HUGONIOTS AND SHOCK-MELTING CRITERIA FOR SOLID AND POROUS H_2O ICE.

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Introduction. Knowledge of the dynamic response of planetary minerals such as H_2O ice is required to model and interpret mutual collisions and impact craters. The Hugoniot of H_2O ice describes the dynamic strength and possible shock-compressed states, which determine the mechanical and thermodynamic work done during an impact event. Previous studies [1, and references within] of the shock properties of ice were centered at ~263 K for terrestrial applications. Because ices on most planetary surfaces exist at ambient temperatures much below 263 K, we conducted a detailed study of the shock response of solid ice Ih at 100 K and ~40 % porous ice at ~150 K to derive Hugoniots that are applicable to most of the solar system.

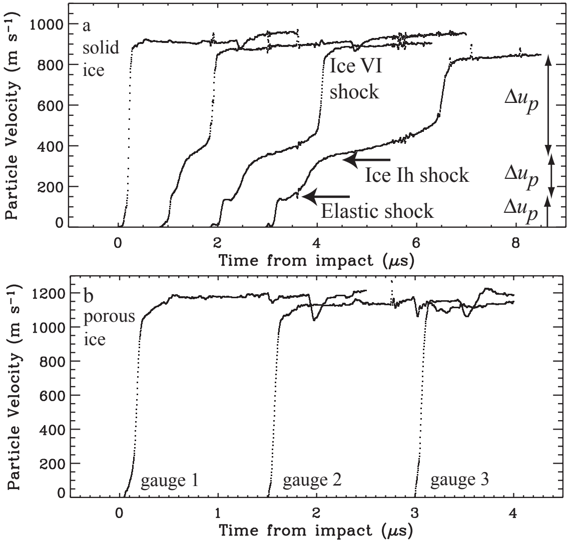

Figure 1. a. Particle velocity vs. time gauge records measured at 3-mm intervals within solid ice target subject to 1473 m s^{-1} impact by polycarbonate projectile producing 3-wave shock front and 2.1 GPa peak pressure. b. Records from 1572 m s^{-1} impact to 1.4 GPa in 40 % porous ice.

Experimental Method. Shock wave profiles, representing Lagrangian particle velocity vs. time (Fig. 1), were integrated to yield shock states (stress and volume) [2-5]. Target assemblies, consisting of 2 thermocouples and 3 or 4 electromagnetic gauges placed between 3-mm thick ice discs, were hung within a planar magnetic field and cooled by liquid nitrogen spray (Fig. 2). Impact-induced particle motion generated voltage across the gauges, which was recorded by 500 MHz oscilloscopes. Solid ice targets were cored from clear carving ice then polished. Density of porous targets, molded from crushed ice grains sifted to 180-355 µm, was determined from measured mass and volume.

Solid Ice Results. The wave profiles record two- and three-wave shock fronts (e.g., Fig. 1a), where each wave represents a different shock process. The present (100 K) and previously published (263 K) ice data are combined to derive five distinct regions on the ice Hugoniot: elastic shocks in ice Ih, ice Ih deformation shocks, and shock transformation to ices VI, VII and liquid water. The Hugoniot is expressed as linear fits between shock velocity, U_S, and the jump in particle velocity, Δu_p, for each wave in the shock front. $U_S - u_p$ data are transformed to pressure-volume via the Rankine-Hugoniot (RH) equations [6]. From the use of Δu_p rather than the more common absolute particle velocity, a single set of equations may be used to define both the 100 and 263 K Hugoniots.

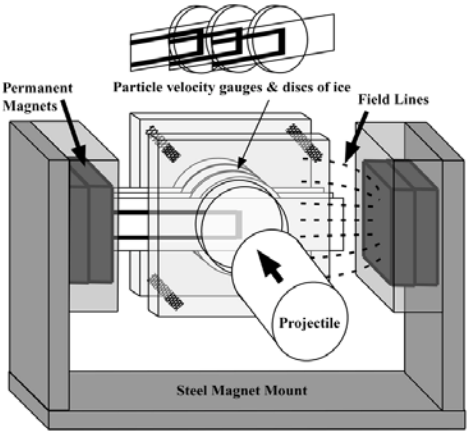

Figure 2. Sketch of particle-velocity gauge method for measuring Hugoniot states. U_S was determined from wave arrival time at each gauge. u_P was calculated from voltage signal, E, using Faraday's law, $u_P = E/(LH)$, gauge length L, and magnetic field strength H.

The Hugoniots are constructed in segments. First, the elastic shock region is derived from the RH equations and the zero-pressure volume. Then, the mean elastic shock is used as the initial condition for the RH equations to describe the second region, and so on. The differences between the 100 and 263 K Hugoniots (Fig. 3) arise from: (1) the initial volume dependence on temperature; (2) the temperature-dependent magnitude of the mean elastic shock, σ_E; (3) the presence of an ice Ih transition shock preceding the ice VI transformation shock on the 100 K curve (forming 3-wave shock profiles, Fig. 1a, which are not observed at 263 K). On the 100 K Hugoniot, shocks between 2.2 and 5.5 GPa have two-wave profiles: an elastic shock and ice VII transformation shock. Above 5.5 GPa, transformation to liquid water occurs via a single wave shock front.

