost ice-free hydrated silicates or formation in a CO-rich environment, implying presence of CO-clathrate and a small ice/rock ratio. Triton and the four largest satellites of Uranus are massive enough to have undergone significant accretional heating and early differentiation; NH_3-H_2O volcanism; partial outgassing of CO, N_2, CH_4; formation of dark surficial deposits of carbon-rich material obtained by UV irradiation of outgassed material; and, at least in the cases of Ariel and Triton, a possibility of weak ongoing icy volcanic activity. Triton may be the largest captured body in the solar system, with an unusual history and composition, including the possibility of substantial liquid or solid nitrogen obtained from either primordial NH_3 photolysis or clathrate decomposition.

INTRODUCTION

Voyager observations at Jupiter and Saturn have yielded a diversity of new worlds for study. The individuality of these satellites leads us to suspect that surprises and further diversity await us in the Uranian and Neptunian systems. Ground-based observations already provide evidence to support this expectation. My goal here is to provide some primarily theoretical arguments, based on very general considerations, which constrain the possible

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nature of these satellites and provide further indication for their suspected individuality and novelty.

Unfortunately, the existing data (described briefly in the next section and in far greater detail elsewhere in this workshop report) are insufficient for quantitative modeling of individual satellites. For this reason, I discuss generic satellites and avoid, as far as possible, any cosmogonic prejudice. However, a few speculative suggestions are offered about the origin and formation conditions since these factors, while not the primary focus of this report, are crucial for understanding composition and evolution. The issues I consider are these:

1) What range of compositions are conceivable for these satellites?
2) What relationship does the composition have to formation conditions?
3) What was the early evolution of these satellites, including the consequences of accretion?
4) How are the constituents distributed internally? (Are there cores? Are there undifferentiated satellites?)
5) What is the <u>present</u> dynamic state?
6) What implications follow for the surficial appearance?

OBSERVATIONAL CONSTRAINTS AND THEIR IMPLICATIONS

The average density is the most important constraint, yet poorly known in all cases as the Table below indicates. The Uranian satellite masses are taken from Veillet (1983). The radii are from Brown et al. (1982, 1983). The Table also lists central pressures, computed from $p_c = 2\pi G\bar{\rho}^2 R^2/3$, useful for characterizing the nature or phase of the material, and nominal

Table I

	Miranda	Ariel	Umbriel	Titania	Oberon	Triton	Nereid
Mass, M (10^{24} g)	$\lesssim 0.2$	1.6	1.0	5.9	6.0	~100?	?
Radius, R (km)	220 ± 70	660 ± 60	560 ± 50	800 ± 60	815 ± 70	1750 ± 250	~300?
Average density, $\bar{\rho}$(g/cm^3)	$\lesssim 3$?	1.3 ± 0.5	1.4 ± 0.6	2.7 ± 0.6	2.6 ± 0.6	?	?
Central pressure P_c(bars)	~600?	~1000	~1000	~6500	~6500	~2 x 10^4?	?
Nominal central temperature, T_c (K)	~85	270	210	375	385	(1600)*	?
Nominal maximum accretional temperature rise T_{acc} (K)	~20	~100	~100	~250	~250	~1000	?
Surface		H_2O ice + low albedo material				CH_4 ice, N_2 liquid? H_2O ice?	?

*Triton is too large to be in conductive steady state.

central temperatures $T_c = QR^2/6k$, for a body in conductive steady state ($k = 1 \times 10^5$ cgs), containing an energy source $Q = 3 \times 10^{-8}$ erg/cm^3-s crudely representative of present day radiogenic heat from a 50-50 mixture of chondritic material and ice. This nominal temperature is <u>not</u> a good estimate for the actual central temperature in most cases, but serves as a basis for more careful analysis. The table also includes a maximum conceivable accretional temperature rise $T_{acc} = 3GM/5RC_p$, where $C_p \simeq 1 \times 10^7$ erg/g-k is the specific heat.

