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"Impact and Collisional Processes in the Solar System"

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Specific science questions

The following were the motivating questions that guided our experimental program.

a. Cratering in Porous Materials

- Collisional processing in the outer solar system: We believe that comets are the most pristine material in the solar system, but before a new comet enters the inner solar system it has already been subject to many relatively low velocity collisions (~1 km/s), and the nucleus is probably a fragment of a collision between larger bodies [Davis and Farinella, 1997]. What effects do collisions within the Kuiper belt have on the state of the material in a comet nucleus? How much thermal processing occurs? What does this imply about the composition of comet nuclei?
- Impacts and penetrators into comets: Rosetta, Deep Impact, and future comet missions including comet nucleus sample return must understand penetration and cratering into porous icy silicate materials. What is the dynamic strength of icy silicate materials with high porosity? Comets have extremely low gravity; are craters dominated by gravity or strength on these bodies?
- Water and Ice on Mars: Rampart craters on Mars appear to have fluidized ejecta blankets. What is the composition of the ejecta from craters in porous ice-silicate mixtures? What are the depths of vaporization and melting of the ice compared to the depth of the crater? Could the cratering event have melted enough water to sustain a fluidized ejecta blanket? What may we infer about the presence of water on Mars?

b. Impact damage

- Meteorite Porosity: Consolmagno and Britt [1998] found that 25% of ordinary chondrites have porosities >10% even though they had experienced shock pressures above 10 GPa. Shocks do collapse large pore spaces, but impacts into brittle materials may create porosity by creating fractures (dilatancy) [Brace et al., 1966]. Given the material properties of chondrites, what is the range of porosity generated from multiple impact events? Can we explain the observed porosity in the meteorite collection?
- Terrestrial Impact Craters: The terrestrial geophysics community has gathered a substantial dataset on impact damage under terrestrial craters (e.g. Pilkington and Grieve [1992]). What is the relationship between impact damage and projectile parameters? What can we learn about the nature of the projectile (e.g. cometary vs. asteroidal origin) by analyzing impact damage information as well as crater size and shape? What can we predict about impact damage beneath the surfaces of other planets?
- Spallation and Meteorite Delivery: How much impact damage occurs in the spallation zone of an impact? How does this damage relate to the damage beneath the crater? At what level of pre-existing damage does spallation cease to produce large fragments? Is this consistent with the current models of meteorite delivery and analysis of the shock history of Martian meteorites?

c. Impact Volatilization

- K/T Impact Vapor Plume: One of the mechanisms proposed for the K/T extinctions involves SO_2 and SO_3 injected into the stratosphere, forming sulfuric acid aerosols, and causing global cooling from a decrease in solar insolation [Brett, 1992]. SO_2 survives longer than SO_3 in the stratosphere, so if most of the sulfur forms SO_2, the global effect on climate is maximized. How much of the K/T impact vapor was SO_3 vs. SO_2?

Research

B.1. Cratering in porous materials

In the past year, we have successfully developed the techniques necessary to conduct impact experiments on ice at very low temperatures. We employ the method of embedding gauges within a target to measure the shock wave and material properties. This means that our data are not model dependent; we directly measure the essential parameters needed for numerical simulations of impact cratering. Our preliminary experiments are published in Stewart and Ahrens [2000]. Since then we have developed a new method for temperature control of icy targets that ensures temperature equilibrium throughout a porous target. Graduate student, Sarah Stewart-Mukhopadhyay, is leading the work on ices and porous materials as the main thrust of her thesis research.

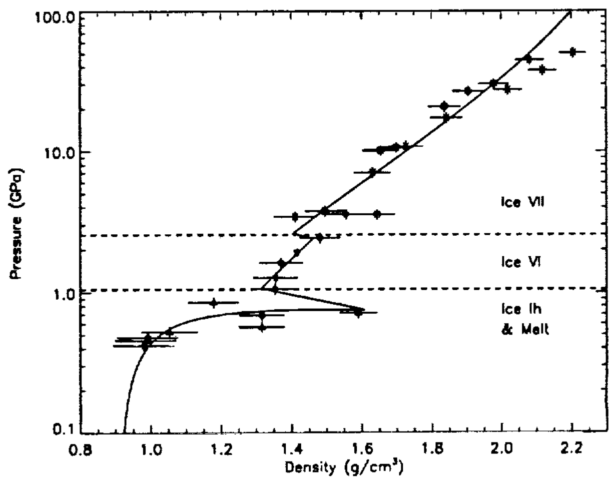
We have experience working with ice and ice-silicate mixtures: e.g. "Low-velocity impact craters in ice and ice-saturated sand with implications for martian crater count ages" Croft et al. [1979], "Identification of ice VI on the Hugoniot of ice I_h" Gaffney and Ahrens [1980], "Fragmentation of ice by low velocity impact" Lange and Ahrens [1981], "The dynamic tensile strength of ice and ice-silicate mixtures" Lange and Ahrens [1983], and "Impact experiments in low-temperature ice" Lange and Ahrens [1987]. Our previous work has focused on icy materials with no porosity, and we propose to extend our research to include porous ice and porous ice-silicate mixtures. There is little shockwave data for porous ice [Bakanova et al., 1976; Furnish and Boslough, 1996], and none of the data was acquired under conditions applicable to the outer solar system. The solid ice Hugoniot is only defined for initial temperatures above –20C [Gaffney, 1985].

