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Weigang Shi and Ningyu Sun contributed equally to this work.

Key Points:

- We determined the single-crystal elasticity of high-pressure salty ice up to 98 GPa and 300 K using Brillouin scattering
- The elastic moduli of the high-pressure ice exhibit anomalous softening between 42.4 and 54 GPa
- The transition from ice-VII to ice X is associated with an apparent increase in the pressure derivative of the elastic moduli

Supporting Information:

Supporting Information may be found in the online version of this article.

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Single-Crystal Elasticity of High-Pressure Ice up to 98 GPa by Brillouin Scattering

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Abstract Knowledge of the elasticity of high-pressure ice is key to constructing the internal structure of various planetary bodies. Here, we present direct experimental constraints on the single-crystal elasticity of ice with 0.5 mol/L (0.9 mol.%) NaCl up to 98 GPa at 300 K. The change from ice-VII to the dynamically disordered ice-VII is characterized by an obvious softening of the longitudinal and bulk moduli between 42.4 and 54 GPa. Further transition to ice X at ~64 GPa results in an apparent change in the pressure dependence for the elasticity. Using the obtained elasticity, our modeling reveals that the boundary between the ice-VII layer and the silicate mantle or core in moderate-size icy planetary bodies would be associated with a sudden velocity jump. In large planetary bodies, the change from ice X to the silicate layer will be characterized by an abrupt reduction in velocity.

Plain Language Summary High-pressure ice, such as ice-VII or ice X, is one of the major components in icy satellites, giant planets, and large ocean exoplanets. Experimental studies on the physical properties of high-pressure ice are of particular importance for understanding the internal composition, structure, and dynamic evolution of these planetary bodies. Here, we provide direct experimental constraints on the single-crystal elasticity of salty ice up to 98 GPa at 300 K. The transition from ice-VII to the dynamically disordered phase and then to ice X is characterized by the anomalous variation in all the elastic constants followed by an apparent change in the pressure gradient of the elasticity. These results provide important information for the internal structure of icy planetary bodies.

1. Introduction

Water, a binary compound of hydrogen and oxygen, is essential for the origin and evolution of life in the universe. Due to the low temperature but high-pressure, the outer portion of many planetary bodies, such as Titan and Ganymede, is dominated by water ice (Fortes, 2012; Lammer et al., 2009; Léger et al., 2004; Sohl et al., 2003; Sotin & Tobie, 2004). Giant planets, such as Jupiter and Saturn, are proposed to have a core with a mixture of water ice and rocks at pressures up to tens of Mbar (Guillot, 1999; Militzer et al., 2008). Water ice has a complicated phase diagram with at least 19 solid phases identified by experiments and predicted by theoretical calculations (Bartels-Rausch et al., 2012; Benoit et al., 1996; Salzmann et al., 2009; Wang et al., 2011). Among these solid phases, ice-VII has received extensive research interest. It is expected to exist in moderate to large planetary bodies below the subsurface ocean and interact with the rocky silicates beneath (Léger et al., 2004; Noack et al., 2016; Sotin et al., 2007). Owing to the dynamic movements, ice-VII has also been proposed to be present in the coldest subduction slab in the Earth's mantle (Bina & Navrotsky, 2000). In addition to ice-VII, the largest ocean planets may even have a mantle layer composed of ice X (Journaux et al., 2017; Sotin et al., 2007).

Both Ice-VII and ice X are in the body-centered cubic structure with the space group $Pn\bar{3}m$ (Caracas, 2008; Hemley et al., 1987; Kamb & Davis, 1964). Hydrogen atoms arrange in random positions in ice-VII, while the protons reside at the center position between two oxygen atoms in ice X (Loubeyre et al., 1999). The phase transition boundary between ice-VII and X, crucial for understanding the layered structure of large ocean planets, remains open to debate and was reported to range between 40 and 65 GPa at 300 K (Aoki

