INTERIOR OF TITAN

David J. Stevenson

Division of Geological and Planetary Sciences

California Institute of Technology

ABSTRACT

There is very little direct information on Titan's interior and even the precisely known mean density allows large uncertainties in volatile content (defined as all components more volatile than H_2O). Volatile-poor models, in which Titan is like Ganymede or Callisto with a thin (observed) volatile veneer, are discussed and discarded. Volatile-rich models are described in which the present Titan consists of a methane clathrate shell overlying a deep water-ammonia ocean and solid ammonia hydrate. The central core of rock (radius ≃ 1900 km) comprises about one half the total mass. The surficial hydrocarbon "ocean" is stored in an "aquifer" (subsurface caverns and pore space) thereby reconciling previous arguments for an ocean with radar and tidal constraints.

Keywords: interior, ocean, evolution, clathrate, ammonia.

1. INTRODUCTION

Titan is largely water, ice and rock, but the most important questions concern its volatile reservoir (defined as all constituents more volatile than water). In particular, we would like to know whether Titan's hydrocarbon reservoir is primary (part of the originally accreted material), volcanic in origin (delivered from the deep interior) or exogenic (delivered by comets, for example). Is Titan essentially Ganymede with the addition of a thin veneer of volatiles (mainly CH_4, C_2H_6 and N_2) or is the interior rich in methane and nitrogen? More generally, we want to understand the relationship between the surface and the interior, an issue frequently encountered in planetary studies.

It is easy to see that the questions of internal volatile content are not directly answered by current observables. Of all the parameters that might define the interior (gravitational moments, surface shape and deformation, heat flow, magnetic field, surface composition), we have only one that is well determined: the mean density of 1.88 g.cm^{-3}. At first sight (Table 1), a comparison of this value with Ganymede and Callisto appears to favor a Titan that is very similar and intermediate to these presumably volatile-poor bodies:

Table 1

	Callisto	Titan	Ganymede
Mass (10^{26}g)	1.08	1.35	1.48
Radius(km)	2410	2575	2640
Mean Density (g.cm^{-3})	1.83	1.88	1.93
Ice Mass Fraction	0.47	0.45	0.43

The ice mass fraction is obtained by assuming that each satellite consists of a core of "rock" (anhydrous silicates and iron as FeS and FeO) with density 3.5 g.cm^{-3}, and a mantle of purely water ice (mean density of about 1.2 g.cm^{-3} because much of this ice is in high pressure phases). The apparent similarity between Titan and the Galilean moons becomes less impressive when we consider the densities of various candidate ices at 200K:

Table 2:

Ice	Density (g.cm^{-3})
H_2O	0.93
$NH_3.H_2O$	0.95
$CH_4.5¾H_2O$	0.93
$(CO,N_2).5¾H_2O$	1.03
NH_3	0.86

Evidently we can replace much of the water ice by methane clathrate (CH_4 .5¾H_2O), for example, without significantly affecting the pattern exhibited in Table 1.

Although volatile-poor and volatile-rich models may be almost indistinguishable in mean density, they differ greatly in the amounts of volatiles. It is convenient to express these volatile inventories in equivalent atmospheres by recalling that for a thin hydrostatic atmosphere, the base pressure $p = \sigma g$, where σ is the column density (g.cm^{-2}) and g is the gravitational acceleration. For a liquid reservoir (an ocean), $\sigma=\rho_l d$ where ρ_l is the liquid density and d is the mean ocean depth. The total mass of a given volatile can be expressed as $M_v=4\pi R^2\sigma$ where R is the radius of Titan. We assume that the dominant volatiles are carbon as light hydrocarbons (CH_4, C_2H_6) and nitrogen as N_2 or NH_3. We define a volatile-rich model as one in which Titan accretes from rock and ice and all the H_2O is combined as either $NH_3.H_2O$ or $CH_4.6H_2O$.

As discussed in more detail later, this mixture will be roughly equimolar (i.e. similar amounts of NH_3 and CH_4). This leads to the following comparison:

Table 3:

	Volatile-Poor Titan	Volatile - Rich Titan
CH_4 Equivalent Pressure (bars)	~12	~1200
N_2 Equivalent Pressure (bars)	~2	~1000

The volatile-poor estimates come from the actual N_2 atmosphere and inferred ethane-methane ocean of Lunine *et al.*(Ref. 1). This is a minimalist model for volatiles. The volatile-rich estimates come from the model described above and the (artificial) assumptions that all the NH_3 is converted to N_2, and all the original carbon is expressed as CH_4. We see about two orders of magnitude difference between the two extremes, an even larger range than commonly given to the amount of water accreted by Earth, for example.

