STABILITY OF ICE/ROCK MIXTURES WITH APPLICATION TO TITAN. Joseph G. O'Rourke[1] and David J. Stevenson[2], [1]Department of Geology & Geophysics, Yale University, New Haven, CT 06511 (joseph.orourke@yale.edu), [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 (djs@gps.caltech.edu).

Introduction: Slow, cold accretion during the late stages of Saturn's formation permits Titan to form partially differentiated [1]. Titan's moment of inertia (MoI) factor (the MoI is CMR^2, where M is Titan's mass and R is its mean satellite radius) was recently measured during multiple dedicated *Cassini* flybys to be C~0.34, with C~0.33 as a lower bound, indicating that Titan's deep interior has relatively low density [2]. This value is intermediate to the previously measured C~0.31 for differentiated Ganymede and C~0.35 for partially differentiated Callisto. Detailed modeling of the Late Heavy Bombardment indicates that impact energy and frequency differences explain the Callisto/Ganymede dichotomy, but that Titan could survive without fully differentiating [3]. Therefore, these recent gravity data could be correctly interpreted as indicating a partially differentiated ice/rock interior. This work models the thermal evolution of Titan's deep interior with double-diffusive convection theory, concluding that an ice/rock interior likely could not avoid differentiating.

Horizontal Density Anomalies Quickly Evolve Into Vertical Gradients: A vertical density gradient inhibits thermal convection if this density gradient arises from composition and is negative (density increasing with depth). If radiogenic heat is not removed from the system, then ice in Titan's deep interior will melt, possibly causing runaway differentiation [4]. The densities of the major Saturnian satellites, excluding Titan (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe), exhibit significant compositional heterogeneity; the average densities of each satellite vary widely, from less than 1.0g/cc to over 1.3g/cc. Titan's mean density is ~1.881g/cc, but its uncompressed density is not much greater than that of the small satellites. Since Titan was plausibly formed from planetesimals of size and composition similar to these satellites, lateral density anomalies on the order of 10% may have existed after accretion.

Unstable lateral anomalies drive a flow that will restructure the ice/rock mixtures so that more dense mixtures underlie less dense mixtures in time $t \sim \mu/\Delta\rho_{lat} gD$, where μ is viscosity; $\Delta\rho_{lat}$ is the lateral density difference; g is gravitational acceleration; and D is the length scale of the anomalies. This time is short compared to the Stokes settling time of individual rock fragments for fragments smaller than ~km in size. Therefore, models of Titan's thermal evolution must consider the possible existence of as much as 10% stabilizing density gradients.

Double-Diffusive Convection Applied to Titan: Double-diffusive convection theory was originally developed to elucidate various phenomena in oceanography. In Titan, double-diffusive convection occurs in the presence of a stabilizing rock mass fraction gradient as its deep interior is cooled from above. The term "double diffusive" is still applicable even though the rock component does not diffuse in the ice. High-pressure ice phases V, VI, and VII exist within Titan's deep interior but do not have major effects on convection. Titan's rock component's mineralogy is not well known, although CI carbonaceous chondrites and Prinn-Fegley rock, an assemblage condensed from the proto-Jovian nebula, are possible analogues [5].

A model consistent with Titan's moment of inertia consists of an interior of radius 2,100 km and an overlying layer of water in ice I, liquid, and high-pressure phases of thickness 475 km [1]. Convection begins at the top of the ice/rock interior, which is cooled from above by the convection of the overlying ice mantle. The growing convecting layer's thickness is,

$$d = \sqrt{2\alpha Ht / \rho\beta C_p (dS/dz)}$$

where H is heat flow out of the convecting layer; t is time; C_p is the specific heat; β is a coefficient of expansion associated with the rock mass fraction analogous to the coefficient of thermal expansion α; and dS/dz is the linear rock mass fraction gradient [6].

Thermal Evolution of Titan's Interior: Titan's temperature profiles are calculated as a time series with one million year time steps for a two-layer model of an undifferentiated Titan. Immediately after accretion, roughly linear temperature gradients were established, with temperature decreasing with depth, causing an effective increase in the compositional gradient by $\alpha(dT/dz)$ [1]. Heat flow out of up to two convecting layers (beyond the first, they are usually negligible) was calculated using the standard convective heat flux equation. Although the deformation of ice is non-Newtonian under the conditions of Titan's deep interior, viscosity can be modeled with an Arrhenius-like equation for low strain rates. The viscosity increase caused by the rock fragments was ignored; it is neither negligible nor a dominant factor in the evolution. Titan's rock component generated heat through the decay of radioactive isotopes ^{40}K, ^{235}U, ^{238}U, and ^{232}Th.

