LASER SIMULATION OF HIGH P-T PLANETARY PROCESSES.

J. L. Remo[1,2,3,4], R. G. Adams[4], M. I. Petaev[1,2], S. B. Jacobsen[1], and D. D. Sasselov[2,3] [1]Department of Earth and Planetary Sciences, Harvard University, Cambridge MA, [2]Harvard-Smithsonian Center for Astrophysics, Cambridge MA, [3]Department of Astronomy, Harvard University, Cambridge MA, [4]Sandia National Laboratories, Albuquerque NM.

Introduction: During and after planet formation, many planetary materials experienced physical and chemical transformations at very high pressures and temperatures that are beyond the limits of most modern experimental techniques. In particular, the behavior of metal relative to silicate is of special interest and may be studied by laboratory shock experiments [1, 2, 3]. The SNL (Sandia National Laboratory) pulsed laser facility is capable of subjecting solid materials to very high temperatures and pressures, comparable to those that may have existed in the deep mantle after the putative Moon-forming giant impact. These conditions have been modeled by [4]. The main objective of this project is to use the SNL pulsed laser facility for experimental studies of the behavior of planetary materials in high-energy density environments that existed during the formation of the Earth. Here we report the measurements of Equation of State (EoS) for different solid materials and mixtures, with the emphasis on metal-silicate interaction during planetary formation. The results of this study can also be used for (i) evaluation of some chondrule-forming mechanisms - high intensity radiation produced by the lasers may simulate some energetic events such as solar flares in the early solar nebula; (ii) establishing equations of state for conditions that may exist in the interior of extrasolar “Super-Earths” [5]; (iii) protection against asteroid impacts on Earth.

Experimental Approach and Setup: 0.15 - 1 ns pulses of the Sandia NLS (1064 nm) and ZBL (527 nm) lasers (maximum energy outputs 300 GW/cm^2 to ~ 10 TW/cm^2, respectively), focused to 1-2 mm spots, were used to generate a shock wave on the surfaces of large mono- and polymineralic targets in a vacuum chamber (<10^{-4} torr).

The experimental setup (Fig. 1) allowed an automatic detection of the arrival of the shock wave, monitoring its propagation through the target, and precise measurement of the target rear surface displacement due to the momentum coupling. The real-time electro-optical recordings of the shock wave propagation coupled with the known irradiation intensity, were used to calculate the front surface radiation pressure (P) and temperature as well as target parameters such as shock wave and particle velocities, rear surface Hugoniot hydrodynamic pressure (P_H), front to rear surface pressure gradient, dP/dz, and momentum coupling coefficient, C_m.

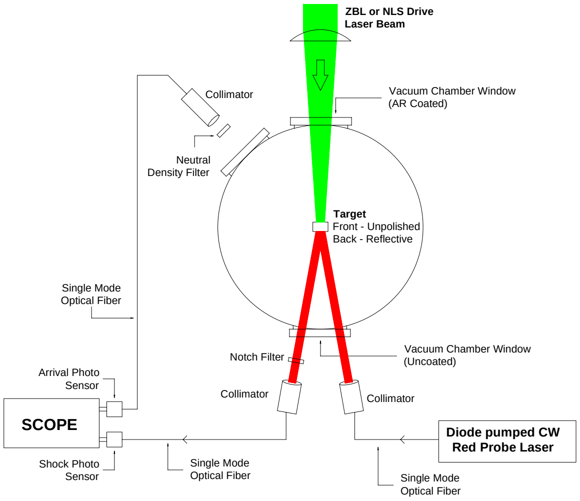

Figure 1. Schematic diagram of the experimental setup.

Light from the pulsed laser impact on the front surface is detected and initiates a time sequence that also records light from continuous wave probe laser signals detected from the rear surface. Reduction of probe laser signal indicates arrival of the shock wave at the rear surface of the diamond-turned metal target surface. No additional reflectors are needed so the rear surface faces of the targets faces a vacuum and the push-out velocity is twice the rear surface particle velocity. The push-out time for the particle is measured from the shock wave arrival time to the time taken for the signal to reach its minimal value, indicating complete probe laser beam displacement from the detector. Some ‘ringing’ can be observed in metal, but usually not in dielectrics or powders.

Targets: All targets studied were disks of ~ 0.5-3 mm thickness and 6.3 mm in diameter, representing different types of materials. The back surfaces of metals were finely polished to create highly reflective surfaces. A reflector consisting of a BK7 glass substrate covered with ~0.25 mm thick Al layer was added to the rear surfaces of non-metallic targets. For ductile materials (metals) disks were cut from pure solid Al, Cu and Ti as well as from a few iron meteorites. Al was mainly used as a calibration standard. For brittle materials (dielectrics) disks were cut from pure crystalline Si or solid ALM-2 dunite which consists of olivine (Fo 93.1±0.5, NiO ~0.4 wt%) with minute grains of clinopyroxene, chlorite, and chromite. Porous materials (powders) such as crushed ALM-2 dunite (~5-300 μm) and vapor-deposited Fe (20-50 μm) and Ni (5-20 μm) powders, either pure or mixed together in different proportions, were pressed into disk-shaped pellets at ~40 kPsi. The porosity of the targets evaluated from their BSE images was in the range of 20-35 vol.%. Because the olivine contains NiO but Fe metal is Ni-free, the dunite-Fe metal mixtures were of special interest for studying the metal-silicate interaction during shock-induced melting.

