ACOUSTIC EXPLORATION OF EXTRATERRESTRIAL OCEANS

Steven D. Vance

Planetary Chemistry and Astrobiology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States
e-mail: steven.D.Vance@jpl.nasa.gov

J. Michael Brown

Earth and Space Sciences, University of Washington, Seattle, Washington, United States
e-mail: Steven.D.Vance@jpl.nasa.gov

Subsurface oceans in the solar system contain more total water than Earth's oceans. Evidence for liquid water in Jupiter's moons Europa, Ganymede, and Callisto, and in Saturn's moons Titan and Enceladus, indicates that characteristic depths are 100s of km. Bottom pressures can exceed 1.5 GPa, well into the stability range for high-pressure ice phases III, V, and VI. Considering the thermodynamics of salty fluids leads to predictions of truly alien "climate" in such worlds, in which ices either float or sink. Determining the dynamics of such oceans is a modeling task requiring new thermodynamic data from acoustic measurements. Future planetary exploration missions could provide opportunities in the coming decades to characterize these oceans using acoustic methods. Here, I briefly describe some of the thermodynamic and acoustic properties of fluids and ices in extraterrestrial oceans.[1]

1. Introduction

The existence of extraterrestrial oceans in our solar system is a new revelation, born from the last four decades of robotic exploration of the outer solar system. Prior to the use of ground-based infrared spectroscopy and launch of the Voyager spacecraft in the 1970's, our understanding of the composition and internal structure of icy satellites in the solar system was comparable to the present level of understanding of exoplanets orbiting other stars. This historical perspective encourages patience in the face of at least another decade before we can probe oceans in greater detail.

ESA's planned JUpiter Icy moons Explorer [JUICE; 1], which will orbit Ganymede starting in 2033, creates the prospect for sensing ocean currents and detecting seamounts. JUICE, and the Europa Clipper mission being studied by NASA, could use combined gravity; radar sounding; and

[1] Figure 2 reprinted with permission from R. E. Gagnon, H. Kiefte, M. J. Clouter, et al. Acoustic velocities and densities of polycrystalline ice Ih, II, III, V, and VI by Brillouin spectroscopy. *J. Chem. Phys.*, 92:1909, (1990). Copyright 1990, AIP Publishing LLC

magnetic field and plasma measurements to detect seamounts with heights comparable to other large mountains in the solar system [2]: Mauna Kea on Earth (10 km dry prominence), Olympus Mons on Mars (30 km), or Boösaule Montes on Jupiter's moon Io [17.5 km]. In the further future, seismo-acoustic investigations on a landed mission would offer the advantage of being able to probe the dynamic ice shells and seafloors of icy worlds, and even to sense their deeper structure [3-9]. Prior to embarking on such investigations, laboratory acoustic measurements provide both the fundamental data needed for seismic interpretation, and the thermodynamic information needed to simulate ocean structures and flow regimes that may be very unlike those on Earth.