et al., 1996; Asahara et al., 2010; Goncharov et al., 1996, 2005; Kuriakose et al., 2017; Loubeyre et al., 1999; Polian & Grimsditch, 1984; Song et al., 1999; Sugimura et al., 2008; Zha et al., 2007). Although X-ray diffraction (XRD) is a powerful tool to study the structure of materials, using it to determine the transition pressure from ice-VII to ice X is difficult because the transition is sluggish and the XRD patterns of these two phases are similar and hard to differentiate at high-pressures (Hemley et al., 1987; Loubeyre et al., 1999; Sugimura et al., 2008). On the other hand, infrared and Raman spectroscopic studies revealed a subtle change in the vibrational spectra associated with the transition from ice-VII to dynamically disordered ice-VII at 53–58 GPa (Aoki et al., 1996; Goncharov et al., 2005; Song et al., 1999). Later XRD experiments identified a weak anomalous volume reduction when ice-VII changes to the corresponding disordered phase (Asahara et al., 2010; Sugimura et al., 2008). In addition to the sudden volume drop, this change in structure was also observed to cause a softening of the longitudinal modulus C_{11} and off-diagonal modulus C_{12} according to Brillouin measurements (Li et al., 2019). Notably, the elasticity can be applied not only to characterize the phase transition of ice at high-pressures but also to provide insights into the internal structure of these icy planetary bodies. However, the elasticity of high-pressure ice in the literature was determined by polycrystalline samples that could develop a strong lattice preferred orientation under compression (Asahara et al., 2010; Kuriakose et al., 2017; Zhang et al., 2019). The obtained elasticity calculated from velocities along the preferred orientation, particularly for ice X, could be biased and contradicts each other (Asahara et al., 2010; Kuriakose et al., 2017; Zhang et al., 2019).

Here, we study the single-crystal elasticity of NaCl-bearing ice (0.5 mol/L, 0.9 mol.% NaCl) using Brillouin scattering up to 98 GPa at 300 K. The presence of NaCl in the deep interior of planetary bodies has been detected in Europa, Ganymede, and Callisto by the Galileo and Cassini-Huygens missions (Dalton, 2010; Saur et al., 2015; Sohl et al., 2010). Water in planetary bodies may react with the chondritic material during accretion and incorporate some amount of salt such as NaCl (Zolotov, 2012). Using a single-crystal sample instead of a polycrystalline sample enables us to provide crucial constraints on the velocity anisotropy of high-pressure ice and track the anomalous softening of elasticity when ice-VII changes to dynamically disordered ice-VII. Single-crystal elasticity of ice X was well determined up to 98 GPa. These results were applied to understand the internal structure of icy planetary bodies.

2. Experiment

A NaCl-H₂O solution was prepared by mixing distilled water with 0.5 mol/L NaCl. This salty aqueous solution was loaded into a BX90 DAC equipped with a pair of diamonds with a 300 or 200- μ m culet (Kantor et al., 2012). Rhenium was used as the gasket material, which was pre-indented to a thickness of 25–35 μ m and drilled with a 120–160 μ m hole in diameter in the center of the indentation. Two ruby spheres were loaded into the sample chamber as the pressure calibrant for Brillouin measurements (Dewaele et al., 2004). To avoid evaporation, the cell was immediately closed and pressurized to 0.1 GPa after the loading. We slowly increased the pressure from 0.1 to $\sim$ 2 GPa to synthesize ice-VII, which can be confirmed by the Raman spectroscopy. Unlike pure ice, we did not detect obvious grain boundaries in our salty ice under the microscope after to the formation of ice-VII (Figure S1). The synthesized ice-VII exhibits strong velocity anisotropies in Brillouin measurements, and was confirmed to be single-crystal using the synchrotron XRD at GSECARS of the Advanced Photon Source (APS), Argonne National Laboratory and BL15U1 of Shanghai Synchrotron Radiation Facility (Figure S2). High-pressure Brillouin measurements were conducted between 4 and 98 GPa at 300 K at the High-Pressure Mineral Physics Laboratory, University of Science and Technology of China (USTC). We also performed XRD measurements for ice up to 80 GPa at 300 K at APS using Pt as the pressure calibrant (Fei et al., 2007).