Table 1. Shock equation of state, $U_S = c + s\Delta u_P$, used to calculate solid ice Hugoniots (Fig. 3). For 100 K: $\rho_0 = 932$ kg m^{-3}, $\sigma_E = 0.55$ GPa, ice Ih cusp at 1.15 GPa. For 263 K: $\rho_0 = 918$ kg m^{-3}, $\sigma_E = 0.2$ GPa.

Hugoniot Region	c (m s^{-1})	s …	Δu_P range (m s^{-1}) Min	Max
1. Elastic	3610 (± 61)	0.92 (±.63)	0	175
2. Ice Ih	3000 (±100)	1.00 (±.80)	0	230
3. Ice VI	388 (± 78)	2.61 (±.14)	100	850
4. Ice VII	1200 (±140)	1.46 (±.11)	600	1540
5. Liquid	1700 (±130)	1.440 (±.035)	1590	…

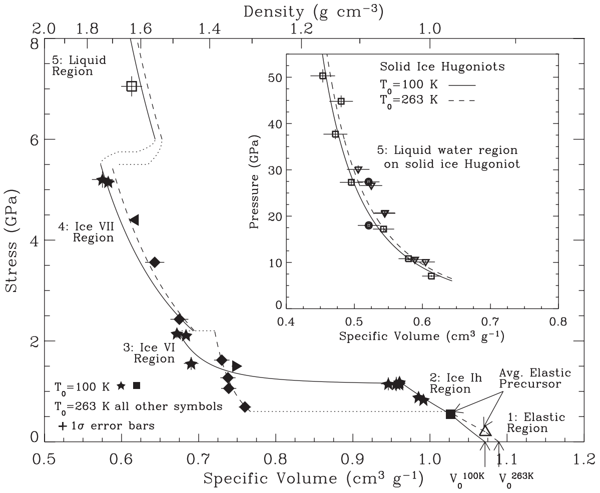

Figure 3. Solid ice Hugoniots centered at 100 K (solid) and 263 K (dashed). Dots connect the 5 Hugoniot regions.

Criteria for shock-induced melting. We calculate temperature and entropy along the 100 and 263 K Hugoniots and derive critical pressures required to induce incipient melting (IM) and complete melting (CM) upon isentropic release. Along the 100 K Hugoniot, the critical pressures are 4.5 GPa for IM and ~5.5 GPa for CM. Whereas along the 263 K Hugoniot, pressures of only 0.6 and 3.7 GPa are required for IM and CM, respectively. On account of the >40 % density increase upon transformation from ice Ih to ices VI and VII, the critical shock pressures required for melting are factors of 2 to 5 lower than earlier predicted [7, 8].

40 % Porous Ice Results. Single-wave shock fronts (Fig. 1b) compressed porous ice to solid density at pressures between 0.25-1.4 GPa. For 40-45 % porous ice, combined ~150 K (this work) and ~250 K [9] data are fit by $U_S = -50(\pm110) + 1.94(\pm.11)u_P$ (m s^{-1}) (Fig. 4). The porous ice Hugoniot is multivalued between 0.85-1.1 cm^3 g^{-1}, indicating phase transformations, as seen in solid ice. The shock states reach a minimum volume of ~0.8 cm^3 g^{-1} near 0.5 GPa. Then, Hugoniot states increase in volume above 1 GPa and decrease again at the 3.5 GPa point.

Criteria for shock-induced melting. The increase in energy with the ~40 % increase in density easily surpasses the latent heat of melting. The volume increase above ~2 GPa signals that liquid water is present in the shock state. All ~250 K data are denser than the solid ice Hugoniot, indicating incipient melting at shock pressures as low as 0.14 GPa. At ~150 K, shock pressures between 0.3-0.5 GPa are required for IM.

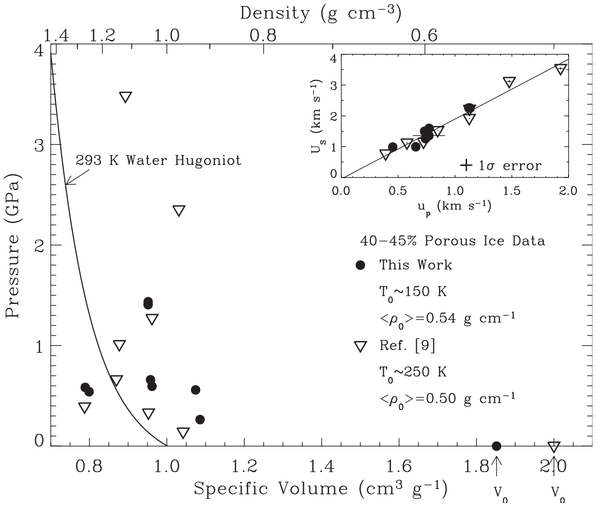

Figure 4. Shock data on ~40 % porous ice compared to liquid water Hugoniot.

Conclusions. Hypervelocity impact cratering on icy planetary surfaces and mutual collisions between porous cometesimals will result in abundant shock-induced melting throughout the solar system. The new H_2O Hugoniots show that the pressures required for shock-induced melting during collisions are even lower than previously assumed. The equations of state for H_2O used in impact simulations should be updated to include the newly defined low-pressure response of solid and porous ice. For compressions above 5.5 and ~3 GPa, solid and porous ice Hugoniots may be modeled as "porous" liquid water, respectively [10]. Below ~3 GPa, more data are required to fully characterize porous ice, and the conditions for incipient melting are highly temperature and density dependent.

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