The estimated average densities allow almost the complete range of conceivable values, from volatile-rich assemblages ($\bar{\rho} < 1$ g cm^{-3}) to rocky, ice-free bodies ($\bar{\rho} \sim 3.5$ g cm^{-3}). The estimates also allow the possibility that all the bodies have similar composition ($\bar{\rho} \sim 2$ g cm^{-3}). The estimated pressures are potentially large enough for high pressure phases of ice to be present in the five largest satellites listed. The nominal central temperatures are large enough in these five bodies to admit the possibility of internal activity (partial melting of NH_3-H_2O, convection, outgassing) but the timing and extent of this activity depends, of course, on the composition. The accretional temperature rises are strictly upper bounds but are again potentially important in the five largest bodies; especially Titania, Oberon and Triton; since they may have caused mobilization of the more volatile phases and perhaps caused transient NH_3-H_2O lakes (Titania, Oberon) or oceans (Triton). The ground-based data on the surfaces are unfortunately <u>not</u> a strong constraint on bulk composition since the materials detected may be minor constituents. The non-detection of CH_4 on the small satellites implies nothing about their nature since CH_4 can rapidly escape and/or undergo UV modification.

COMPOSITIONAL MODELS

The likely ingredients of a satellite can be classified as follows, in order of increasing volatility (Lewis, 1971): ''rock'' (anhydrous or hydrated), water ice, ammonia hydrate ($NH_3 \cdot H_2O$), ice clathrate ($\sim X \cdot 6H_2O$; X = CH_4, CO, N_2...), more volatile ices (CH_4, etc). In accordance with the cosmogonic argument that these constituents formed by condensation from the gas phase, it is usually assumed that no member of this list is present in a

Table II. Generic Satellites

	Composition (mass fractions in brackets)	Uncompressed Density ($g\ cm^{-3}$)	Examples
I.	Hydrated ''rock'' (1.0)	~2.5*	Primordial Europa
II.	Rock (0.4) + H_2O ice (0.6)	1.3	Ganymede, Callisto
III.	Rock (0.35) + H_2O ice (0.55) + $NH_3 \cdot H_2O$ ice (0.1)	1.25	Enceladus + ?
IV.	Rock (0.35) + $CH_4 \cdot 7H_2O$ (0.55) + $NH_3 \cdot H_2O$ ice (0.1)	1.25	Iapetus + ? Titan
V.	Rock (0.25) + $CH_4 \cdot 7H_2O$ (0.4) + $NH_3 \cdot H_2O$ (0.1) + CH_4 ice (0.25)	~0.9	Pluto?
VI.	Rock + $(CO, N_2) \cdot 7H_2O$	~1.8	(? Possibly Uranian)

*Somewhat uncertain. This uncertainty propagates systematically through all the subsequent values in this Table.

satellite unless all preceding members on the list are present. This might be wrong if the formation conditions are unusual (e.g. formation from a debris cloud following a large collision). Even if the sequential nature of the list is adhered to, the relative mass fractions can be significantly modified by the chemical nature of the gas phase. The most important factor is the CO/CH_4 ratio. If most of the carbon is in the form of CO, then because carbon is ~60% as abundant as oxygen (Anders and Ebihara, 1982), this reduces the amount of H_2O present. A satellite of rock and H_2O ice forming from a cosmic composition environment is then ~70% rock, 30% ice by mass (average uncompressed density ~1.7 to 1.9 $g\ cm^{-3}$). If carbon is in the form CH_4 then the body which forms is ~40% rock, 60% ice by mass (average uncompressed density ~1.3 $g\ cm^{-3}$). Lewis and Prinn (1980) and Prinn and Fegley (1981) sought to establish the CO/CH_4 ratio in the solar and protoplanetary nebulae, respectively, by a consideration

of the kinetics of the summation reaction $CH_4 + H_2O \longleftrightarrow CO + 3H_2$. They found CO-dominance for the solar nebula but a high probability of CH_4-dominance for protoplanetary nebulae. However, this is an oversimplification since much of the gas may have retained its interstellar CO/CH_4 (because it is never heated above $\sim 10^3$ K) and some of the gas may have been heated under conditions substantially different from those assumed (e.g. giant impacts). Similar concerns apply for the N_2/NH_3 ratio.

The generic models considered here encompass most (but not all) possible contingencies. In subsequent sections, I examine the evolution and structure of each model class.