2. GENERAL PRINCIPLES OF TITAN FORMATION AND EVOLUTION

Even with some uncertainties in the starting constituents, some general principles hold. First, there is no way of avoiding the gravitational energy release of formation, of order GM/R per gram (G= gravitational constant, M = Titan mass, R = Titan radius). Some of this energy will go into heating the interior of the primordial Titan, while some will be lost by radiation. In the former extreme of entirely trapped energy, there is sufficient energy to completely vaporize all the water ice since $GM/RL \sim 1.4$, where L is the latent heat of vaporization (~600 cal/gm). The large energy of formation for Titan, Ganymede and Callisto might explain why these bodies are mildly ice-poor relative to small icy satellites of Saturn, for example, since some water may escape during accretion (Ref. 2). Obviously, only a small fraction of the formation energy needs to be trapped to guarantee extensive melting of water ice, which requires almost an order of magnitude less energy than vaporization. Indeed, models of satellite formation (Ref. 3, 4) typically predict extensive melting. At one time it was thought that Callisto may have avoided this melting and that the striking differences between the surficial appearance of Ganymede and Callisto arose through differences in primordial melting (Ref. 3, 5). This "primitive" view of Callisto was always difficult to sustain in the face of simple energetic arguments like those above. Recent work on possible tidally induced resonances and resulting eccentricity pumping of Ganymede (Ref. 6, 7) now strongly suggests that the differences between Callisto and Ganymede can be traced to their different tidal evolutions. The implications of this point of view is that all the large satellites of Table 1 underwent extensive melting of water ice and associated formation of a rocky (or rock-rich) core.

We can also assess the consequences of the energy of formation from the other extreme point of view in which all of this energy is radiated away in time τ and at an effective temperature T_e:

$$4\pi R^2\sigma\,(T_e^4 - T_0^4) \simeq \frac{GM^2}{R\tau} \qquad [1]$$

where T_0 is the background temperature due to insolation (possibly augmented or modified by the solar nebula, if still present, or an early high luminosity of Saturn). For $T_e^4 >> T_0^4$

$$T_e \simeq (240K)(10^6 yr/\tau)^{1/4} \qquad [2]$$

In fact, most dynamical arguments predict that τ is less than about a million years (Ref. 8), so T_e is indeed quite large. If volatiles produce a dense greenhouse atmosphere for primordial Titan (Ref. 9) then the surface temperature (e.g. at the surface of a liquid water ocean) can easily be far greater. Once again, the main point is that extensive melting is likely.

The total integrated radioactive heating due to the rock component is roughly comparable to the gravitational energy of formation. Although stronger during the early history (mainly because of ^{40}K), the long-lived and gradual nature of radioactive heating allows a very different response by the satellite. As recognized over a decade ago (Ref. 10), this heat can be accommodated by solid state convection of ice. This does not necessarily mean that the interior of Titan is entirely solid since there may be antifreeze components in the water; ammonia is especially effective in this regard as we discuss later. The differentiated rock core should certainly have received sufficient internal heat to decompose water-bearing (hydrous) mineral phases, irrespective of the composition of the mantle above. This justifies the anhydrous rock assumption in Table 1. It could be speculated that these hydrous phases, upon incipient or partial dehydration become very weak and capable of allowing solid state convection at temperatures far below the conventionally defined (some would say incorrectly defined) "solidus" of order 1400 K. The problem with this view is that a fluid phase will form and migrate. Hydrothermal circulation is the consequence, but with a net release of water from the core. Since there is no reason to expect compensating subduction, the inevitable consequence over geologic time is to drive the core to a largely anhydrous state.

Tidal heating is probably less important for Titan. Integrated over geologic time, it is about $e_i^2 GM_s/2a$ per unit mass, where e_i is the initial eccentricity of Titan's orbit (assumed to be substantially larger than the present e_0=0.028), M_s is Saturn's mass and a is the orbital radius. This energy is equal to Titan's formation energy for $e_i \approx 0.45$, and small for a more reasonable value of $e_i \approx 0.1$. In fact, the question of the origin of Titan's eccentricity is very interesting since Titan is the only large satellite in the solar system with both substantial current eccentricity and an absence of companion satellites that are sufficiently massive to excite eccentricity. We know that $e_i \gtrsim e_0$, and this leads to the interesting possibility that Titan was hit by an object at least as large as one of the other moons of Saturn!