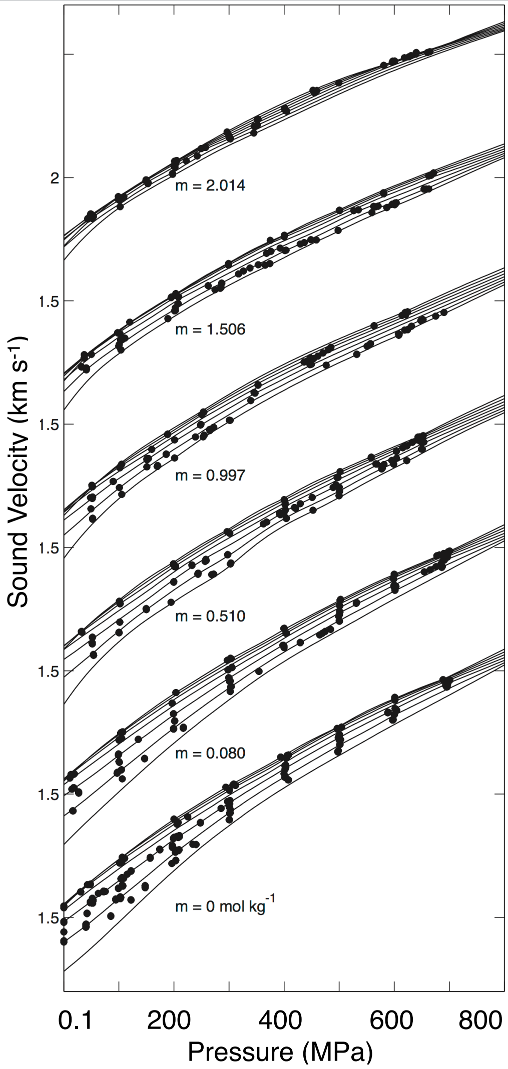

Figure 1. Measured sound speeds for $MgSO_4$(aq) vs pressure in MPa. The y-axis has increments of 0.5 km s^{-1}, with 1.5 km s^{-1} as the starting point for each composition. Modified from Ref. 15. Solid lines portray contours in temperature from 250 to 390 K.

2. Oceans unlike Earth's

Europa's ocean is on the order of 100 km deep, 25 times deeper than Earth's. We know little about its salinity or pH, features that are critical for determining whether it is habitable. Geochemical modeling of Europa's ocean, applicable to other icy satellite oceans, suggests that ocean compositions should either be Mg or Na dominated, depending on the hydrogen content of the waters [10]. In spite of these unknowns, Europa's is probably the most Earthlike of extraterrestrial oceans in the solar system, owing to the existence of a rocky seafloor at pressures comparable to those in Earth's ocean. In the larger moons, Ganymede, Callisto, and Titan, the role of high pressure ices in thermal evolution and ocean chemistry is unknown. A well conceived seimo-acoustic experiment might return the sort of detailed ocean structure information now becoming available for Earth's oceans [10].

3. Acoustic probes of ocean chemistry

Because the adiabatic acoustic sound speed v is a second derivative of free energy in pressure, measurements of sound speed provide a sensitive probe of free energies. Prior work [12-17] demonstrates how solutions to a numerical forward problem based on measured sound speeds give accurate densities at high pressure. These quantities are related to the Gibbs free energy, G, as:

(1,2) $$v^2 = \left(\frac{\partial G}{\partial P}\right)^2 \frac{\partial^2 G}{\partial T^2} \Big/ \left(\frac{\partial^2 G}{\partial P \partial T} - \frac{\partial^2 G}{\partial T^2}\frac{\partial^2 G}{\partial P}\right), \qquad V = \left(\frac{\partial G}{\partial P}\right)_{T,m}$$

(3,4) $C_P = -T(\frac{\partial^2 G}{\partial T^2})_{P,m}, \quad \alpha = \frac{\partial^2 G}{\partial P \partial T}$

where ρ is the specific density, α is the thermal expansivity, C_P is the specific heat capacity, and V is the specific volume. G is both a compact representation of quantities of geophysical interest, but also the key parameter in computing geochemical phase equilibria.

Creating a comprehensive representation of fluid properties for ocean solutions requires adequate measurements covering the pressure, temperature, and compositions of interest, and integrating constants of reference heat capacities at a single pressure and all temperatures and compositions. Smooth integration over large multidimensional surfaces is a problem in geophysical inversion more familiar to the field of seismology than that of geochemistry. Creating a chemical data set suitable for modeling diverse icy satellite oceans and their acoustic properties is thus a great opportunity for cross-disciplinary research.