FORMATION AND POST-ACCRETIONAL CONDITIONS

Consider an accreting satellite of instantaneous mass M which forms in an ambient gas-free (or optically thin) environment of temperature T_o. A characteristic accretion time is $\tau = M/(dM/dt)$ and is likely to be of order 10^3-10^4 years (Safronov and Ruskol, 1977), much less than that for planets. A crude estimate for the <u>surface</u> temperature T_s during accretion can be obtained from the energy balance:

$$\sigma(T_s^4 - T_o^4)\cdot 4\pi R^2 = \frac{M}{\tau}\left[\frac{GM}{R} - C_p(T_s - T_o)\right] \qquad (1)$$

where M, R are the instantaneous mass and radius, σ is the Stefan-Boltzmann constant, and C_p is the specific heat of the accreted material. The model assumes that the impact velocity $\simeq$ escape velocity. The solution of this equation is shown in Figure 1 for $T_o = 55$ K, $C_p = 1 \times 10^7$ erg/g and $\tau = 10^4$

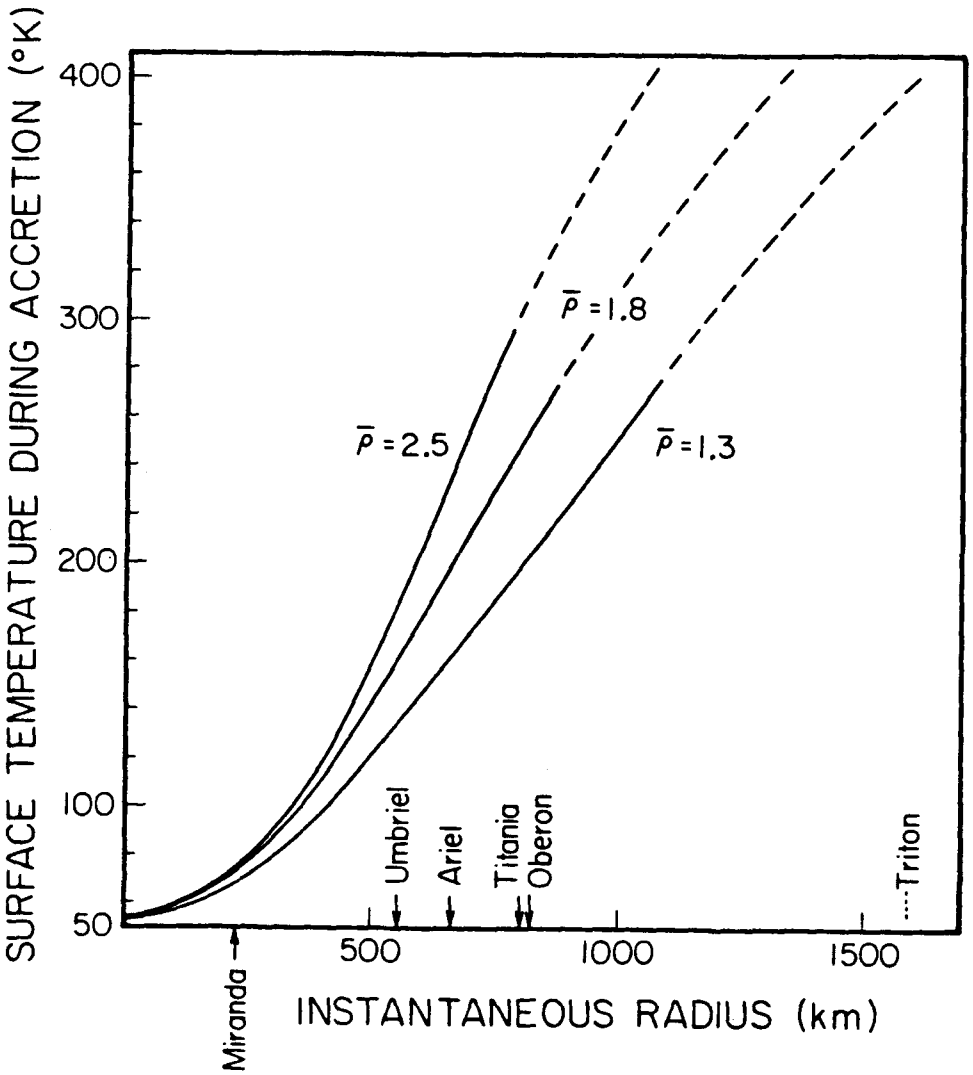


Fig. 1. Surface temperature during accretion, for three choices of average density $\bar{\rho}$.