Brillouin signals were excited by a laser with a wavelength of 532 μ m and a power of 500 mW. Brillouin spectra were recorded by a six-pass Sandercock tandem Fabry-Perot interferometer. The acoustic velocities of ice were calculated from the measured Brillouin frequency shift as

$$v = \frac{\Delta\nu_B \lambda_0}{2 \sin(\theta/2)}, \quad (1)$$

where v is the acoustic velocity, $\Delta\nu_B$ is the measured Brillouin frequency shift, λ_0 is the laser wavelength of 532 nm, and θ is the external scattering angle of 49.3°.

All the high-pressure ice phases studied here are characterized by three independent elastic constants. The C_{ij} s were derived by fitting the measured acoustic velocities following the Christoffel equation (Every, 1980):

$$\left| C_{ijkl} n_j n_l - \rho v^2 \delta_{ik} \right| = 0, \quad (2)$$

where C_{ijkl} is the full elastic tensor, n_j and n_l are the direction cosines in the photon propagation direction, which can be described by the azimuthal angle (θ, χ, ψ) of the sample platelet, ρ is the density, v is the acoustic velocity derived from the Brillouin frequency shift, and δ_{ik} is the Kronecker δ . Since the pressures in the Brillouin measurements were determined using ruby, which was different from the Pt calibrant in our XRD measurements, the densities for analyzing the Brillouin data were determined by a self-consistent method (Speziale & Duffy, 2002). With the obtained single-crystal elasticity, the adiabatic bulk modulus, K_S , and the shear modulus, G , can be calculated as follows:

$$K_S = (C_{11} + 2C_{12}) / 3, \quad (3)$$

$$G_{\text{Voigt}} = (C_{11} - C_{12} + 3C_{44}) / 5,$$

$$G_{\text{Reuss}} = 5C_{44} (C_{11} - C_{12}) / [3(C_{11} - C_{12}) + 4C_{44}], \quad (4)$$

$$G = (G_{\text{Voigt}} + G_{\text{Reuss}}) / 2,$$

where G_{Voigt} and G_{Reuss} are the Voigt and Reuss bounds of G , respectively. The compressional wave velocity, V_P , and shear wave velocity, V_S , were calculated using

$$V_P = \sqrt{(K_S + 4/3G) / \rho}, \quad (5)$$

$$V_S = \sqrt{G / \rho}, \quad (6)$$

The relationship between the pressure and elasticity is described following a modified equation of state (Sata et al., 2002):

$$P = \left\{ P_r - \frac{1}{2} (3K_r - 5P_r) \left[1 - \left(\frac{\rho}{\rho_r} \right)^{\frac{2}{3}} \right] + \frac{9}{8} K_r \left(K'_r - 4 + \frac{35P_r}{9K_r} \right) \left[1 - \left(\frac{\rho}{\rho_r} \right)^{\frac{2}{3}} \right]^2 \right\} \left(\frac{\rho}{\rho_r} \right)^{\frac{5}{3}}, \quad (7)$$

$$K = K_r \left\{ 1 + \frac{1}{2} (5 - 3K'_r) \left[1 - \left(\frac{\rho}{\rho_r} \right)^{\frac{2}{3}} \right] + \frac{27}{8} \left(K'_r - 4 + \frac{35P_r}{9K_r} \right) \left[1 - \left(\frac{\rho}{\rho_r} \right)^{\frac{2}{3}} \right]^2 \right\} \left(\frac{\rho}{\rho_r} \right)^{\frac{5}{3}}, \quad (8)$$

where P_r is the reference pressure, and ρ_r , K_r , and K'_r are the density, bulk modulus, and pressure derivative of the bulk modulus at pressure P_r . The densities at 11.1, 14.3, and 17.1 GPa as well as those at 46, 50.1, and 53.5 GPa were directly constrained by the pressure-density relation in XRD measurements.

Figure 1. Representative Brillouin spectra (a, c, e, g) and acoustic velocities (b, d, f, h) of single-crystal salty ice at high-pressures and 300 K. (a) and (b) At 20 GPa. (c) and (d) At 42 GPa. (e) and (f) At 50 GPa. (g) and (h) At 85 GPa. Black line: experimental data; circles: measured velocities; green, blue, and red lines: fitting results of V_{S1} , V_{S2} , and V_P , respectively.