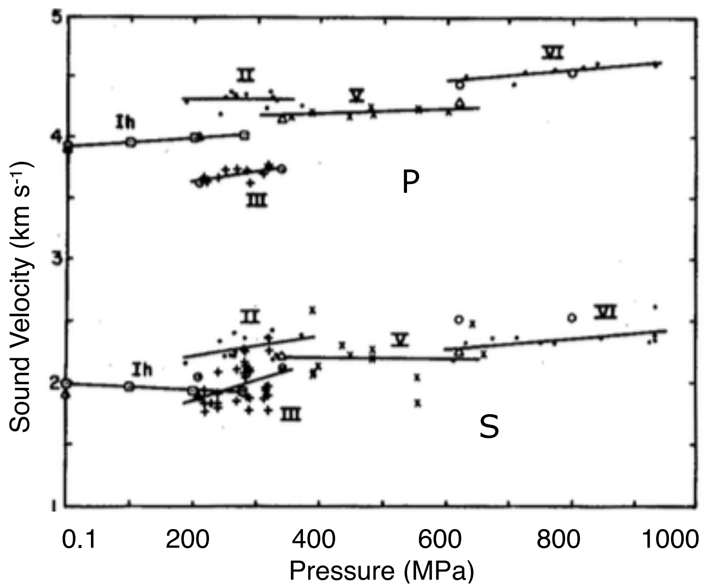

Figure 2. Measured acoustic velocities vs pressure in unoriented polycrystalline water ice phases Ih, II, III, V, and VI at -35°C, from Ref. 25. Symbols △ and ◯ from Ref. 23 were collected at -25°C. Different phases have distinct velocities for seismic precisions better than about 100 m s^{-1}. Shear wave sound speeds overlap with sound speeds of highly saline $MgSO_4$ (Figs. 1, 4, 5).

Chemical oceanography on Earth uses the theory of ionic solutions to represent additive contributions of dissolved ions to the free energy of solution. Seawater properties have been measured in a narrow range of pressure and temperature, with high concentrations and diverse compositions that might occur in icy satellites measured mostly at standard temperature, and modest concentrations less than 0.5 moles kg_{H2O}^{-1} and to 100 MPa pressures [17] comparable to pressures at the bottom of the Marianas trench. The basis set of aqueous chemistry at standard temperature and pressure is much more comprehensive, providing much (but not all) of the needed constants of integration for constructing multi-dimensional equations of state. Evaluating pressures, temperatures, and compositions where measurements are needed provides physical data that may also be of use for understanding briny subglacial lakes in polar regions, which have come under more intensive study as part of the effort to assess global climate change.

Interestingly, for higher frequency seismo-acoustic measurements in icy satellites, attenuation of acoustic energy in seawater is primarily due to dissolved magnesium sulfate from 10 to 1000 kHz [18] with a small contribution from boric acid near 10 kHz [19]. The degree of attenuation, coupled with the pressure and temperature dependent sound velocity, may thus provide an additional constraint for determining the dominant constituents of icy satellite solutions.

3. Seismology of ices

Icy satellites replace near surface geodynamics of rock with that of ice, so knowing the properties of ices is essential for understanding how icy satellites work [20]. As anisotropic materials with multiple crystalline phases, water and other ices existing in icy satellites resemble mantle minerals that are more familiar targets for seismology. Direct sound speed and attenuation measurements have been made in single and polycrystalline ice Ih [4, ibid.; 21; 22], but not to temperatures below 240 K. Sound speeds have also been studied in high-pressure ices expected to exist in icy satellites—phases I, II, III, V, and VI— [23, 21, 24, 25], but again only in a very limited range of temperatures from 237 K to 298 K (20; Figure 2). Recent studies at GPa+ pressures for ices anticipated in exoplanets have yielded relevant compressional data for ice VI [e.g., 26] at elevated temperatures. For polycrystalline samples, the density, ρ, adiabatic bulk modulus, K_S, and adiabatic shear modulus, μ, may be inferred from, or used to infer, the shear and compressional wave speeds (v_p, v_s):

(5,6) $K_S=\rho(v_p^2-4/3v_s^2)$ $\mu=\rho v_s^2$

Equations of state for ice Ih [27], II, III, V, VI [28] provide self consistent thermodynamic properties, including density, which can be coupled with available elastic moduli to estimate sound speeds vs pressure and temperature.

As with mantle materials, impurities in the mineral structure introduce additional thermodynamic complexity. For example, the volumetric effects of substantial ammonia, methane, and ethane clathrates in Titan's ice have only recently been studied [28-30], and shear wave velocities appear to be unavailable.

