MECHANICAL AND THERMAL PROPERTIES OF PLANETOLOGICALLY IMPORTANT ICES Steven K. Croft, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

Two "sequences" of ice composition have been proposed for the icy satellites: 1) a dense nebula model (1) in which C and N are CH_4 and NH_3, yielding, in order of decreasing condensation temperature, hydrated rock, H_2O ice, $NH_3 \cdot H_2O$, CH_4-ice clathrate and finally solid CH_4; and 2) a solar nebula model (2) in which C and N are in CO and N_2 yielding hydrated rock, H_2O ice and finally CO- or N_2-ice clathrate. Careful modeling of the structure, composition, and thermal history of satellites composed of these various ices requires quantitative information on the: 1)density, 2)compressibility, and 3)thermal expansion of the rock and ices (incorporated as an equation of state or EOS), as well as the 4)heat capacity and 5)thermal conductivity. EOS's and thermal data have been given previously for the H_2O ices (3) and CH_4 (4). However, much recent interest in structures of molecular ices by physical chemists has resulted in a large increase in the data available on ices of planetological interest. Thus, data have been gathered from the literature to update equations of material properties for the H_2O and CH_4 ices and to calculate such equations for the first time for NH_3, CO, N_2 and CO_2 ices.

Pure Ice Data. EOS's have been fit to the density data of the molecular ices shown in table 1. The # phases includes the number of solid phases plus one liquid phase (except for $CH_4 \cdot 5.75H_2O$) analyzed for each compound. Compared to silicate minerals, the bulk moduli (K_{oo}) of the ices are one to two orders of magnitude smaller, the K'_p's are about the same, and the K'_T's are about half. The inferred thermal expansions show enormous variability, increasing from rock to H_2O ice to the other molecular ices. The effect is not trivial: increasing the interior temperature of an icy satellite from accretion temperatures near 100°K to around 300°K yields a 0.2% volume increase in the rocks, ≈ 3% increase in the H_2O ices, and > 30% increase in the other molecular ices. The assembled heat capacity data show the same trends, increasing dramatically from rock to H_2O ice to the other ices. Of particular note here is that the heat capacity of rock assumed in previous models was near 1.2 Joules/g°K, appropriate for the high interior temperatures of rocky planets, but far too large for the 100K to 300K temperatures appropriate to the icy satellites. The net affect on icy satellite thermal histories, because of the large mass fraction of the rock, is to shorten the times for internal heating and melting by factors of 2x to 3x. Finally, the assembled thermal conductivity data (figure 1) again show a definite trend: decreasing from rock to H_2O ice to the other molecular ices. Of particular interest is the extremely low thermal conductivity of CH_4-clathrate compared to H_2O ice or rock - a point returned to below.

Binary/Multiple Ice Systems. The simple molecular ices represent end-numbers of more complex ice "minerals" that form when the simple ices are mixed. Ammonia hydrates ($NH_3 \cdot nH_2O$) and ice clathrates (CH_4, N_2, $CO \cdot nH_2O$) are likely forms (5,6). The thermodynamics of ice clathrates have been studied by (7). A preliminary EOS for CH_4- and N_2-clathrates have been constructed here from the meager data available, but much work needs to be done to directly determine thermal expansion and bulk modulus derivatives. Data for the $NH_3 \cdot H_2O$ system are limited: heat capacities and latent heats, liquid densities near room temperature, single density measurements $2NH_3 \cdot H_2O$, $NH_3 \cdot H_2O$ and $NH_3 \cdot 2H_2O$, and some high pressure measurements at selected compositions (8). Approximate bounds on the thermal and mechanical properties of the ammonia hydrates may be set by looking at the properties of the end-members: NH_3 and H_2O. For example, heat capacity data for the ammonia hydrates are intermediate between ammonia and water. However, actual measurements are preferred and thus analytical, experimental, and theoretical studies of the ammonia hydrates have been initiated. An equation for the density of liquid NH_3-H_2O (at all NH_3 concentrations) has been constructed using previous high temperature data and our own low temperature data. The liquid densities have been combined with thermodynamic and solid density data to determine the low pressure portion of the $NH_3 \cdot 2H_2O$ phase diagram. Combining our results with the high pressure data, we infer at least two solid phases of $NH_3 \cdot 2H_2O$ with the transition near 1kb and with a fairly large density difference. A phase change at such a low pressure is an important one structurally even for fairly small icy satellites.