3. Results

Single-crystal salty ice-VII was synthesized at ~ 4 GPa, which enabled us to collect high-quality Brillouin data (Figure 1 and S3). We have performed two runs of Brillouin scattering experiments. The first run (run 1) was conducted up to 98 GPa at 300 K without annealing, whereas the velocities of single-crystal ice-VII/X in the second run (run 2) were obtained both before and after annealing at 600 K (Figure 1). Adding 0.5 mol/L (0.9 mol.%) NaCl into water which is below the maximum amount of NaCl that can be dissolved in high-pressure ice also helped to grow nice single-crystal ice at high-pressures (Frank et al., 2006). We also performed single-crystal XRD to confirm that the synthesized high-pressure ice was single-crystal. The XRD pattern collected at 60 GPa and 300 K revealed that ice remained in the form of a single crystal, although it was under stress (Figure S2). To evaluate the stress state of our salty ice inside the diamond anvil cells (DACs), we have calculated the differential stress t values up to 79 GPa (Figure S4; Menéndez-Proupin & Singh, 2007; Singh, 1993). The influence of the increased differential stress was considered when evaluating the uncertainties of the obtained elasticity.

Figure 2. Unit-cell volume and elasticity of salty ice at high pressures and 300 K. (a) Pressure-volume relations. Red circles and line: measured unit-cell volumes and fitting results using the third-order Birch-Murnaghan equation of state in this study, respectively; blue circles: salty ice with ~ 1.6 mol.% NaCl (Frank et al., 2006); purple circles: pure ice (Frank et al., 2004); green circles: pure ice (Sugimura et al., 2008); orange circles: pure ice (Hemley et al., 1987). Pressures in previous studies have been recalibrated using the metal pressure scale from Fei et al. (2007) and the ruby scale from Dewaele et al. (2004). (b) Red circles: the difference in volume (ΔV) between the measured XRD data and the fitting results of ice-VII; black lines: a guide to the eye. (c) Single-crystal elasticity. Green, blue, and red circles: C_{11} , C_{12} , and C_{44} in run 1; green, blue, and red solid stars: C_{11} , C_{12} , and C_{44} in run 2 before annealing; green, blue, and red open stars: C_{11} , C_{12} , and C_{44} in run 2 after annealing; lines: fitting results. C_{12} (C_{11}) before annealing (solid star) at 26 GPa (72 GPa) overlaps with the value after annealing, so only open stars can be seen. (d) Aggregated bulk (K_s) and shear (G) moduli. Red circles: K_s ; blue circles: G ; lines: fitting results. Open stars: results in run 2 before annealing; solid stars: results in run 2 after annealing. The orange shade indicates the pressure range where C_{12} deviates from C_{44} , while the blue shade shows the pressure range for the existence of dynamically disordered ice-VII.

The shear modulus C_{44} and off-diagonal modulus C_{12} of our salty ice-VII followed the Cauchy relations with values nearly equal to each other up to 42.4 GPa except at 11.1 and 14.3 GPa (Figure 2 and Table S1). Sudden drops in the longitudinal (C_{11}), off-diagonal (C_{12}), and bulk (K_s) moduli occurred between 42.4 and 46 GPa, which indicates the beginning of the change from ice-VII to the corresponding dynamically disordered phase (Figure 2). In contrast, this change hardly influences the shear moduli C_{44} and G (Figure 2). Our pressure-volume (P - V) data obtained from XRD studies also show a sudden drop in the unit-cell volume across the ice-VII to disordered ice-VII transition (Figures 2 and S5). Due to the overlap of the ice longitudinal modes with diamond shear modes in the Brillouin spectra, the elasticity of the high-pressure ice cannot

be constrained between 54 and 64 GPa at 300 K (Figure 2). Above 64 GPa, we observed an apparent change in the pressure dependence of all the elastic moduli up to 98 GPa, indicating that the disordered ice-VII ice inside our DACs had completely transformed into the high-pressure phase at 64 GPa.