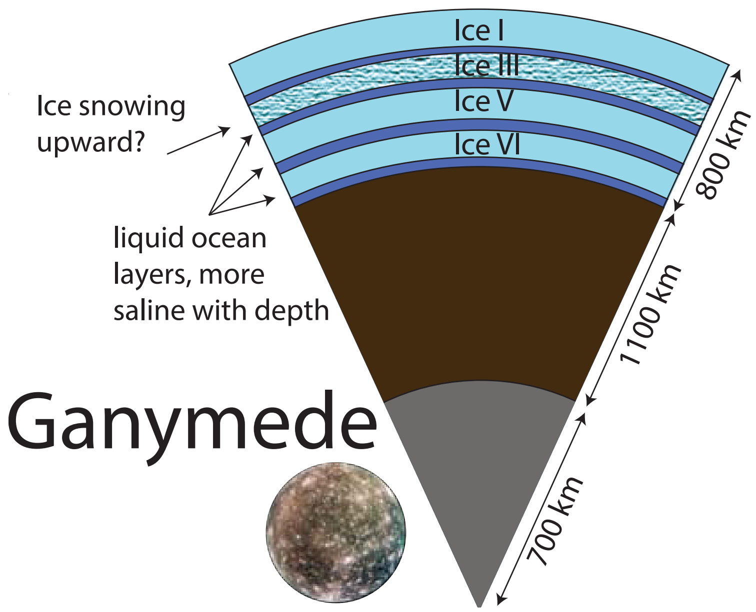

Figure 3. Ganymede's high pressure ices may interlayer with dense salty solutions [31]. In models with ocean temperatures low enough to form ice III, the required solution concentrations, as low as 30 ppt $MgSO_4$, create fluids that are denser than the ice. Interlayering of ices would thus be a dynamic process. An appropriately designed seismic investigation could probe for such features.

4. Predictions testable by future seismo-acoustic exploration: Multi-layered oceans

One result from our measurements of the thermodynamics of aqueous solutions at elevated pressures is to demonstrate that salty ocean fluids inside Ganymede can be denser than high pressure ices likely to exist near its water-rock interface at 800 km depth [15]. Sound speeds were measured in $MgSO_4$ (Fig. 1). Density surfaces obtained from the integration of sound speeds revealed regions in P-T space where fluid densities exceeded those of ices I, III, V, and VI. Multilayered oceans, liquids both above and below high pressure ice phases (Fig. 3), are geodynamically stable for realistic thermal profiles of