years. Bodies larger than ~10^3 km are not accurately modeled, primarily because of latent heat effects (which buffer the rise of temperature) but also because of transient (e.g. steam) atmosphere effects. The temperature estimates in Figure 1 may also be somewhat high because of unmodeled effects such as radiative cooling from ejected particulate impact debris immediately after individual impacts. For comparison, the <u>sub-surface</u> temperature is bounded above by the values given in Table I; a more realistic estimate may be $\lesssim$50% of

these values since only a fraction of the input energy is deposited below the thermal boundary layer (see Schubert et al., 1981, for a similar calculation applied to the Jovian satellites).

These calculations show that the expected temperature rise during accretion may be sufficient to evaporate the more volatile ices (i.e. CH_4, CO, N_2) even for satellites ~500 km radius. If this material is not effectively buried during individual impacts then it may undergo hydrodynamic blow-off. Even if it is buried, it may be warm enough to melt and migrate immediately to the surface. Clathrates should at least partially survive, however, since hydrostatic pressure helps to stabilize these compounds. (There are several misconceptions in the existing literature concerning clathrates. One is the notion that clathrates gradually decompose, causing outgassing of the satellite. This is not true, in general, unless the temperature is raised by a large amount or the pressure exceeds ~10 kbar. See Lunine and Stevenson, 1984.) In satellites $\gtrsim$800 km in radius, partial melting of H_2O-NH_3 may occur at or near the surface but melting of pure water ice is unlikely until the body becomes about the size of Triton. It is certainly possible that Triton possessed a primordial NH_3-H_2O ocean caused by accretional heating. This can also occur if the accretional environment is optically thick because of the presence of a dense, gas phase (a situation analyzed for the Jovian satellites by Lunine and Stevenson, 1982a).

The accretional and immediate post-accretional states can be summarized for each satellite class in Table II, as follows. Type I (hydrated silicates) undergoes no accretion modification unless the temperature exceeds ~600-800 K; this requires a body $\gtrsim$1500 km in radius, perhaps a body ~ Europa, if the body forms in a cold environment. The consequence is an ice layer overlying the

silicates. Type II (rock + H_2O ice) has already been modeled in the Jovian system (Schubert et al., 1981; Lunine and Stevenson, 1982a). It is probable that bodies $\gtrsim$1500 km undergo partial melting and resurfacing although the critical size might even be near the size of Callisto, perhaps explaining the striking surficial dissimilarity of Ganymede and Callisto. Type III ($NH_3 \cdot H_2O$ added) may undergo partial melting and primordial resurfacing at R ~ 500-1000 km, a size range which encompasses the four larger Uranian satellites. Type IV (CH_4 clathrate added) would behave similarly, with the addition of some explosive CH_4 release (discussed by Stevenson, 1982) as 'hot' (~180 K) NH_3-H_2O magma comes into contact with near-surface clathrate. Type V (CH_4 added) should be almost 'explosive' if R $\gtrsim$ 300-500 km, with a large fraction of the CH_4 undergoing melting, surface evaporation and rapid escape. Type VI (CH_4 poor; CO as clathrate) may not undergo melting or decomposition during accretion, unless R $\gtrsim$ 700-1000 km. Some N_2, CO may migrate to the surface, undergoing escape less rapidly than CH_4 because of the higher molecular weight.

THERMAL HISTORIES

Although a pure ice satellite is conceivable, it is very likely that all satellites contain a sufficient complement of rock to undergo significant radiogenic heating after accretion. Unless the giant planets and their satellites formed very rapidly ($<10^6$ years after the initiation of solar system formation), ^{26}Al should be unimportant, and the heat is derived from long-lived isotopes, primarily ^{40}K, ^{235}U, ^{238}U, and ^{232}Th. The thermal history of a conductive sphere containing heat sources is easy to compute if the conductivity is constant and known (e.g. the asteroid evolutions of Allen and Jacobs, 1956). In the case of icy satellites, this simple approach, using the conduc-

tivity of crystalline H_2O ice, leads to the prediction that bodies with $R \lesssim 700$ km would not even achieve partial melting of NH_3-H_2O (Consolmagno and Lewis, 1978). The problem is that even a relatively thin (~few kilometers), low conductivity regolith layer can dramatically alter the evolution. The presence of $NH_3 \cdot H_2O$ and clathrate substantially lower the thermal conductivity of the interior (Stevenson, 1982). My calculations show that these factors can allow satellites $\gtrsim 300$ km in radius to undergo significant partial melting, even assuming that the evolution begins from a cold state. Amorphous ice is also a possible reason for higher temperatures and igneous activity because of its very low conductivity (Smoluchowski, 1978; Klinger, 1982).

