
The ammonia hydrates are likely constituents of the icy satellites (1), comprising as much as 10% of the total mass. They are of particular interest since the presence of ammonia in water ice lowers the melting point of a eutectic mixture (≈ 35% by mass NH₃) to about 174°K (2). This melting temperature is low enough to be reached in the interiors of 500 to 1000 km radius icy satellites by internal radioactive heating alone, possibly accounting for the resurfacing observed on satellites in this size range in the Saturnian and Uranian systems. Unfortunately, many of the physical properties of the ammonia hydrates are poorly determined. We have therefore assembled the data that are available in the literature and have initiated theoretical and experimental studies to derive the desired physical properties and fill in gaps where they occur. This report presents the result of our analysis of the liquid ammonia-water system at one bar.

An equation of state (EOS) relating density, temperature, and composition (0% to 100% NH₃) for liquid water-ammonia at one bar and between 175K and 300K was derived by a least-squares fit to 182 data points drawn from published sources (3,4) and our own experiments (5). The EOS is of the form:

\[ p(T) = p(To) \exp(-a(T)dT), \]

where \( a(T) \) was assumed to be parabolic in temperature. The final equation contains 17 empirical constants and uses polynomial fits to the four sections of the melting curve in the NH₃-H₂O phase diagram. The final fit, shown in graphical form in fig. 1, matches the data within a formal rms error of 0.0004 g/cm³. The bulk moduli of ammonia-water liquid have not been measured. However, the bulk moduli of the end-members NH₃ and H₂O are both between 20 and 50 kb up to a few kilobars pressure. Thus, the densities shown in figure 1 will be accurate to within a few percent at all depths within Titania, Rhea and smaller satellites. Non-trivial corrections must be applied before using the derived EOS in the interiors of Pluto, Triton, and Titan.

Ammonia Monohydrate Density at One Bar. Single measurements exist for the densities of each of the three ammonia hydrates: ammonia dihydrate, monohydrate, and hemi-hydrate. Using the calculated liquid densities, measured latent heats (6), and the Clapeyron slope \( dT/dP \) at melting (7) enables calculation via the Clausius-Clapeyron relation of a second solid density for ammonia monohydrate and thus an estimate of the thermal expansion and densities at one bar as a function of temperature. The resulting empirical equation for NH₃.H₂O, \( \rho(T) = 0.9588 \exp(-9.427E-8 T^{2.375}) \), yields thermal expansions that are very nearly the geometric mean of the thermal expansions of pure solid H₂O and NH₃.

Ammonia Dihydrate Phase Diagram. Similarly, we have used the calculated liquid density, solid density (8), thermal data (9), and estimates of the thermal expansion to find \( dT/dP = 35\pm10°K/GPa \) at one bar for NH₃.2H₂O. This is substantially smaller than \( dT/dP = 150°K/GPa \) estimated from the data of (7) at pressures above about 10kb. More recent work (10) in the 2 to 4 kb range exacerbates the inconsistency between the high pressure and atmospheric pressure clapeyron slopes, thus we postulate the existence of a solid-solid phase change in the dihydrate near 1 kb. A possible congruent melting curve is shown in figure 2 which is consistent with the available data. The density of the dihydrate I is about 0.97 g/cm³ and that of dihydrate II is near 1.3 g/cm³. The inferred density change is rather large and dependent on assumptions concerning liquid compressibility. Internal pressures in icy
satellites exceed one kilobar at diameters near 1100 km, thus the postulated phase change may be structurally important in satellites such as Ariel, Rhea, and Titania. It is certainly important in the interiors of the larger satellites such as Triton and Titan if ammonia hydrates are present (11).

Solid-Liquid Density Contrast and Ammonia-Water Volcanism: The density of the ammonia-water eutectic liquid at the melting temperature of 174.4°K is calculated to about 0.941 g/cm³. The solid density is about 0.937 if it consists of water ice and monohydrate, and about 0.963 g/cm³ if it consists of dihydrate and monohydrate. The uncertainty in these densities is about 1%. The liquid is very nearly neutrally buoyant, and possibly negatively buoyant, relative to the solid. Thus, ammonia-water volcanism will occur in sufficiently warm, undifferentiated satellites (density nominally 1.3 g/cm³ or greater), creating surface layers of nearly pure ammonia hydrates and water ice. In larger satellites, such as Titania, where temperatures exceed the eutectic melting point over most of the interior, the surface layer of ammonia hydrates could become quite thick, as much as of several 10's of kilometers. Continued penetration of this thick crustal layer by liquid of eutectic composition becomes difficult due to lack of buoyancy, particularly if there is substantial porosity in the surface layers. Thus, volcanism may become largely plutonic in the later stages, producing limited surface flooding but possibly extensive surface tectonics.

References