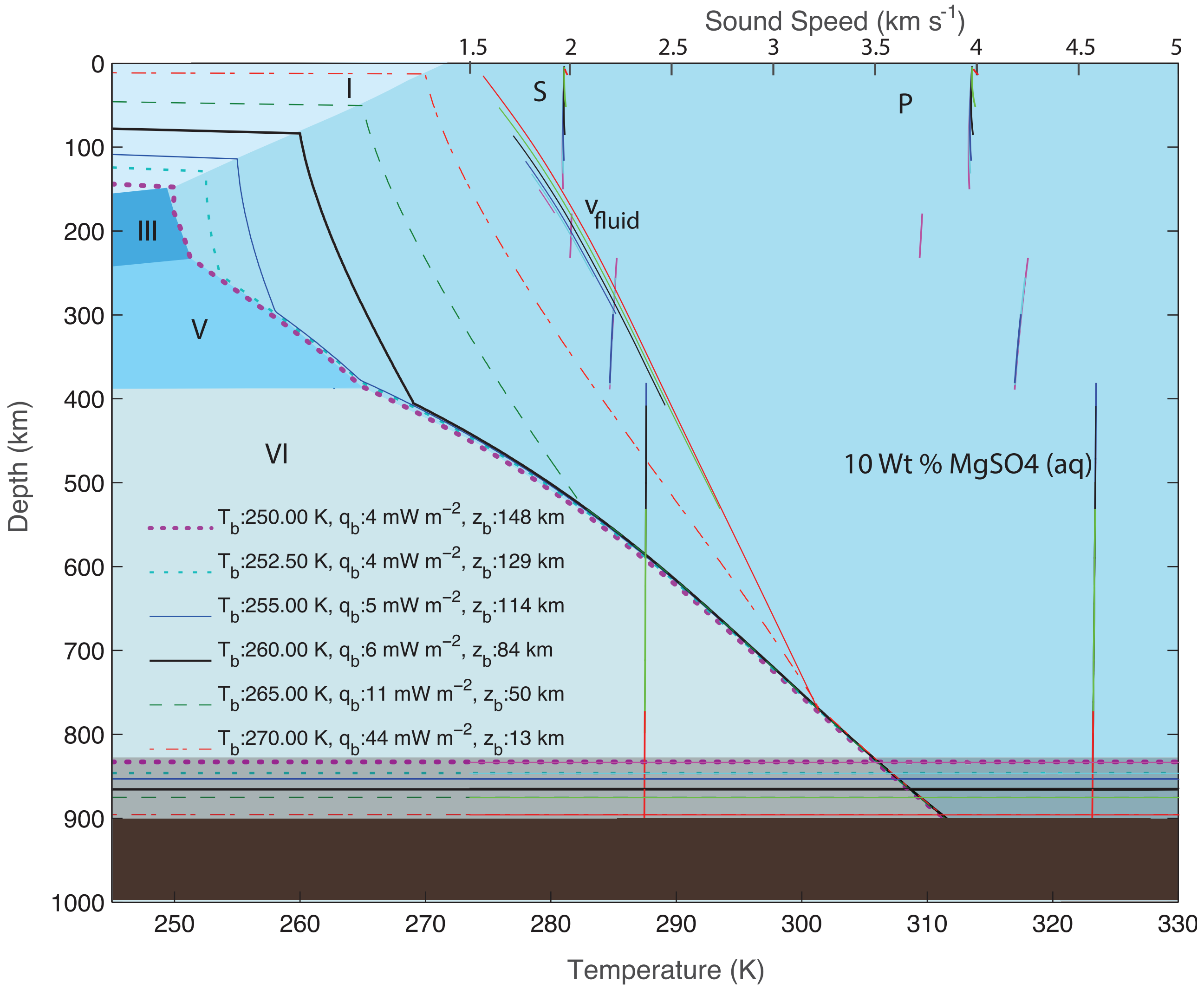

Figure 4. Depth-Temperature profiles for Ganymede's interior, assuming a uniform ocean salinity of 10Wt% $MgSO_4$ from the model of Ref. 23, consistent with Ganymede's gravitational moment of inertia measured by the Galileo spacecraft. The model illustrates where high pressure ices form for different assumed basal temperatures of the ice Ih layer (T_b). Equivalent heat fluxes (q_b) and ice thicknesses (z_b) are plausible for estimates of Ganymede's radiogenic heating. Sound speeds in fluids are from Ref. 12; sound speeds in ices are computed from available densities (Ref. 27) and assuming uniform elastic constants for individual phases from Ref. 20.

Ganymede that account for the chemistry of ice formation in the presence of $MgSO_4$ [31]. It remains to be confirmed whether layered oceans and ices are a likely result from Ganymede's thermal evolution.

Seismic monitoring could not only confirm the presence of subsurface oceans, but could also be designed to look for multi-layered structures and buoyant oceanic "snow" of high pressure ices. Here, I have constructed a velocity model for Ganymede's ocean and ices using pressure-temperature profiles from Ref. 31, with constant values of elastic moduli for individual phases taken from Ref. 25 and specific densities from Ref. 28. Ocean salinity is assumed to a uniform 10Wt% $MgSO_4$. Oceanic sound speeds increase under the increasing temperature of the convective ocean (Figure 4). The high compressibility of the fluid relative to ices over the 1.6 GPa pressure range means that ices can float in a sufficiently saline ocean (Figure 5).