A different problem, acting in the opposite sense, is subsolidus convection of ice. This was neglected in earlier work on icy satellites (Consolmagno and Lewis, 1976, 1978) but is unquestionably important in all large, icy satellites (Reynolds and Cassen, 1979), including even satellites with radius ~700 km (Ellsworth and Schubert, 1983). Heat transport by subsolidus creep is sufficiently efficient to prevent melting of pure water ice by radiogenic heating, and probably even prevents melting of the water component of a rock-ice mixture, unless the satellite is about the same size and rock-ice ratio as Ganymede (Friedson and Stevenson, 1983). However, subsolidus creep probably <u>never</u> prevents the partial melting of a satellite containing both H_2O and NH_3. The reason is that the viscosity is likely to be dominated by water ice and is very large at 173 K, the eutectic of H_2O-NH_3. Above this temperature, a cosmic abundance of NH_3 (~18% mole fraction relative to H_2O) can be incorporated into a eutectic melt (~67% H_2O, 33% NH_3) and migrate upwards by percolation through the porous water ice matrix. The unimportance of convection under these circumstances can be seen from consideration of the Rayleigh number

$$Ra \equiv g\alpha\Delta T d^3 / K \qquad (2)$$

together with a likely viscosity law for water ice (Weertman, 1983)

$$\nu \simeq 10^{15} \exp\left[25\left(\frac{273}{T} - 1\right)\right] \ cm^2/s \qquad (3)$$

where the pre-exponential constant corresponds to the low deviatoric stresses encountered in icy satellites. At T = 173 K, $\nu \gtrsim 10^{21}$ cm^2/s. Substituting g $\simeq$ 3 (R/100 km) cm/s^2, R = satellite radius, d ~ 0.5R, $\alpha = 10^{-4}$ $°K^{-1}$, ΔT ~ 20°K, K = 10^{-2} cm^2/s and $\nu = 10^{21}$ cm^2/s yields Ra $\simeq$ 0.6 $(R/10^2 \ km)^4$. Onset of convection occurs at Ra ~ 2 x 10^3 (since it is likely to be a rigid boundary condition) and requires R $\gtrsim$ 760 km at this temperature of 173 K. Even at R ~ 1500 km, the enhancement of heat transport relative to conduction is only ~ twofold. As a consequence, generation of H_2O - NH_3 melt is not prevented by solid state creep.

Migrating, buoyant water-ammonia magma can cause decomposition of near-surface clathrates (Stevenson, 1982) perhaps leading to explosive venting, resurfacing by magma, ejection of hydroclasts (ice tektites) and formation of transient rings such as the E-ring (Herkenhoff and Stevenson, 1984). However, these are all likely to occur early in the history of the satellite, when the temperature first reaches 173 K. They may not occur at all in large satellites (R$\gtrsim$ 1500 km) which undergo extensive melting during accretion and may evolve differently (see the section on Triton below). The generation of melt will, in all cases, cause settling of the dense silicate-rich residue to form a core.

If a large amount of the much more volatile CH_4 ice is present and retained, then there is rapid upward differentiation to form a CH_4 outer shell (cf. Lupo and Lewis, 1982, in their work on Pluto). Subsequent contact between

NH_3 - H_2O magma and CH_4 can cause explosive CH_4 volcanism, since the ~ 180 K water-ammonia magma is capable of causing a hot, buoyantly rising CH_4 plume which expands explosively into a gas. (At one bar pressure and 180 K, CH_4 gas occupies over one hundred times more volume than the same mass of liquid CH_4.) Although the latent heat of vaporization limits the amount of gas produced, events of this kind could be spectacular and might even continue to occur in larger bodies ($R \gtrsim 1000$ km) for which the present day internal temperatures exceed 173 K.