Our program uniquely measures the properties of ice at temperatures directly applicable to the solar system. Previous experiments were conducted at ambient temperatures soon after removing the target from a cold environment, usually just below freezing, or in a room just below freezing (e.g. Arakawa [1999]). Since ice has an extremely complicated phase diagram, see Figure 1, it is important to conduct experiments at lower temperatures to determine the true outcome of impacts in the outer solar system (e.g. Gaffney and Matson [1980]).

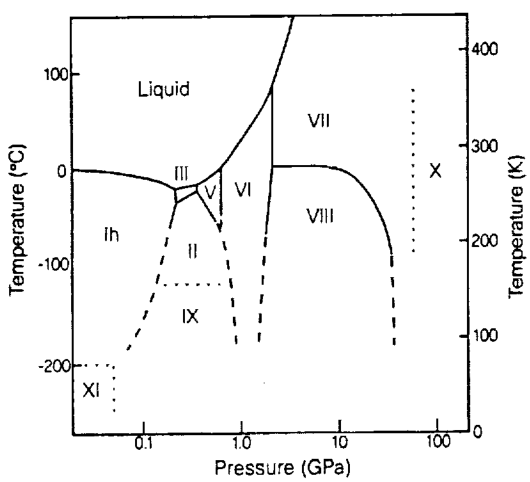
This research is complementary to other programs on icy materials. Other researchers currently focus on measuring the effects of the shock wave using rear surface particle velocities (e.g. Arakawa [1999], Arakawa et al. [2000]) or on measuring macroscopic properties such as crater size, ejecta distribution and disruption energies (e.g. Ryan et al. [1999]). The method of measuring free particle velocities at the rear of the target is difficult to extend to porous materials. To infer material properties from the macroscopic properties of a crater, numerical simulations must be employed to fit the observed crater size and disruption conditions. Cratering experiments are essential to form scaling laws in the laboratory strength regime, but it is difficult to extend them to the gravity regime. Our work focuses on the inherent material properties by measuring the shock wave directly; this complements the macroscopic observations and immediately provides the parameters necessary to extend this research to the gravity regime.

Our numerical simulations of impacts in porous ice under very low gravity conditions, such as found on comets, show that the final crater size and shape is very dependent on the dynamic strength of the material. There is some controversy over whether or not solid ice has a Hugoniot Elastic Limit (HEL), the maximum dynamic stress the material may bear before yielding. The data, based primarily on experiments near –10C, have alternatively been interpreted as a phase change (melting) instead of an HEL. This demonstrates the importance of conducting experiments at the appropriate temperature to understand the ice phases involved.

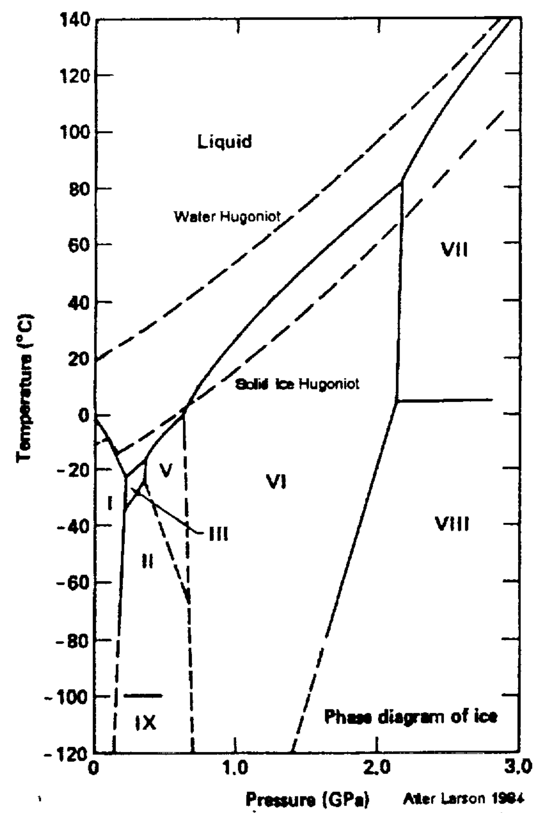
Until our research, there has never been a measurement of the HEL in porous ice and it was assumed that porous ice had no inherent dynamic strength. We have discovered a small HEL in porous ice. We are conducting further experiments to verify this detection and understand its porosity and temperature dependence as well as the effects of thermal processing (sintering).



