

Laboratory Simulations of Ammonia-Rich Oceans in Icy Worlds S. D. Vance¹ and J. M. Brown², ¹Jet Propulsion Laboratory, California Institute of Technology (svance@jpl.nasa.gov, 183-401, 4800 Oak Grove Dr., Pasadena, CA 91109) for first author, ²Department of Earth and Space Sciences and Astrobiology Program, University of Washington (351310, Seattle, WA 98195-1310).

Introduction: Improved equations of state for ammonia-water solutions are important for properly understanding the interiors of large icy satellites hosting deep interior oceans. Titan is the primary example of such a world, but water-rich dwarf planets. Measurements of solution density are now possible at relevant pressures (above ~250 MPa) using the Simulator for Icy World Interiors [1]. Analysis of sound velocity measurements in aqueous magnesium sulfate obtained in our laboratory, shows a correction on the order of 5% to 700 MPa (7 kbars) from -20 to 100 °C and to 3 m (~30 Wt %) concentration [2,3]. Accurate prediction of density as a function of pressure, temperature, and ammonia concentration are needed for interpretation of remote observations to address questions of interior liquid layer depth, composition, and fluid dynamics.

Deep Interiors of Large Icy Worlds: The satellites Callisto, Ganymede, and Titan have similar sizes and densities. All three likely have oceans in their interiors to 200-500 km depth. Thermal models predicting an internal liquid ammonia-water layer in Titan [4,5,6] are supported by recent analyses of Titan's obliquity and spin state from Cassini gravity data [7,8]. A low ³⁶Ar/³⁸Ar ratio relative to solar abundances is suggestive of the incorporation of ammonia in the kronian satellites during their formation [9].

The Need for Measurements in (aq) Ammonia Relevant to Deep Icy World Oceans: In large icy objects like Titan, Callisto and Ganymede, a revision to the average density of aqueous ammonia of 5% would change the inferred moments of inertia by roughly 2% [10].

A subsurface ocean in Titan may be linked to hydrologic and cryovolcanic features still being revealed by Cassini observations. Relating these features to subsurface properties requires an understanding of material properties under Titan-interior conditions. Hydrostatic pressure at the bottom of Titan's putative ocean approaches 1 GPa. Similar pressures are obtained in the ice layers of Ganymede and Callisto.

Available Data for (aq) Ammonia: A working description of density and phase behavior for aqueous ammonia and associated ice and clathrate phases has been proposed, but its authors note an important lack of experimental data above 250 MPa [11]. The phase diagram for the water-ammonia system has been described from direct observation ([12] 0-0.23 M to 300 MPa at 200-273 K; [13] 25 Wt % to 1 GPa at 273-175

K; [14]), but few measurements of density exist at high pressures for aqueous ammonia. The equation of state reported by Croft *et al* [15] from 0-100 Wt % to 1 GPa is based on measurements in pure NH₃ to 500 MPa [16]. The behavior of intermediate compositions comes from one set of published measurements to only 140 MPa [17]. Bulk moduli inferred by Croft *et al* [15] differ in extrapolation from those of the end members by a few percent, suggesting that a study in our lab will yield improvements in the equation of state for aqueous ammonia.

Methods: Impulsive stimulated scattering is employed to measure sound velocities [18,19,20]. The method works as follows. An acoustic excitation is created in an optically-accessible sample by the convergence of picosecond infrared pulses from a NdYAG laser at a known angle. Sites of constructive interference form a grating in two dimensions. The heated regions impulsively expand, creating two counter-propagating sound waves. A subsequent diffracted pulse, delayed by time-of-flight, probes the interaction of these waves at a given time. The modulation of the probe pulse over the excitation's ~30 ns evolution gives the sound frequency in the material at the temperature, pressure, and solution composition of interest. Speeds of sound are inferred from this frequency and the known wavelength—set by the condition for Bragg scattering.

At temperatures where the density and heat capacity of a fluid are known for at least one pressure, the equation of state at fixed composition is determined by recursive integration of thermodynamic relations between speed of sound and density. Having calculated the density, all other thermodynamic properties may be obtained. Measurements over a range of concentrations additionally allow calculation of partial molal volumes and chemical potentials.

Discussion and Conclusions: The above analysis demonstrates the need for equation-of-state measurements in ammonia-water solutions at non-standard pressures and temperatures. Additional future studies will examine other single-component aqueous systems relevant to icy satellites (*e.g.* Na₂SO₄, CaSO₄, NaCl). It is desirable to also examine multi-component systems, but the large parameter space limits the investigator to a targeted selection of such measurements. Available thermodynamic models for multi-component systems [21,22,23,24] are based on a self-consistent

database of individual ion properties and the models extrapolate from the range of near-standard temperatures and pressures in which measurements are made. We can test the accuracy of such predictions for multi-component systems with a selection of equation-of-state measurements in multicomponent systems.

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