A sample temperature profile time series for the first 2Gyr after accretion is shown as Figure 1. The convecting layer slowly grows, only encompassing the entirety of the ice rock interior after ~1.6Gyr. Although the deep interior is heated considerably, the maximum temperature of the convecting layer is reached after roughly 1.5Gyr and remains tens of K below the melting point. After ~2Gyr, for this set of initial conditions, the system gradually cools because radiogenic heating is considerably reduced. For any set of initial conditions, melting first occurs (if at all) at the top of the ice/rock interior, where the pressure-dependent melting temperature of water ice is lowest.

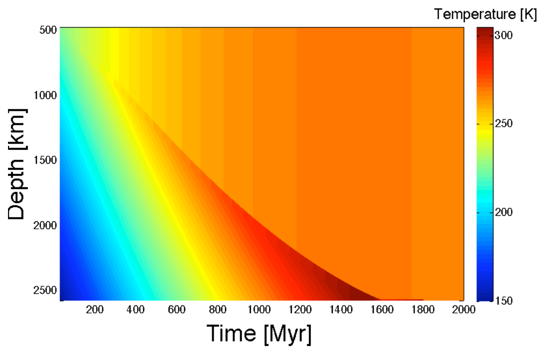

Fig. 1. *Sample time series with 2% density gradient; initial temperature 225K at the top of the ice/rock layer; initial temperature 150K at Titan's center;* $\eta_{eff} = 10^{15}$ *Poise near melting; and one fourth of the radiogenic heating indicated by CI chondrites. Melting at the top of the ice/rock layer is barely avoided.*

The stability of the proposed partially differentiated model of Titan's interior is strongly dependent on several loosely constrained parameters. In particular, the effective Newtonian viscosity of water ice near its melting temperature at high pressures is poorly known. Furthermore, radioactive isotopes, especially the volatile ^{40}K, could be significantly less abundant than indicated by CI carbonaceous chondrites. Extensive sensitivity analyses (Figure 2), however, demonstrate that differentiation is inevitable for density gradients >5%.

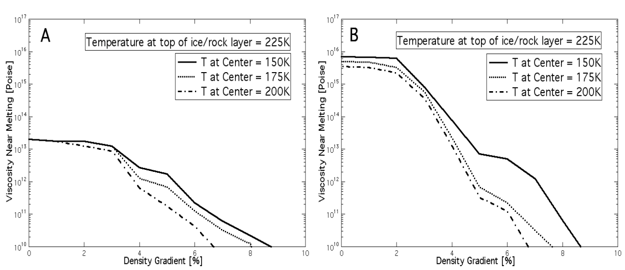

Fig. 2. *Two members of a family of sensitivity analyses. In the parameter space above the plotted lines, an undifferentiated Titan is possibly stable from accretion to the present. Below the plotted lines, an undifferentiated Titan melts and differentiates, usually within ~2Gyr. Panel A has radiogenic heating indicated by CI chondrites; Panel B has one fourth of that heating.*

For compositional gradients higher than ~5%, melting occurs before the entire ice/rock interior begins to convect, so the simulations are not sensitive to a decrease in the initial temperature at Titan's center. For plausible initial temperature gradients and compositional gradients of ~10%, the effective viscosity of ice near its melting point would have to be far below what is usually considered possible to avoid melting. Although Titan can avoid differentiation if initial compositional gradients are below a few percent, accretion from planetesimals with density heterogeneity indicated by the modern Saturnian satellites yields an unstable ice/rock mixture.

Implications: A two-layer model of a partially differentiated Titan that survived accretion and the LHB features an ice/rock interior that is unstable over geologic time for compositional gradients greater than a few percent because convection does not quickly remove radiogenic heat. In 1.5-2Gyr, the ice at the top of the ice/rock interior melts, fully differentiating Titan. If the magnitude of radiogenic heating were less than that indicated by CI chondrites by a factor greater than four, it is possible that an ice/rock mixture with a >5% compositional gradient would be stable over geologic time. Indeed, reactions between silicates and an ammonia water ocean could leach the volatile ^{40}K into Titan's outermost ice layer/ocean [7]. This would primarily occur soon after Titan's accretion, when temperatures near Titan's surface would be very high and the ammonia/water ocean would be thicker than at the present. Despite this possibility, alternative models of Titan's current structure consistent with the recent gravity data should be considered.

A differentiated Titan with a very low core density is consistent with the gravity data. An interior structure consisting of a shell of methane clathrate, high-pressure ice phases, and a subsurface ocean surrounding a core formed primarily from the hydrous silicate mineral antigorite has been proposed [8]. Temperatures of ~900K dehydrate the silicates, but, if radioactive potassium has been leached into the overlying ocean, temperatures in Titan are low enough such that only the innermost ~800km dehydrate [9]. The paradigm of double-diffusive convection, a novel approach in planetary science, is also relevant to many other problems related to icy planets and satellites.

Acknowledgements: JGO was supported by the NASA Planetary Geology and Geophysics Undergraduate Research Program.

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