(a) Solid Ice Hugoniot centered at −10C, 1 bar. Data from Gaffney [1985], 3σ error bars.



(c) H2O Phase Diagram [Lobban et al., 1998]



(b) (after Larson [1984])

FIGURE 1. Importance of initial temperature on shock Hugoniot of H_2O. (a) The different segments of the ice Hugoniot centered at −10C correspond to the shocked phase as illustrated in (b). (b) An estimate of the path of the ice Hugoniot shown in (a). (c) H_2O phase diagram down to absolute zero. The importance of the initial temperature is evident from the many different phases of ice that can be reached by moderate shock pressures.

B.2. Impact-induced damage

In the past year we have conducted more recovery experiments to measure sound velocity deficits in shock-damaged materials, and we are working on relating the deficits to the impact conditions: impact velocity and projectile mass. Figure 2 shows P-wave speed profiles beneath craters created with spherical projectiles at the impact velocities indicated. Ultrasonic velocities are a good indicator of impact damage because the wave speed is a strong function of the crack or pore density in the material (e.g. O'Connell and Budiansky [1977]). Graduate student Kaiwen Xia, has participated in this project.

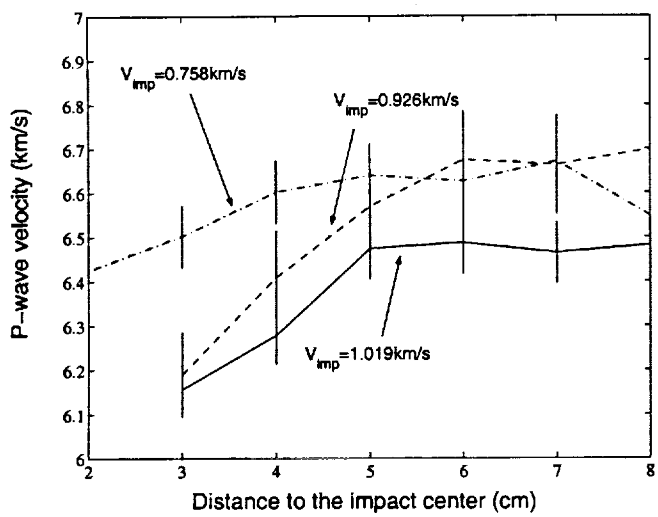


Figure 2. P-wave velocities in San Marcos gabbro. The sound speed is measured in targets impacted with a spherical Al projectile at the noted velocity. The data shown are from directly beneath the center of the crater. The sound speed deficit near the crater indicates impact damage. The higher the impact velocity, the lower the wave speed, and the larger the impact damage. The regions further from the crater remain undamaged and retain the pre-impact wave speeds. The difference in undamaged sound velocities between the samples is attributed to heterogeneities in San Marcos gabbro. 3σ error bars.

There is currently very little work in this area in the geophysics community whereas headway has been made in the ceramics community (e.g. Camacho and Ortiz [1996]). Our previous work includes: "Mechanical properties of shock-damaged rocks" He and Ahrens [1994] and "Stress wave attenuation in shock damaged rock" Liu and Ahrens [1997]. Our examination of the literature on terrestrial impact craters (e.g. Pilkington and Grieve [1992]) shows that there seems to be a log-log relationship between the crater diameter and the depth of the impact-damaged zone, see Figure 3. We are quantifying this relationship based on the impact physics and the new insight gained from the research on impact damage in ceramics. Our program on impact damage in geologic materials will allow the planetary science community to quantify the effects of cratering in another dimension: below the surface. We also expect to conduct multiple impact experiments to understand cratering in previously damaged materials.