We turn now to more detailed considerations of the end-member volatile-rich and volatile-poor models.

3. VOLATILE-POOR MODELS

What would happen if we took Ganymede (or, perhaps even more realistically, Callisto) and simply added the minimal veneer of Table 3? The uppermost temperature of the water ice would increase somewhat (though it would still be far less than that of Ganymede or Callisto) and erosional processes might modify or degrade the cratered landscape (Ref. 11), but the interior would scarcely be affected by or aware of the external changes. We would expect a differentiated rock core of roughly 1900 km in radius, overlain by a convecting water-ice mantle. The pressure range in this mantle encompasses several water-ice phases; the outermost 100 km would be ice I followed by about 300 km of ice II and 200 km or so of ice VI. There may also be some ice V. This assessment arises from the application of parameterized convection recipes to sub-solidus convection in ice. While there are still large uncertainties in this procedure, it seems certain that the low present day heatflow from within Titan, due to radioactive decay, would be readily accommodated by solid-state convection (Ref. 12). For a heatflow of 6 erg/cm^2.s, the predicted mean temperature in the convecting ice I would be around 220° K, corresponding to a viscosity of roughly 10^{18} Poise. The main uncertainties are the behavior of ice II, which is much more viscous at a given temperature (Ref. 13), and the transition from ice II to ice VI, where the negative Clausius-Clepeyron slope may cause the convection to become layered (Ref. 14). This volatile-poor model would probably have frozen internally only a few hundred million years or so after formation and would have behaved qualitatively similar then as now. In summary, the evolution is rather dull and poses no major issues in addition to those already encountered in our efforts to understand Ganymede and Callisto.

There are several problems with this volatile-poor scenario:

1. It is not thermodynamically consistent, if the volatiles were delivered during primary accretion from Saturn-orbiting planetesimals. The reason is that CH_4 and (to a lesser extent) N_2 are thermodynamically stable *inside* Titan, incorporated as clathrates (Ref. 15), and would not automatically form an atmosphere merely because they are "volatile." (This illustrates the danger of loose concepts such as volatility: methane tied up within a water-ice lattice is not necessarily volatile). The analogy of water in the earth's mantle is partly appropriate here.

2. Delivery of volatiles by sun-orbiting bodies (e.g. comets) is problematic because these impacts are extremely high velocity and hence tend to ablate rather than augment atmosphere (Ref. 16). Moreover, high velocity impacts process CH_4 into heavier hydrocarbons (if no oxygen source such as water is available) or CO (in the presence of H_2O). This will shift the nature of the atmosphere and ocean away from a state that is compatible with observations, unless the primitive (pre-impact) reservoirs of CH_4 are much larger than the equivalent of ~ ten bars. Some aspects of impact delivery of Titan's atmosphere are discussed by Zahnle (Ref. 17).

3. There is some evidence for the role of volatiles in the appearance and evolution of other Saturnian satellites (Ref. 18). Iapetus exhibits dark crater floors, Dione exhibits "wispy" terrain and Enceladus shows extensive resurfacing, all of which have proved difficult to explain by models in which rock and water ice are the only major constituents. If these satellites retained more volatile constituents then Titan should likewise have at least partially retained the same constituents since it presumably formed in the same environment (Ref. 8).

4. As a related argument, it is cosmogonically implausible to have formed Titan in either the solar nebula or (much more likely) in orbit around Saturn without retaining constituents more volatile than H_2O. This follows from thermodynamic considerations and estimates of the temperature and pressure in plausible formation regions (e.g. Ref. 8).

These problems can be reduced or perhaps even largely eliminated by a modest enhancement of volatiles, but as we shall now see, an immodest volatile-rich model has several attractive features.

4. VOLATILE-RICH MODELS

Once we admit large amounts of NH_3 and CH_4 (cf. Table 3), the thermodynamic considerations become far more complicated. Let's first summarize briefly the behavior of two end-member systems H_2O-NH_3 and H_2O-CH_4.