Examples of cratered metal targets: The targets which remained completely or partially intact contain more or less rounded craters 1-2 mm in diameter. These samples were studied by optical microscopy, SEM, and EPMA in order to evaluate the extent of mineralogical and chemical changes, including shock-induced melting. The results of these studies are reported in an accompanying abstract [6].

Figure 2 shows craters formed in metallic targets by ZBL laser shots of different intensities. The external rims of each target were protected from the laser radiation by a stainless steel flange of the sample holder. Al disks display either a nearly perfect round crater (for a low energy density of 3.4 TW/cm^2) or a hole (for a high energy density of 6.5 TW/cm^2) surrounded by wide ablation zones. The powdered sample (50% Fe + 50% Ni) is covered with a melted crust of up to 10 μm in thickness, which shows clear evidence of a fluid flow.

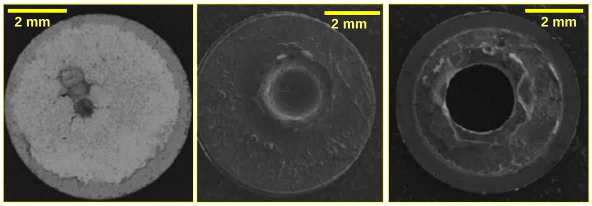
ZBL-17 shot (4.53 TW/cm^2) on mixture of Fe and Ni
ZBL-11 shot (3.4 TW/cm^2) on Al
ZBL-1 shot (6.5 TW/cm^2) on Al

Figure 2. Examples of metallic cratered targets.

Pressures and Temperatures: Results for a variety of target materials are summarized in Table 1. Corona pressures, P (TPa) above the target front surfaces were calculated from the known radiation intensity, I (W/cm^2) and wavelength, λ (μm) using an approximate formula: $P = (10^{-14} \times I/\lambda)^{2/3}$. The corona pressures above the target front surfaces reached up to 270 GPa in some experiments and by implanting more energy we can reach at least 600 GPa. When the current upgrade of the ZBL is completed, it should be possible to reach a few TPa. The high pressures very rapidly dissipated to ~20 GPa upon traveling ~ 0.1 mm into the target, suggesting pressure gradients of ~ 1,000 GPa/mm. Temperatures experienced by the target surfaces are estimated to be in excess of 10^4 K, similar to those obtained for silica at similar pressures in laser shock measurements [7]. A melt or plasma cloud formed at the front surface, was driven into the porous targets so thatit could be studied petrographically on grain boundaries and analyzed by EMPA [6].

Table 1. Results for a variety of targets.

Target	***I*** *(TW/cm^2)*	***P*** *(GPa)*	***P_H*** *(GPa)*	***dP/dz*** *(GPa/mm)*	***C_m*** *(s/m x 10^{-5})*
Metals (ZBL)	0.5 - 6.0	30 - 250	10 - 50	20 - 200	0.08 - 0.2
Iron meteorites (Z)	0.19 - 0.26	250 - 315	1.4 - 2.5	250	0.07 - 0.10
Armco Fe (Z)	0.19	254	5.32	250	0.28
Iron: NLS	0.58	131	0.51	148	0.01
Iron: ZBL	5.11	211	15.3	214	0.03
Aluminum (NLS)	0.17 - 0.75	22 - 71	~15.6	~ 30	~ 0.21 - 0.97
Aluminum (ZBL)	5 - 6.63	208 - 251	23 - 24	~ 200	~ 0.05 - 0.38
Stony meteorites (Z)	0.3 - 5.0	25 - 200	5 - 50	20 - 150	0.025 - 0.25
Powder: Metal	0.3 - 6.0	23 - 234	1.5 - 2.0	~40	5×10^{-4} – 5×10^{-3}
Powder: Dunite	0.3 - 7.5	22 - 270	0.07 - 2.0	~50	2.5×10^{-4} – 5×10^{-3}

Conclusions: We have developed a new experimental technique for measuring EoS parameters and momentum coupling coefficients of different targets at very high pressures and temperatures. The advantage of our approach over conventional high-pressure experiments is that it allows studying relatively large, mm-sized targets, which, in many cases, remain completely or partially intact and can be studied by conventional petrographic, mineralogical, and chemical techniques [6]. We found drastic differences in the EoS response among ductile (metals), brittle (solid ALM-2 dunite), and porous (silicate-metal powders) materials. In general, both shock wave and particle velocities in powdered targets are about an order of magnitude less than those in the solids, depending upon the porosity. The momentum coupling coefficients of powdered targets are several orders of magnitude smaller than those of solid targets. Our ability to produce metal-silicate melts in targets of Fe-dunite mixtures provides an opportunity to study metal-silicate partitioning at temperatures and pressures comparable with those estimated for the Earth's core-mantle boundary.

References: [1] Tschauner O. et al. (2005) *LPS, XXXVI*, abstract # 1802. [2] Remo J.L. et al. (2006) *AGU Fall 2006*, abstract#MR51B-0967. [3] Petaev M.I. et al. (2006) *AGU Fall 2006*, abstract#MR53D-05. [4] Canup R. (2004) *Icarus, 168*, 433-456. [5] Valencia D. et al. (2006) *Icarus 181*, 545-554. [6] Petaev M.I. et al. (2007) *LPS, XXXVIII, this volume*. [7] Hicks D.G. et al. (2006) *PRL, 97,* 25502-1 to 25502-4.