Based on these general comments, it is possible to construct a likely evolution outcome for each of the satellite classes listed in Table II. These qualitative models are shown in Figure 2 and are intended to correspond to satellites in the Uranian size range (500-1000 km radius), rather than the substantially larger (but very poorly constrained) Neptunian moon, Triton. The models are largely self-explanatory; a few additional comments follow:

I. Hydrated rock bodies in this size range do not become hot enough to undergo large scale dehydration. However, impacts can cause local dehydration and a partial or complete layer of water ice.

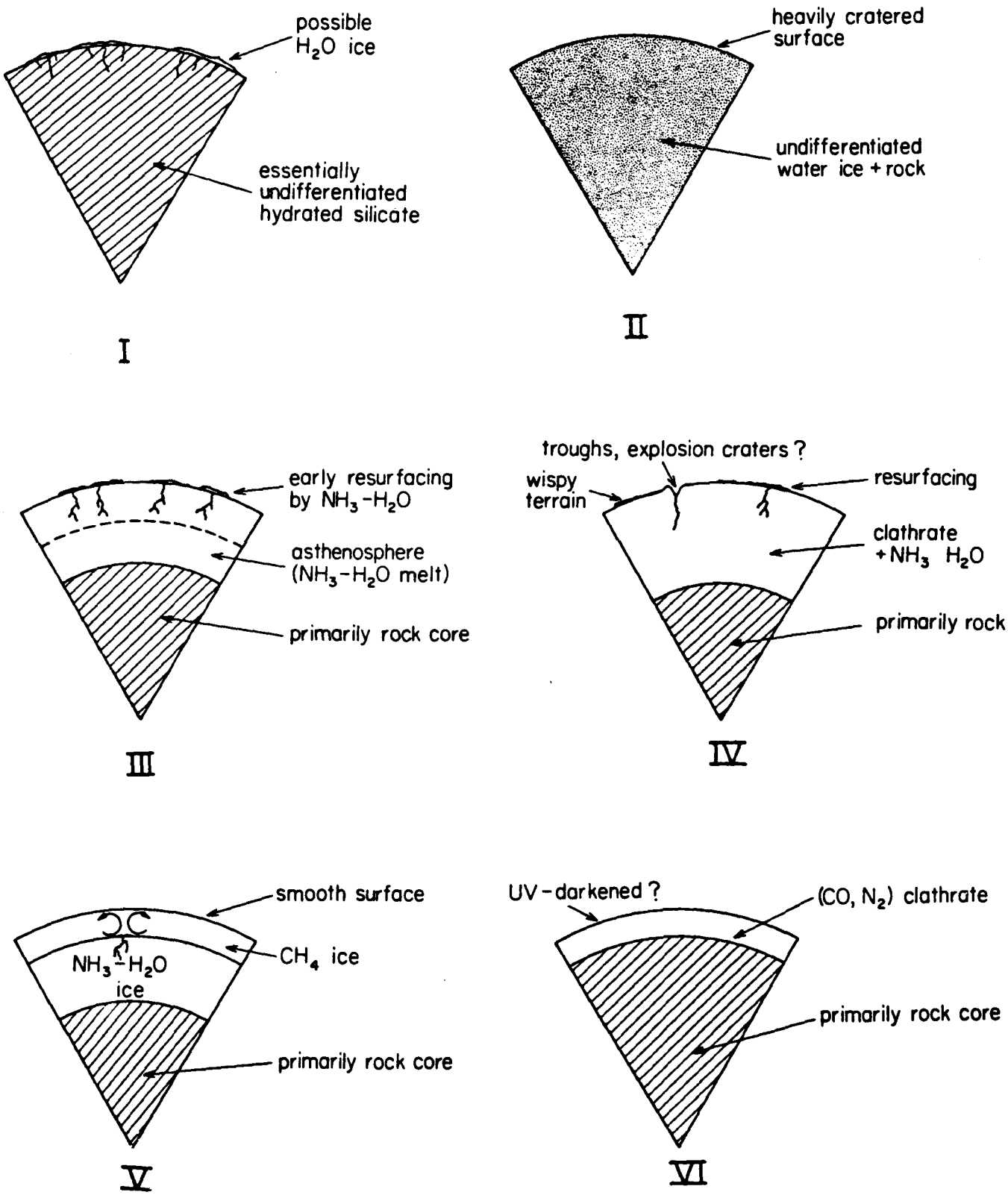
II. Water ice and rock satellites are likely to show no evidence of endogenic processes (they may look like Callisto).

