**Thickness of undifferentiated crust on Kuiper Belt objects experiencing Rayleigh-Taylor instabilities.** Mark Rubin[1], Steven J. Desch[1] and Marc Neveu[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 1404, Tempe AZ, 85287-1404, USA. (mark.e.rubin@asu.edu)

Since their discovery two decades ago, Kuiper Belt Objects (KBOs) have emerged as exciting worlds with interesting geology. Models of their thermal structure and evolution indicate that despite their frigid surface temperatures $\approx 40\,\mathrm{K}$ and small sizes ($< 1000\,\mathrm{km}$ in radius), KBOs can have substantial liquid water in their interiors [1-2]. Models by [2] indicate that even KBOs as small as Charon ($R = 603\,\mathrm{km}$, $\rho = 1.63\,\mathrm{g\,cm^{-3}}$) can retain liquid water in their interiors, at the present day, provided they accreted ammonia hydrate ices. These models predict substantial water $\sim 10^{22}\,\mathrm{g}$ in each KBO of this size, suggesting almost an Earth's ocean's worth of liquid water beyond the orbit of Neptune. Another prediction of these models is that intermediate-sized ($R \approx 400 - 1000$ km) KBOs should only *partially* differentiate. Radiogenic heating will cause separation of rock and ice in their interiors, but their surfaces remain too cold, and their ice too viscous, too allow differentiation.

Two objections to the models of [2] exist. First, differentiation is presumed to take place when ammonia-bearing ice is heated above 176 K. The viscosity of ice drops by many orders of magnitude above this threshold [3], and Stokes flow of meter-sized rock through ice can occur on geological timescales; but rock may not exist as such large particles, and centimeter-sized particles would not separate from the ice except at much higher temperatures. Second, the internal structure of a partially differentiated KBO is potentially unstable to Rayleigh-Taylor (RT) instabilities. Differentiation produces a rocky core ($\rho \sim 3\,\mathrm{g\,cm^{-3}}$), surrounded by an icy mantle ($\rho \sim 1\,\mathrm{g\,cm^{-3}}$), which in turn is surrounded by an undifferentiated crust of mixed rock and ice ($\rho \sim 1.5 - 2.0\,\mathrm{g\,cm^{-3}}$). The existence of a denser layer on top of a lower-density layer is gravitationally unstable and prone to Rayleigh-Taylor instabilities. It is perhaps even possible that these instabilities could completely overturn the crust. Here we quantify the ability of RT instabilities to overturn the undifferentiated crust of KBOs.

Any unstable density stratification will eventually succumb to RT instabilities, but the rate of growth depends on the viscosity, which can slow the growth rate to Gyr or more. For planetary bodies the growth rate is

$$n \rightarrow \frac{\alpha_2 - \alpha_1}{2}\,\frac{\lambda}{2\pi}\,\frac{g}{\eta/\rho_{\mathrm{ice}}},$$

where $\lambda$ is the wavelength of the disturbance (parallel to the interface) and $\eta$ is the viscosity [4]. Long wavelengths grow fastest but $\lambda$ is limited to the planetary radius, so there is a limit to how fast RT instabilities can operate. For the case of Charon in particular, amplitudes increase by less than a factor of 10 in 1.6 Gyr (roughly the time the interface will be at its maximum temperature; see below) if $\eta > \eta_{\mathrm{crit}} \approx 7.5 \times 10^{22}\,\mathrm{Pa\,s}$. Of course RT instabilities may always operate, but if the viscosity exceeds $\eta_{\mathrm{crit}}$ they are irrelevant to the planetary structure. Since $\eta$ generally increases with colder temperatures, the surfaces of KBOs may be cold enough to suppress RT instability-driven overturn.