The water-ammonia system is a classic example of an "antifreeze": any water-rich mixture will, upon progressive cooling and freezing, retain some small amount of liquid down to 173° K, a full 100 K below the freezing point of H_2O. This characteristic of H_2O-NH_3, qualitatively similar to the (more complex) olivine-basalt system of terrestrial planet upper mantles, allows a large *partial melting* range and introduces the possibility of volcanism and present-day liquid in analogy to basaltic volcanism. Recent work on the H_2O-NH_3 system at high pressures (Ref. 19) reveals that the solidus of this system remains low even at quite high pressures. For example, at 220° K (a temperature suggested above for present day subsolidus convection in a pure water ice Titan), $(NH_3)_x(H_2O)_{1-x}$ is liquid at x ~ 0.2, P ~ 2 kbar and liquid at x~0.3 for the entire pressure range of interest (0-10 kbar). Unlike earlier experimental work, the recent study (Ref. 19) does not give the prominence to the dihydrate phase ($NH_3.2H_2O$) which appears in earlier assessments of Titan's structure (Ref. 20). Instead, it seems likely that a Titan which has $NH_3/H_2O = 1/6$ (cosmic abundance) evolves to a present-day structure consisting of an outer 150 km thick ice I shell, and a 300 km thick ammonia-rich ocean overlying a layer of high pressure phases of water ice (most likely ice VI). The very thick internal ocean is in stark contrast to pure ice models in which any ocean freezes completely at an early epoch.

It is important in these considerations to know the densities of the various phases, especially for deciding whether the ammonia-rich liquid is buoyant relative to a particular solid phase or mixture. Recent work on the density of this liquid (Ref. 21) fills an important gap in our knowledge and shows that there is a large temperature and compositional dependence in the liquid density. Below, we see how this may influence the evolution.

The water-methane system has a completely different behavior because methane has no dipole moment and is much more volatile than ammonia. Provided the methane partial pressure (or fugacity) is sufficiently high, a modified form of water ice can form in which methane is incorporated in *cages* created by the water molecules. This inclusion compound, called a clathrate, has been extensively studied (Ref. 15, 22); it can even form above 300° K if the methane pressure is sufficiently high. As noted in Table II, the resulting compound has a similar density to Ice I. It is a non-stoichiometric compound, however, in which some cage sites are empty or can be filled with other molecules (e.g. N_2). Thus the formula $CH_4 . 5\,3/4\, H_2O$ is an idealization. If ammonia is also present, it does not participate in the clathrate structure but mildly reduces its thermodynamic stability field by providing an alternative, favorable environment for H_2O.

With this brief background, we now consider how a volatile-rich Titan might evolve. (Some of these ideas were already developed in J. Lunine's Ph.D. thesis, Ref. 9). We envisage the accretion of a mixture of rock, $NH_3.H_2O$ and $CH_4.6H_2O$ (Table 3). From cosmic abundances, we expect $NH_3/H_2O \simeq 1/6$, implying $NH3/CH4 \simeq 1$. The high temperatures created by the gravitational energy release of accretion cause the formation of a rock core, a water-ammonia ocean (in roughly cosmic abundance proportions) and a dense, greenhouse methane-rich atmosphere from the thermal decomposition of the clathrate. As this system cools, a point is reached where methane-clathrate can reform at the ocean surface. For a kilobar atmosphere, this occurs at above 300K where the clathrate ($p \simeq 0.925$ g.cm^{-3}) is probably more dense than the ocean. An interesting phenomenon then occurs: as more clathrate forms and sinks, the ocean actually becomes *less* dense because it becomes progressively NH_3-rich. However, it should be stressed that this only occurs for models in which the initial total CH_4 is the equivalent of ~ 600 bars or more (i.e. at least one half the volatile-rich end-member of Table 3). However, the ocean cooling eventually also allows $NH_3.H_2O$ freeze-out, and this solid ($p \simeq 0.95$ g.cm^{-3}) accumulates at the base of the ocean below the clathrate. At even lower temperatures (~220 K), the clathrate actually becomes buoyant again, because the temperature dependence of the liquid density is far greater than that of the clathrate, and the liquid contracts to a 1-bar density of ~ 0.93 g.cm^{-3}. All of this is early in Titan's history, while a greenhouse atmosphere maintains a surface temperature $\gtrsim$ 200 K. This picture predicts that most of the methane is in a clathrate mantle, but that about 100 bars equivalent (sufficient for a 10 km ocean) remains trapped at or near the surface at the time that the clathrate rises buoyantly to the surface and prevents further ingassing. Some of this surficial veneer will fill pore space and caverns in the porous clathrate shell. This model predicts more than sufficient CH4 at the surface, a good feature because of the loss mechanisms (early UV, ongoing photolysis, impacts) that have operated since. Some CH_4 may also be delivered volcanically (Ref. 20). The model also predicts some near-surface trapping of NH_3 (the vapor pressure of the NH_3-H_2O ocean at freeze-over), marginally enough for the current atmosphere, should this NH_3 be converted to N_2 by impacts (Ref. 23) or photolysis. However, it is probably desirable to have some primordial N_2 or coaccretional production of N_2. The latter may be accomplished by even low velocity impacts (Ref. 24).