III., IV. The surficial appearance of these bodies should be similar to Dione, Rhea, etc.

V. This model is only meaningful if significant CH_4 can remain for the age of the solar system. (However, the photochemical residue may remain to darken the surface, even if all the CH_4 escapes.)

VI. The clathrate is stable in the absence of heating events (such as NH_3-H_2O magma). Thus, these bodies may show little evidence for endogenic activity. Differentiation is also unlikely for essentially the same reason (lack of a fluid phase).

Fig. 2 Pie diagrams for the six classes of generic satellites described in Table II.



TRITON

In the absence of reliable radius and mass determinations, comments about Triton are necessarily highly speculative. Guided only by the observation of CH_4 frost and the probable detection of liquid N_2 (Cruikshank et al., 1983), it seems possible that Triton has some similarity to Titan, but failed to form a massive atmosphere because of less severe heating during accretion and a lower ambient temperature. Analysis of Titan (Hunten et al., 1984) is partially transferable to Triton and suggest that:

a) CH_4 might come from decomposed clathrate, if the central pressure $\gtrsim$ 10 kbar, or from ''trapped'' CH_4 left at the surface after a primordial H_2O-NH_3 ocean froze over (analogous to the Titan scenario proposed by Lunine and Stevenson, 1982b). It might also be derived from the <u>thermal</u> decomposition of clathrate that occurs if Triton was captured by Neptune and underwent an early, extremely vigorous tidal heating episode (McKinnon, 1983).

b) N_2 might come from photolysis of NH_3 overlying a primordial H_2O-NH_3 ocean, or from impacts, or from clathrate. However, the latter possibility strongly suggests the presence of CO (not yet detected).

c) Ongoing NH_3-H_2O volcanism is marginally possible.

d) A differentiated internal structure is expected, with a liquid H_2O-NH_3 layer at ~ 200 km depth persisting up to the present day, provided significant NH_3 was incorporated.

ORIGIN OF THE URANIAN SATELLITES

I proceed now to some speculative comments, motivated by the possibility (Table I) that the Uranian satellites are more dense on average than would

normally be expected, with the outer two satellites (Titania and Oberon) possibly being ice-poor. The following speculation may eventually prove unnecessary, but deserves consideration for the present. Suppose the Uranian satellites formed from a disk that was created immediately after an impact on Uranus by a body of mass ~ one or two earth masses. This impact at ~ 20 km/s could cause the present striking (98°) obliquity of Uranus as well as rendering the equatorial belt of material rotationally unstable (provided the pre-impact Uranus was near rotational instability). The material flows out from this belt into a disk, redistributing angular momentum by eddy diffusion. The outermost material in this disk is likely to be a mixture of shocked atmosphere and ablated projectile. Later, inner additions to the disk are likely to be similar in composition to the present, deep atmosphere of Uranus. The interesting feature of this scenario is that when an H_2-CH_4-H_2O atmosphere is shocked, it quenches into an H_2-CO dominated mixture (possibly including heavier hydrocarbons and even elemental carbon) which contains very little water. This is shown semiquantitatively in Figure 3. The release adiabats in the shock process are clearly in the CO equilibrium field at T ~ 1200 K, a likely quench temperature at the relevant timescale of hours. (See Lewis and Prinn, 1980 for the relevant kinetics and thermodynamics; also Lewis et al. 1982, for a related problem of impact in the earth's atmosphere).

The outer satellites would subsequently form from a nebula which was H_2O-poor, but containing some rock derived from ablated projectile. Some CO and N_2 might be incorporated as clathrate, corresponding to model VI in Table II. If very little water remains, then the satellite might even be almost entirely anhydrous or hydrated silicate (model I in Table II).