Ice at the low temperatures of interest is likely to exhibit non-Newtonian rheology, and the relationship between viscosity and temperature is not simple. Based on [5], we compute the strain rate $\dot{\epsilon}$ as a function of the stress $\sigma$, for each of 4 processes (volume diffusion, basal slip, grain boundary sliding, and dislocation creep). For each process the relationship $\dot{\epsilon} = A\sigma^n d^{-p}\exp(-Q^\star/RT)$ holds, with different parameters $A$, $n$, $p$ and $Q^\star$ for each process and different dependencies on ice grain size $d$. The total strain rate is then found using $\dot{\epsilon}_{\mathrm{total}} = \dot{\epsilon}_{\mathrm{diff}} + \dot{\epsilon}_{\mathrm{disl}} + \left(\dot{\epsilon}_{\mathrm{bs}}^{-1} + \dot{\epsilon}_{\mathrm{GBS}}^{-1}\right)^{-1}$. From there the viscosity is $\eta = \sigma/(2\dot{\epsilon}) \times f(\phi)$, where $f(\phi)$ represents an enhancement to the viscosity due to the presence of rock with volume fraction $\phi$. Using the formulas of [6] for Charon, $\phi \approx 0.30$ and $f(\phi) \approx 3.1$. In Figure 1 we plot the relationship between $\sigma$ and $\dot{\epsilon}$ at different values of $T$. In Figures 2 and 3 we plot $\eta(T)$ for various values of the stress $\sigma$ or grain size $d$. We find that the temperature $T_{\mathrm{crit}}$ that yields $\eta(T_{\mathrm{crit}}) = \eta_{\mathrm{crit}}$ is $\approx 134\,\mathrm{K}$ for pure ice with $d = 1\,\mathrm{mm}$ and $\sigma = 1\,\mathrm{MPa}$, and slightly higher, $\approx 137$ K, when rock is included. We find $T_{\mathrm{crit}}$ is insensitive to $d$, but is slightly dependent on $\sigma$.

Based on these results, we have run the thermal evolution code of [2] for the case of Charon, assuming that zones that reach $T > T_{\mathrm{diff}} = 140\,\mathrm{K}$ differentiate, but zones that always remain below

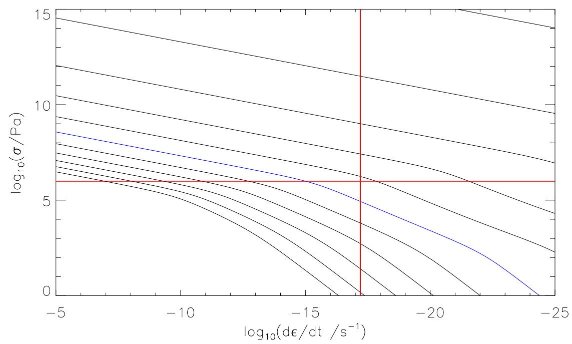


Figure 1: Relationship between stress and strain in ice at various temperatures $T$. Red lines represent the likely values $\sigma = 1\,\mathrm{MPa}$ and $\dot{\epsilon} \sim (5\,\mathrm{Gyr})^{-1}$, which intersect at $T = 142$ K.

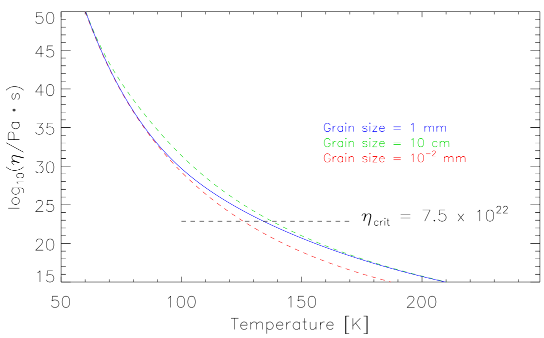


Figure 2: Viscosity $\eta$ versus temperature $T$ for various grain sizes. The value of $T$ that yields $\eta = \eta_{\mathrm{crit}}$ (dashed line) varies by about 5 K as the grain size is varied by 2 orders of magnitude.

