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Laser shock experiments for the equation of state of hydrogen at extremely high pressure

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The properties of hydrogen at high pressure and high density are of great scientific interest. The equation of state (EOS) of hydrogen at these conditions is essential for modeling of the interior structure of gas giant planets. The large diversity in the estimation of Jupiter's core mass is resulted from the uncertainty in the EOS data especially in the region around the insulator-to-metal transition. Chemical free-energy models and ab initio simulations have been used to predict the properties of warm dense hydrogen, but the results vary widely and have not converged yet. Therefore accurate experimental data for the hydrogen EOS are required for evaluation of the theoretical models and for further understanding of the fundamental nature of hydrogen.

It is more difficult to generate high pressures in hydrogen than in deuterium because of its lower shock impedance. For this reason, most of the recent experimental measurements by shock compression have focused on the heavier isotope. There is a large gap in the experimental achievement of shock compression between liquid hydrogen and deuterium. The principal Hugoniot for liquid deuterium was measured up to 220 GPa using laser-driven shock waves. For the case of liquid hydrogen, the Hugoniot was studied experimentally only to 10 GPa by a gas gun and explosive method more than two decades ago. The metallization of hydrogen on the Hugoniot is expected to occur at much higher pressure. In this work, we carried out laser-shock experiments of liquid hydrogen to pressures exceeding 10 GPa in order to make a quantitative comparison of the hydrogen Hugoniot around the metal transition with the deuterium data.

The experiment was performed on the GEKKO HIPER laser facility at the Institute of Laser Engineering, Osaka University. The principal Hugoniot for liquid hydrogen was obtained up to 55 GPa under laser-driven shock loading. Pressure and density of compressed hydrogen were determined by impedance-matching to a quartz standard. The shocked temperature was independently measured from the brightness of the shock front. Hugoniot data of hydrogen provide a good benchmark to modern theories of condensed matter. The initial number density of liquid hydrogen is lower than that for liquid deuterium, and this results in shock compressed hydrogen having a higher compression and higher temperature than deuterium at the same shock pressure. As for the study of planetary interiors, the hydrogen EOS data at much higher pressure are required since the transition to metallic hydrogen is anticipated to be at P = 200-400 GPa in Jupiter. However, the hydrogen temperature must be kept lower because the Hugoniot temperature at this pressure range is too high to reproduce Jupiter's conditions. Therefore off-Hugoniot measurements of hydrogen by means of reflection shocks and/or precompressed samples will be a quite important next step.

Keywords: gas giant planets, interior structure, hydrogen at high pressure, equation of state,
laser shock compression