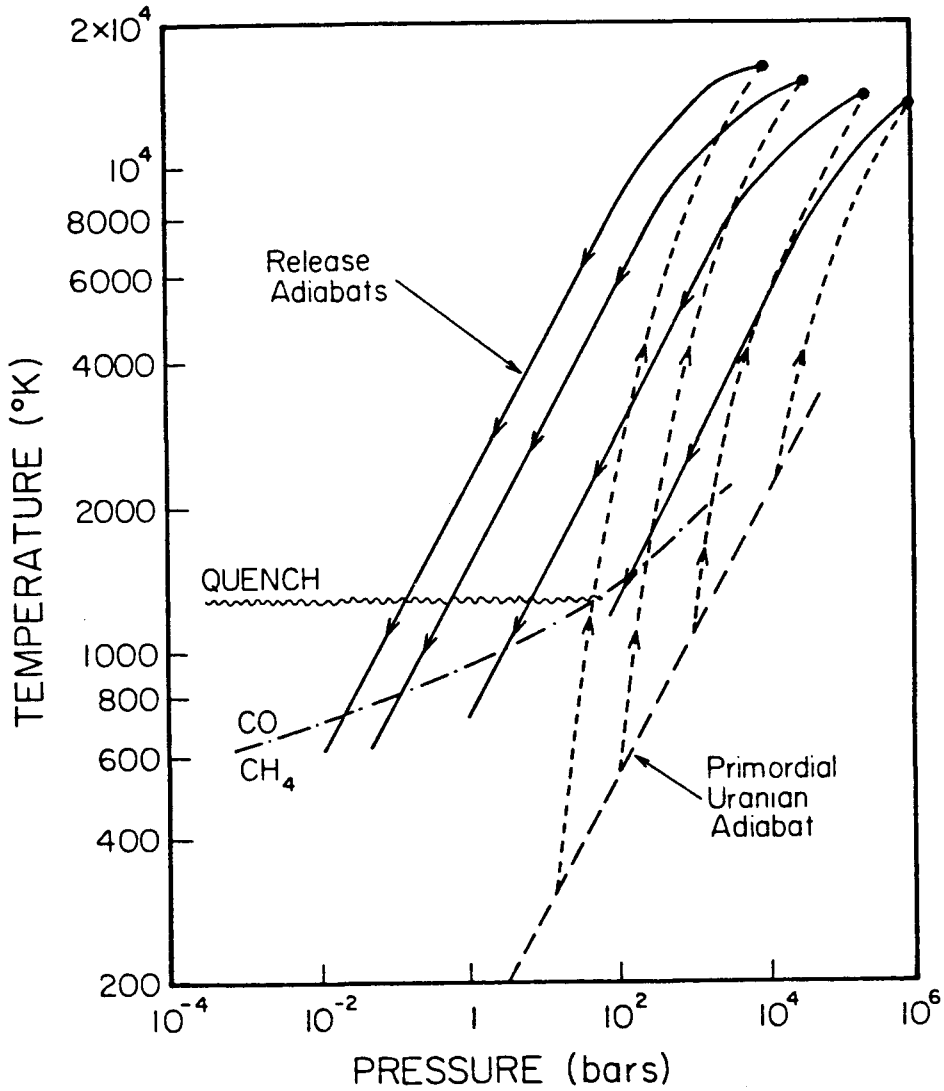


Fig. 3. Consequences of impact into the early Uranian atmosphere. The long dash line is the primordial T-P relation for the Uranian atmosphere assumed in the calculation. The short-dashed lines are the thermodynamic trajectories of this gas as it is shocked. The solid lines are the release adiabats for this shocked gas after impact. The wiggly line represents the approximate temperature below which there is kinetic inhibition and failure to achieve thermodynamic equilibrium. Since most of the release adiabats achieve quench before crossing the CO-CH_4 equilibrium line, the quenched gas will be CO rich (at the expense of H_2O).

CONCLUDING COMMENTS

I have not covered all possible outcomes. For example, there is a slight possibility that Ariel undergoes significant tidal heating (Squyres and Reynolds, 1983) if the reported near resonance configuration is actually an exact resonance or was exact in the recent geologic past. It is also possible that the assemblage of ices in these bodies is more complex than I have considered above, including significant amounts of CO_2, for example. The general impression is of a bewildering range of possibilities and a strong likelihood of interesting, perhaps unexpected, surface appearances and internal properties. The satellites are likely to be one of the highlights of the Voyager encounter of Uranus, and Triton may prove to be <u>the</u> highlight of the Neptune encounter.

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