4. Discussion and Implication

4.1. Single-Crystal Elasticity of High-Pressure Ice

Single-crystal elasticity of ice was determined up to 98 GPa at 300 K. We noted that C_{44} has a value nearly equal to C_{12} followed the Cauchy relations up to 42.4 GPa except at 11.1 and 14.3 GPa (Li et al., 2019; Shimizu et al., 1995). The deviation of C_{12} from C_{44} at 11.1 and 14.3 GPa could be caused by ordering of the dipole following the Ising model or hydrogen bond symmetrization which needs to be further investigated by future studies (Figure 2; Loubeyre et al., 1999; Meier et al., 2018). Such deviation in C_{12} and C_{44} between 10 and 20 GPa has also been observed in pure single-crystal ice-VII in a previous study (Li et al., 2019). An anomalous softening in both C_{11} and C_{12} occurred between 42.4 and 46 GPa, consistent with the anomalous change in the unit-cell volume in the XRD measurements (Sugimura et al., 2008). The anomalous change in the elastic moduli and unit-cell volume should be caused by the change from ice-VII to the dynamically disordered phase.

Above 64 GPa, single-crystal elasticity of ice exhibits an apparent change in the pressure dependence, indicating that the dynamically disordered ice-VII has transformed to a new phase. Some experimental and theoretical studies proposed that the dynamically disordered ice-VII would first transform into ice X' at ~60 GPa, and then changed to ice X at ~110 GPa (Benoit et al., 1998). However, we cannot tell whether the ice in our experiments is ice X' or ice X and thus still use ice X to represent the high-pressure ice between 64 and 98 GPa. Previous Raman measurements and theoretical study suggested that the transition pressure from ice-VII to ice X can be shifted to a higher pressure by 20–30 GPa with the addition of salt (LiCl or NaCl; Bove et al., 2015; Bronstein et al., 2016). However, we did not note an obvious change in the transition pressure potentially due to the low NaCl concentration in our ice.

Due to the difficulty of synthesizing single crystals, the single-crystal elasticity of ice X has only been determined using polycrystalline samples (Figure S6; Kuriakose et al., 2017; Zhang et al., 2019). The obtained elasticity of ice X in the literature is clearly different from our results and could be biased by the use of velocities along the preferred orientations because compression can produce a strong lattice preferred orientation of ice inside DACs (Figure S6; Asahara et al., 2010; Kuriakose et al., 2017; Zhang et al., 2019). More importantly, all the elastic constants determined from polycrystalline ice did not show any anomalous change from ice-VII to ice X but continuously increased with pressure up to 100 GPa (Figure S6; Kuriakose et al., 2017; Zhang et al., 2019). Although Asahara et al. (2010) observed a change in the pressure dependence of K_S and V_P across the transition from ice-VII to X, most previous studies showed that the elasticity moduli and sound velocity of ice X were indistinguishable from those of ice-VII (Figures S7 and S8) (Ahart et al., 2011; Kuriakose et al., 2017; Zhang et al., 2019). Here, we provide the direct experimental constraints on the single-crystal elasticity of ice X up to 98 GPa at 300 K and depict the change in elasticity across the phase transition from ice-VII to ice X (Figure 2). All the elastic moduli of ice X exhibit a stronger dependence on pressure than those of ice-VII, in contrast to the previous results in which polycrystalline samples were used (Figures S6, S7 and S8; Kuriakose et al., 2017; Zhang et al., 2019).

Addition of NaCl was noted to lower the unit-cell volume of the high-pressure ice (Figure 2; Frank et al., 2004, 2006; Hemley et al., 1987; Sugimura et al., 2008). For a better comparison, we have recalculated the pressures in previous studies using a self-consistent pressure scale in Fei et al. (2007) and Dewaele et al. (2004). The presence of Na^+ and Cl^- can cause a partial ordering of the protons by interionic attractions (Na^+ with O and Cl^- with H) in ice-VII based on a previous Raman study (Frank et al., 2006). This may lead to the reduction of the unit-cell volume compared to the pure ice, which is in contrast to the influence of LiCl on the unit-cell volume of ice (Klotz et al., 2009, 2016).