The long-term evolution of this scenario is uncertain because of our incomplete knowledge of the rheologies of ammonia-bearing and clathrate ices, but the existing laboratory data (Ref. 25) suggest similar viscosities to water ice, implying similar but perhaps slightly lower internal temperatures to those usually proposed for Ganymede or Callisto (cf. previous section). For T~ 200–220 K, a substantial water-ammonia ocean persists. It is conceivable, though unlikely, that liquid from this ocean could rise up through the overlying mantle if the mantle were sufficiently contaminated with "dirt" (rocky material added late in the accretion and unable to settle into the core).

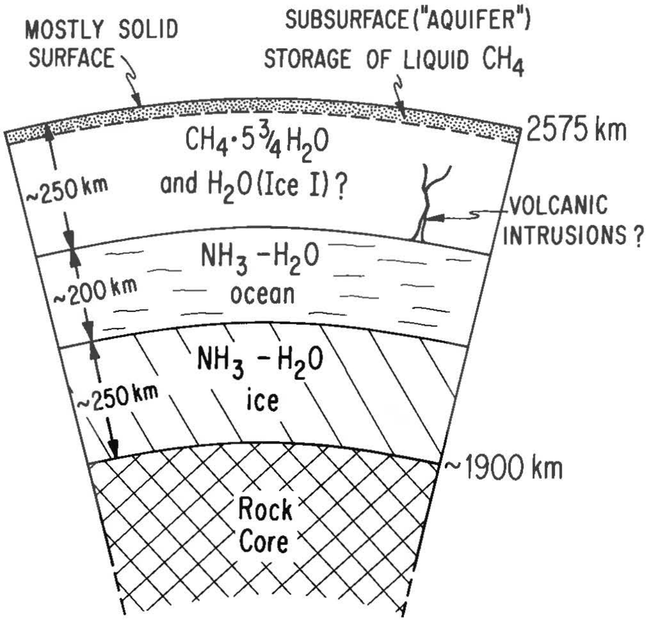

Fig. 1 Present day Titan for volatile-rich models

Figure 1 is a cartoon of present Titan for many volatile-rich scenarios. It has the virtues of providing sufficient surficial reservoirs of CH_4 and N_2 to explain the observational properties. It may also be adaptable to a near-surface structure in which the hydrocarbon ocean is stored in pore space and caverns. Such a model may reconcile the *absence* of a surficial ocean in the radar signal (Ref. 26) with the undeniable need for the mass equivalent of an ocean as liquid or gas (Ref. 1), and the tidal arguments against a global ocean (Ref. 27). The radar data are explained because the radar "sees" the water or clathrate bedrock but not the several kilometer-thick "aquifer" of methane beneath; and the tidal constraint is reconciled because methane stored in thin "aquifer" channels cannot respond hydrostatically to the tidal potential associated with Titan's eccentric orbit. These arguments are developed more fully elsewhere (Ref. 28).

5.CONCLUSIONS

Much of Titan's interior is unknown, perhaps even unknowable in the foreseeable future. However, the history of Titan's volatiles is intimately connected to the internal structure and arguments have been presented here favoring volatile-rich models in which the known atmospheric and "oceanic" reservoirs of carbon and nitrogen species are but a small fraction of the total volatile reservoir. The Cassini mission may test these ides primarily through an enormous increase in knowledge about the surface morphology and composition, rather than through any measurement directly pertinent to the interior (e.g. oblateness, J_2). In particularly, it is speculated that the hydrocarbon "ocean" is stored in a porous, uppermost few kilometers of methane clathrate or water ice "bed rock". A better understanding of Triton and Pluto may also aid the interpretation of Titan's geology (surface ice morphology). Based on past empirical experience, this geology is likely to be surprising and remarkable.

ACKNOWLEDGMENT

This work has been supported by NASA Geology and Geophysics grant NAGW-185. Contribution No. 5109 of the Division of Geological and Planetary Sciences, California Institute of Technology.