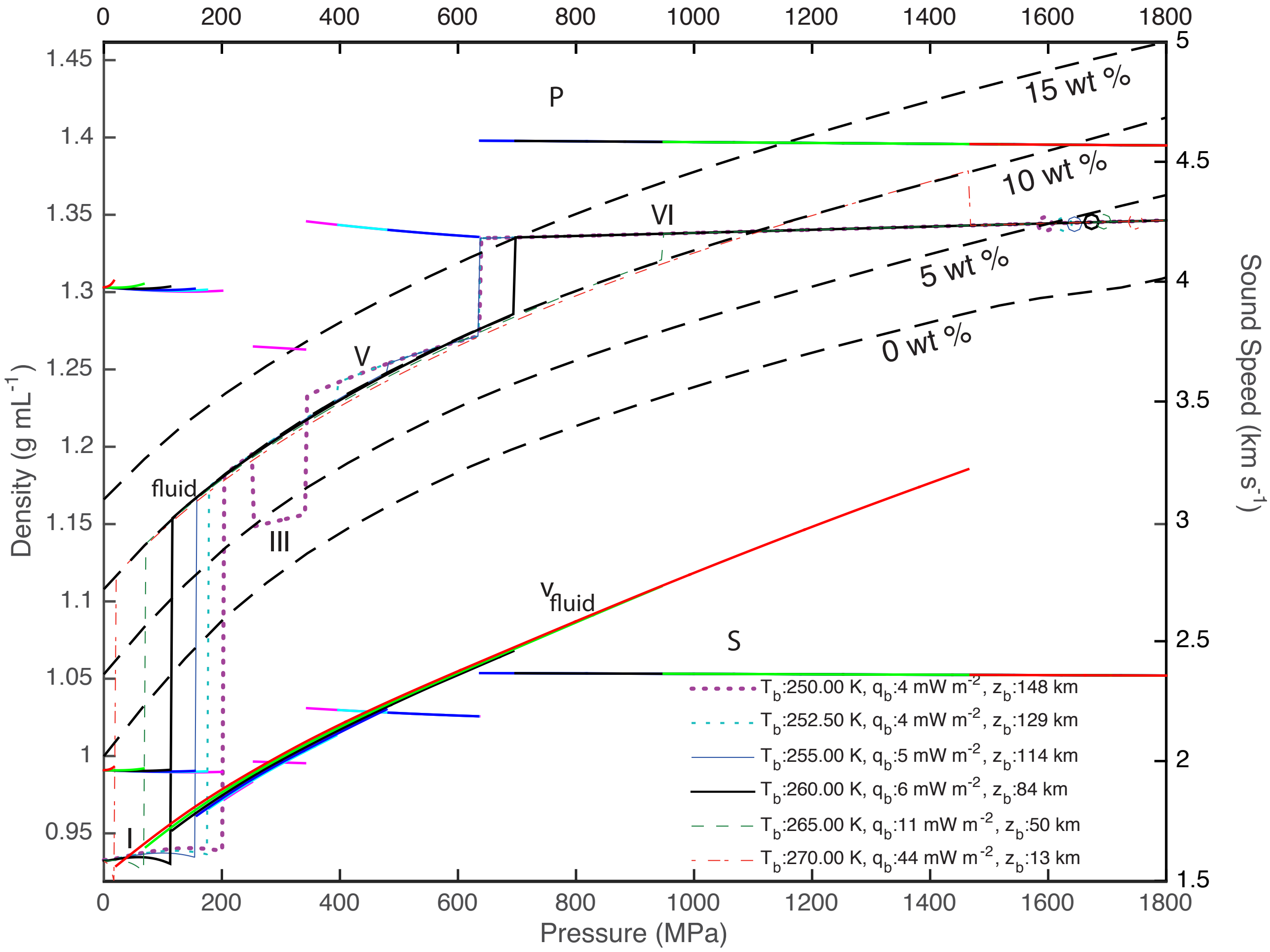

Figure 5. Densities-Pressure profiles for Ganymede's interior, assuming a uniform ocean salinity of 10Wt% $MgSO_4$ from the model of Ref. 31. Sound speeds are the same as in Fig. 4. Circles show the pressure of transition from the H_2O to silicate layer. Ices III forms only for the lowest value of heat flux (T_b = 250 K) and is always buoyant. Ice VI is buoyant in the warmest model (T_b = 270 K).

This simple 1D model suggests ices may form "snows" due to pressure and temperature perturbations as oceanic flows move over Ganymede's ice or seafloor topography, or as Ganymede's ocean and ices respond to tidal forcing. A seismic network on Ganymede could investigate the active "weather" in the ocean of Ganymede, or in similar satellites Titan and Callisto. Presently available sound speed measurements are sufficient to distinguish among the different phases of ice. Before conducting such an expedition, experimental measurements of elastic constants can address discrepancies between measured elastic constants of up to 10% [20], and provide more comprehensive coverage of in the multi-dimensional space of pressure, temperature, and composition.

5. Conclusions

Seismic investigations offer the most comprehensive view into the oceans and deeper subsurfaces of icy satellites. They may do for ocean worlds what orbital mapping has accomplished at Mars and Titan: reveal topographic features of alien worlds that are strikingly Earthlike. The canyons and seamounts of Europa may hold clues to the presence of underwater volcanoes or other geological activity familiar to Earth. Oceans in larger worlds may come alive with previously unimagined geological phenomena. The decades between now and the first landing on an ocean world provide the chance to conduct needed measurements of the properties of likely ocean and ice materials—sound speeds, elastic moduli, and associated thermodynamic free energies—and to use them to predict what may be awaiting discovery.

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