Figure 3. Velocity anisotropy of salty ice at high-pressure and 300 K. (a) Maximum compressional wave anisotropy (A_P). (b) Shear wave splitting (A_S^{PO}). Red line: salty ice in this study; purple line: ice obtained from a polycrystalline sample (Zhang et al., 2019); blue line: ferropericlase (Fp; Fan et al., 2019; Jackson et al., 2006; Jacobsen et al., 2002; Marquardt et al., 2009; Sinogeikin & Bass, 2000; Yang et al., 2016); orange line: bridgmanite (Brg; Kurnosov et al., 2017; Wentzcovitch et al., 2004); green line: cubic CaSiO₃-perovskite (Ca-Pv) at 580 K (Kawai & Tsuchiya, 2015); black vertical lines: error bars. The blue shade shows the pressure range for the existence of dynamically disordered ice-VII.

4.2. Velocity Anisotropy

Ice develops a strong lattice preferred orientation under stress (Asahara et al., 2010; Kuriakose et al., 2017). The single-crystal elasticity is essential to model the velocity distribution of ice in space and understand the potential anisotropic structure of planetary bodies. With the obtained single-crystal elasticity, we calculated the maximum shear wave splitting [$A_S^{PO} = (V_{S2} - V_{S1}) / V_{Savg}$] and azimuthal anisotropy of the compressional wave [$A_P = (V_{Pmax} - V_{Pmin}) / V_{Pavg}$] up to 120 GPa at 300 K (Figure 3 and supporting information). At 4 GPa and 300 K, the A_S^{PO} and A_P of ice-VII are 18% and 41%, respectively. An increase in pressure leads to a substantial increase in the A_S^{PO} and A_P of ice-VII (Figure 3). A previous experimental study predicted continuous increases in both the A_S^{PO} and A_P of ice up to 100 GPa at 300 K because the phase transition from ice-VII to ice X had no detectable effect on the elasticity and sound velocity (Zhang et al., 2019). Here, we show that the change from ice-VII to dynamically disordered ice-VII can cause a sudden jump in A_P but a softening of A_S^{PO} (Figure 3). Further increasing the pressure leads to a weak decrease in the A_P of ice X, whereas A_S^{PO} is independent of the pressure variation. The computed A_S^{PO} and A_P of ice-VII are much greater than the values estimated in the literature using polycrystalline samples, yet the anisotropies of ice X are lower (Zhang et al., 2019).

4.3. Velocity of Ice Compared to Silicates

Models as well as results from missions such as Galileo and Voyager reveal that icy satellites and ocean exoplanets are composed of an icy outer shell on the top of a rocky silicate mantle or even a silicate core (Fortes, 2012; Léger et al., 2004; Noack et al., 2016; Sohl et al., 2003; Sotin et al., 2007; Sotin & Tobie, 2004). Comparing the sound velocity and anisotropy of ice with those of typical silicates provides new insights into the layered structure of icy satellites and ocean exoplanets. Here, we show that the A_S^{PO} and A_P of salty ice-VII and ice X are significantly greater than those of typical silicates up to 120 GPa at 300 K (Figure 3). Since ice easily develops a strong lattice preferred orientation under compression (Asahara et al., 2010; Kuriakose et al., 2017), the outer shell of icy satellites and ocean exoplanets could exhibit strong anisotropy in velocity, much greater than that of the silicate mantle or core beneath.