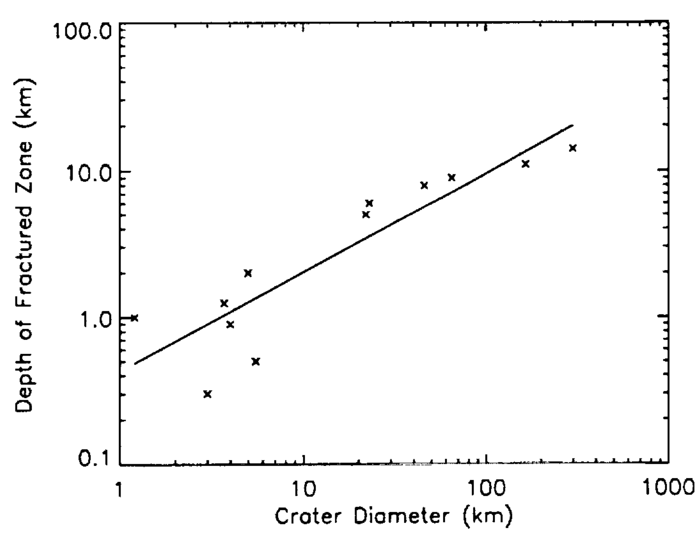


Figure 3. Damaged zones beneath terrestrial craters inferred from seismic refraction measurements. Using published data, we have estimated the relationship between the crater diameter and the depth of the damaged zone for a dozen terrestrial craters. This empirical relationship has not yet been explained quantitatively. The least squares fit is $\log H\,(\text{km}) = -0.367 + 0.673 \log D\,(\text{km})$ where D is the crater diameter and H is the depth of the damaged zone.

B.3. Impact volatilization and speciation

In the past year, we have revisited the question of how much vapor was produced from the K/T impact [Gupta et al., 2001]. New analysis of data on shock vaporization of anhydrite [Yang and Ahrens, 1998] has produced revised values for the shock pressures required for incipient and complete vaporization. Together with a revised size for the transient diameter of the Chicxulub crater [O'Keefe and Ahrens, 1999], the amount of sulfuric vapor that could have produced sulfuric acid aerosols has been decreased to 11-39 gigatons, compared to 200 gigatons estimated by Pope et al. [1997]. Assuming a maximum production of sulfuric acid aerosols, the global temperature decreased 12-19K for about a decade, compared to the 5-31 K drop for 12 years reported by Pope et al. [1997]. Since the Earth's surface temperature during the K/T epoch was 18-20K warmer than present values (e.g. Savin and Yeh [1981]), this cooling event could not produce global freezing conditions at the Earth's surface.

Even with this new result, the global effects of the K/T impact cannot be accurately assessed without an understanding of the speciation in the vapor plume. If most of the sulfur ends up in SO_2, the global impact may still be considerable and long-lived. We have been developing a method to detect impact vapor species using a time-of-flight mass spectrometer (TOFMS). Our collaboration with Professor J. Beauchamp and his graduate student in chemistry and chemical engineering, Daniel Austin, has led to the successful development of an impact vapor TOFMS under a PIDDP grant. We have been analyzing speciation data collected using laser vaporization of minerals, but it is not clear how to use this data to understand impact-induced vaporization. We propose are continuing our investigation of impact speciation by directly measuring species in impact vapor plumes.

Another application of impact volatilization is the accretion of the Earth and the role of serpentine, which is illustrated by the following reactions:

$$\underset{\text{(serpentine)}}{Mg_3Si_2O_5(OH)_4} \rightarrow \underset{\text{(forsterite)}}{Mg_2SiO_4} + \underset{\text{(enstatite)}}{MgSiO_3} + \underset{\text{(water)}}{2H_2O} \quad (1)$$

$$MgSiO_3 + Fe + H_2O \rightarrow \frac{1}{2}\, Fe_2SiO_4 + \frac{1}{2}\, Mg_2SiO_4 + H_2 \quad (2)$$

(enstatite)(iron)(water) (fayalite) (forsterite) (hydrogen)

Under the present grant, we have previously conducted a fairly detailed study of reaction (1), which included determining the Hugoniot of serpentine (e.g. Tyburczy [2001]; Tyburczy et al. [1991]; Tyburczy [1990], Ahrens [1990]). We also note that serpentine is one of the most abundant hydrous minerals in primitive meteorites [*Lange et al.*, 1985; *Ringwood*, 1979]. It has been inferred that serpentine was abundant in planetesimals and was the carrier of most of the water to the terrestrial planets. Abe and Matsui [1985] directly utilized the Caltech impact devolatilization data on serpentine to define their model of a super greenhouse overlying a magma ocean during accretion of the Earth, a condition that prevailed for a large fraction of the accumulation of the planet. After about 0.26 of the final mass of the Earth had accreted, further impacts devolatilized creating a thick hydrosphere.

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