REFERENCES

1. Lunine, J. I. et al. 1983, Ethane Ocean on Titan, *Science*, 222, 1229-1230.

2. Ahrens, T. J. and O'Keefe, J. D. 1985, Shock vaporization and the accretion of the icy satellites of Jupiter and Saturn, *Ices in the Solar System*, ed. J. Klinger et al., NATO ASI Series, publ. D. Reidel, Dordrecht, 631-654.

3. Lunine, J. I. and Stevenson, D. J. 1982, Formation of the Galilean satellites in a gaseous nebula, *Icarus* 52, 14-39.

4. Schubert, G. et al. 1986, Thermal histories, compositions and internal structures of the moons of the solar system, *Satellites*, ed. J. Burns and M. Mathew, Un. Arizona Press, 224-292.

5. Friedson, A. J. and Stevenson, D. J. 1983, Viscosity of rock-ice mixtures and applications to the evolution of icy satellites, *Icarus* 56, 1-14.

6. Tittemore, W. C. 1990, Chaotic motion of Europa and Ganymede and the Ganymede-Callisto dichotomy, *Science*, 250, 263-267.

7. Malhotra, R. 1991, Tidal origin of the Laplace resonance and the resurfacing of Ganymede, submitted to *Icarus*

8. Stevenson, D. J. et al. 1986, Origins of satellites, *Satellites*, ed. J. Burns and M. Mathews, Un. Arizona Press, 39-88.

9. Lunine, J. I. 1985, Volatiles in the Outer solar system, Ph.D. Thesis, California Institute of Technology, unpublished.

10. Cassen, P. et al. 1980, On the comparative evolution of Ganymede and Callisto, *Icarus* 41, 232-239.

11. Lunine, J. I. and Stevenson, D. J. 1985, Evolution of Titan's coupled ocean-atmosphere system and interaction of ocean with bedrock, *Ices in the Solar System*, ed. J. Klinger et al., NATO ASI series, publ. D. Reidel, Dordrecht, 741-758.

12. Hunten, D. M. et al., Titan. *Saturn*, eds. T. Gehrels and M. Mathews, Un. Arizona Press, 671-759.

13. Kirby, S. H. et al. 1985, Rhelologies of H_2O Ices I, II and III at high pressures: A progress report. *Ices in the Solar System*, eds. J. Klinger et al., publ. D. Reidel, Dordrecht, 89-108.

14. Sotin, C. 1991, Internal Dynamics of Titan: Comparison with models for Callisto and Ganymede, presented at this Symposium on Titan.

15. Lunine, J. I. and Stevenson, D. J. 1985. Thermodynamics of clathrate hydrate at low and high pressures with application to the outer solar system, *Astrophys. J. Suppl.* 58, 493-531.

16. Melosh, H.J. and Vickery, A. M. 1989. Impact erosion of the primordial Martian atmosphere. *Nature* 338, 487-489.

17. Zahnle, K. 1991, Origin and evolution of the atmosphere, presented at this Symposium on Titan.

18. Stevenson, D. J. 1982, Volcanism and igneous processes in small icy satellites, *Nature* 298, 142-144.

19. Cynn, H. C. et al. 1989, Phase diagram for ammonia-water mixtures at high pressures: Implications for icy satellites, *Proc. 19th Lunar and Planetary Science Conference*, LPI, Houston, 433-441.

20. Lunine, J. I. and Stevenson, D. J. 1987, Clathrate and ammonia hydrates at high pressure:Application to the origin of methane on Titan, *Icarus* 70, 61-77.

21. Croft, S. K. et al. 1988, Equation of state of ammonia-water liquid: Derivation and Planetological applications, *Icarus* 73, 279-293.

22. Miller, S. L. 1985, Clathrate hydrates in the solar system, *Ices in the solar system*, eds. J. Klinger et al., NATO ASI series, publ. D. Reidel, Dordrecht, 49-58.

23. Jones, T. D. and Lewis, J. S. 1987, Estimated impact shock production of N_2 and organic compounds on early Titan. *Icarus* 72, 381-393.

24. Anderson, W. W. and Stevenson, D. J. 1987, Origin of nitrogen on Titan and Triton by accretion shock-processing of primordial ammonia-rich atmospheres. *Origin and Evolution of Planetary Atmospheres*, abstract volume, Un. Arizona.

25. Kirby, S.H. private communication.

26. Muhleman, D. O. et al. 1990, Radar reflectivity of Titan, *Science* 248, 975-980.

27. Sagan, C. and Dermott, S. F. 1982, The tide in the seas of Titan. *Nature* 300, 731-733.

28. Stevenson, D. J. 1992. In preparation.