Figure 4. Sound velocities of salty ice a at high pressure-temperature. (a) V_P and V_S of ice at high pressure-temperature. Solid lines: at 300 K; dashed lines: at 600 K; short dashed line: at 920 K. (b and c) V_P and V_S of ice and silicates at 300 and 920 K, respectively. Red lines: ice in this study; blue lines: ferropericlase (Fp; Fan et al., 2019; Jackson et al., 2006; Jacobsen et al., 2002; Mao et al., 2011; Marquardt et al., 2009; Sinogeikin & Bass, 2000; Wu et al., 2013; Yang et al., 2016); orange lines: bridgmanite (Brg; Kurnosov et al., 2017; Li & Zhang, 2005; Murakami et al., 2007, 2012); green lines: tetragonal CaSiO_3 -perovskite (Ca-Pv) at 300 K and cubic Ca-Pv at 900 K from Gréaux et al. (2019) (Gréaux et al., 2019; Kurashina et al., 2004); black vertical lines: error bars. The blue shade shows the pressure range for the existence of dynamically disordered ice-VII.

We further modeled the velocity of ice at 300, 600, and 920 K up to 120 GPa, respectively, and compared with silicates (Figures 4 and S9). Thermal expansion coefficient (α) of ice-VII and ice X were assumed to be the same as that of pure ice (Fei et al., 1993; Frank et al., 2004; Sugimura et al., 2010, 2012). Due to lack experimental constraints, temperature derivative of the shear modulus of ice-VII was treated to be half of the temperature derivative of the bulk modulus and ranged between 0.35 and 0.45 GPa/K (Fei et al., 1993). Ice X was assumed to have the same temperature derivative of the shear modulus as ice-VII. Our modeling has shown that both the compressional (V_P) and shear wave (V_S) velocities of ice-VII are much lower than those of silicates at the investigated temperatures, but the difference in V_P and V_S between ice-VII and silicates dramatically decreases with increasing pressure because the velocity of ice-VII shows a stronger dependence on pressure (Figure 4). As a result, the transition from the icy outer shell with ice-VII as the dominant phase to the silicate layer beneath moderate-size icy satellites will lead to a sudden jump in velocity.

Large ocean exoplanets may also have a mantle layer composed by ice X (Journaux et al., 2017). At 300 and 600 K, the change from ice-VII to the corresponding dynamically disordered phase results in a softening of V_P but hardly affects V_S . A further transition from the dynamically disordered phase to ice X leads to an apparent change in the velocity gradient. In this case, when the temperature in a large ocean exoplanet is very low, the phase change from ice-VII to the dynamically disordered phase and subsequently to ice X will thus generate a velocity discontinuity and separate the outer shell into two icy layers. But in most cases, when the pressure is as large as 40–60 GPa, temperature in the large ocean exoplanets will be greater than 920 K (Sotin et al., 2007). The dynamically disordered ice-VII will no longer exist, and ice-VII will directly transform into ice X (Sugimura et al., 2012). Here we showed that both the V_P and V_S of ice X will become greater than those of silicates above 80–100 GPa at 920 K. As a result, the ice X to silicate layer transition will be characterized by an abrupt reduction in velocity.

In summary, we have determined the single-crystal elasticity of high-pressure salty ice up to 98 GPa at 300 K. Both longitudinal (C_{11}) and off-diagonal moduli (C_{12}) exhibit an anomalous softening from 42.4 to 64 GPa, which is associated with the presence of the dynamically disordered ice-VII. Further transition to ice X leads to an apparent change in the pressure dependence of the elastic moduli. Incorporation of this amount of NaCl can cause an apparent decrease in the unit-cell volume of ice-VII but has a negligible effect on the elasticity of ice-VII. Using the obtained elasticity data, we have compared the velocity and velocity anisotropy of high-pressure ice with typical silicates, including bridgmanite, ferropericlase, and CaSiO_3 -perovskite. High-pressure ice exhibits a much greater velocity anisotropy than these silicates at high pressures. Meanwhile, our modeling reveals that the boundary between the ice-VII layer and the silicate

mantle or core in moderate-size icy planetary bodies would be associated with a sudden velocity jump. In large planetary bodies, the change from ice X to the silicate layer will be characterized by an abrupt reduction in velocity.

Conflicts of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Experimental data for Figure 2 are listed in Tables S1 and S2. A more detailed information of the experimental results and methodology are also available in the supplementary material. All the modeling is easily reproducible and described in detail in the supplementary material. They can also be downloaded online (<https://zenodo.org/record/4433433>).

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