$T_{\mathrm{diff}}$ do not. We find that shells whose maximum temperature is near $T_{\mathrm{diff}}$ tend to remain at those temperatures for only 1.6 Gyr or so. This justifies our earlier assumption that RT instabilities have to operate in this time frame to be effective.

The maximum distance out to which differentiation is seen to occur is 524 km. This value is uncertain to within several km based on model assumptions, but it is distinctly far from the surface. The previous results of [2], assuming $T_{\mathrm{diff}} = 176\,\mathrm{K}$, found that differentiation only proceeded to 515 km, so differentiation is more complete with the inclusion of RT instabilities. Still, a substantial thickness of crust, 76 km, does not experience overturn because the viscosity is too high to allow the RT instability to operate in $< 1.6$ Gyr. This undifferentiated crust contains fully one third of the planet's mass.

The actual value of $T$ that will suppress RT instabilities will vary among KBOs and icy worlds.

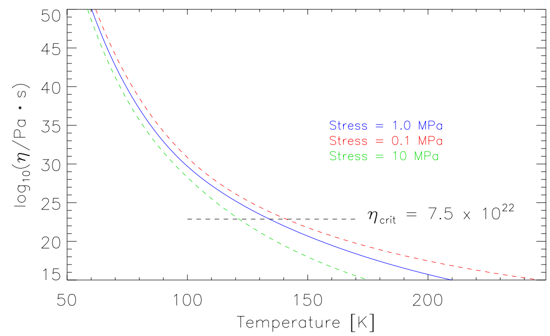


Figure 3: Viscosity $\eta$ versus temperature $T$ for various stresses. The value of $T$ that yields $\eta = \eta_{\mathrm{crit}}$ (dashed line) varies by about 10 K as the stress varies by an order of magnitude.

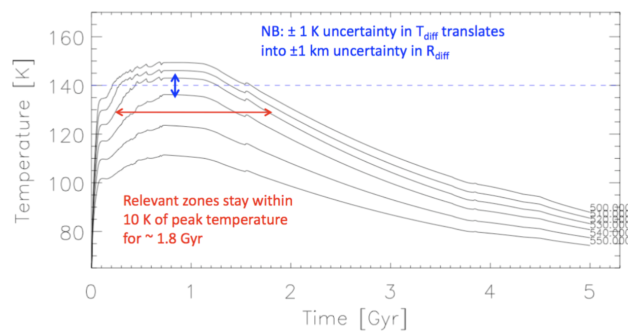


Figure 4: Temperature versus time for shells at various distances from Charon's center. The surface is at 600 km.

In future work we will apply these calculations to other icy bodies to assess whether or not they can retain thick, undifferentiated crusts. Given the relatively high value of $T_{\mathrm{diff}} \approx 140\,\mathrm{K}$ for Charon, it is possible that Rhea (surface temperature $\approx 80$ K) may also be only partially differentiated. This would have measureable effects on Rhea's moment of inertia factor, putting it somewhere between the value 0.4 for a fully homogenous body, and $\approx 0.3$ for a fully differentiated body. This idea can be tested using data from the recent and upcoming flybys of Rhea by *Cassini* [7-8].

**References**: [1] Hussmann, H., Sohl, F. & Spohn, T. 2006, *Icarus* 185, 258. [2] Desch et al. 2009, *Icarus* 202, 694. [3] Arakawa, M. & Maeno, N. 1994, *GRL* 21, 1515. [4] Chandrasekhar, S. 1961, *Hydrodynamic and Hydromagnetic Stability*. [5] Goldsby & Kohlstedt 2001. [6] Friedson, A. J. & Stevenson, D. J. 1983, *Icarus* 56, 1. [7] Iess, L., et al. 2007, *Icarus* 190, 585. [8] Anderson, J. D. & Schubert, G. 2010, *PEPI* 178, 176.