Applications. Detailed structural and thermal modeling of icy satellites has commenced based on the new data. For example, one of the real surprises of the Voyager Uranus encounter was the presence of endogenic resurfacing and fracturing on tiny Miranda. The implied volume increase of Miranda represented by the fractures is ≈ 6%. How does Miranda become warm enough to exhibit such activity? One possible approach is illustrated by the thermal profiles in figure 2. If Miranda consists of simple ice and rock, the maximum interval temperature rise is ≈ 10°K, perhaps yielding temperatures in the core capable of melting a little CH_4 (if any is present in pure form). Such small amounts would likely freeze en route to the surface. However, if the ice is in the form of CH_4 clathrate, the temperature rise in the core is ≈ 120°K, sufficient to melt CH_4 through much of the interior and probably to drive it through the resulting thin crust to the surface (the dark flows on Miranda may be radiation-darkened CH_4 (9)). Even partial melting of eutectic NH_3-H_2O is possible (depending on boundary conditions). The large internal heating due to clathrate and the presence of molecular ices of high thermal expansivity may also account for the observed fracturing via simple heating and thermal expansion. Thus, the difference between resurfaced Miranda and primitive Mimas may simply be the presence of clathrate. The effects of the clathrate vs. pure ice on larger satellites is not as great (cf. Titania curves in fig. 2) because convection provides a fairly low temperature cutoff (detailed values depend on surface conditions and assumptions concerning viscosity). Thus, the unusual thermal and mechanical properties of the molecular and binary ices suggest a larger range of phenomena than previously anticipated, sufficiently complex perhaps to account for many of the unusual geologic phenomena found on the icy satellites.

References

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TABLE 1. MOLECULAR ICES

Compound	#Phases	K_{oo}	K'_p	K'_T
H_2O	8	114 Kb	5.5	-0.101 Kb/°K
NH_3	4	75	5.5	-0.186
CH_4	4	21	4.9	-0.074
N_2	6	28	3.8	-0.108
CO	5	20	6.6	-0.092
CO_2	3	77	7.0	-0.183
$CH_4 \cdot 5.75H_2O$	1	≈88	(5.5)	(-0.1)

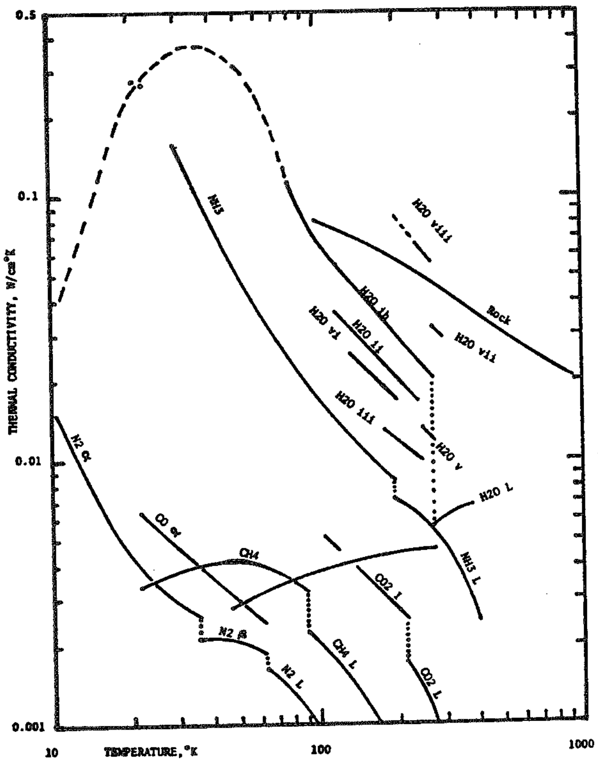

Figure 1.

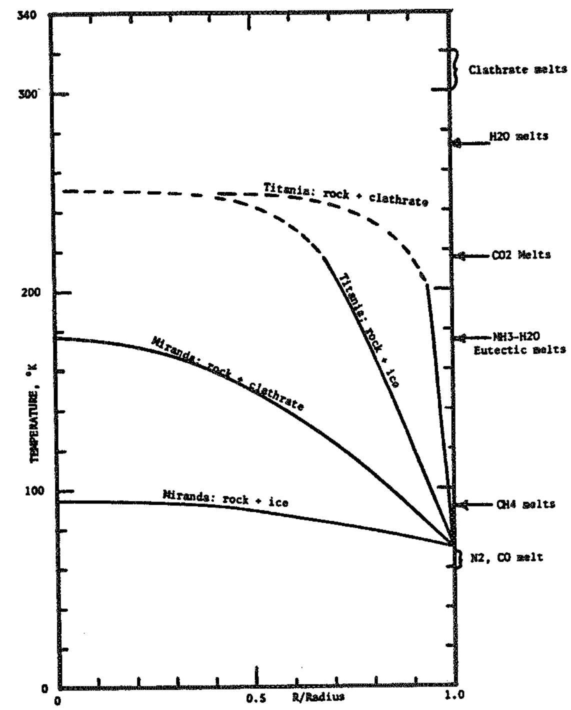

Figure 2.