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Physics and Chemistry of the Interiors of Large Planets: A new generation of condensed matter using NIF

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Auspices Statement

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Physics and Chemistry of the Interiors of Large Planets:
A new generation of condensed matter using NIF

Introduction:

Matter at extreme densities is predicted to have truly exotic properties, including high-temperature superconductivity, superfluidity, and Wigner crystallization to name a few. However, these extreme states of matter exist only in the deepest interiors of large planets, brown dwarfs, and low-mass stars, and there are no data to test these predictions. Integral to developing predictive models for the evolution of both terrestrial and gas giant planets is an understanding of the materials states that occur deep inside these massive objects. Since we are not able to drill into the deep interiors of planets such as Jupiter to explore these extreme material states of During the last year we initiated a world wide effort to explore such material states using the National Ignition Facility (NIF). This effort has mobilized a new effort in extreme condensed condensed matter science. Over the course of the year we developed several experimental designs showing how NIF might be used to accurately characterize states of matter predicted to exist at the center of both large terrestrial and gas planets. In particular, we identified ways to compress iron to TPa conditions while keeping it solid and hydrogen to near TPa conditions at < eV temperatures using a variety of novel compression techniques. Then several of these diagnostic and compression techniques have been tested on the Jupiter laser facility and the Omega laser facility leading to several publications. In addition, several conference sessions and meetings were held which generated significant enthusiasum in the community for this new field of science. Below we give a brief synopsis of some of the resultant publications.

Research Activities and Results

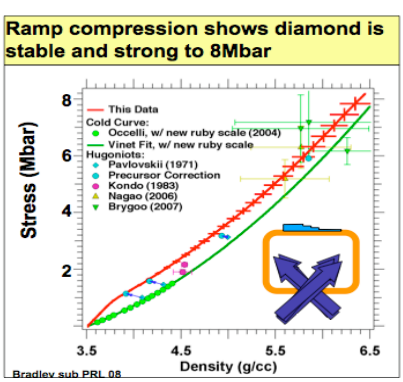

Fig. 1. New ramp compressed diamond stress vs density (red line) compared to cold curve (green line) and several shock Hugoniot data. These data are the highest pressure solid state equation of state data ever collected and show diamond is stable and strong up to 800 GPa (8 Mbar=8

To compress materials to very high pressures and densities and keep the material in the solid state, we developed a new ramp compression technique, that extended to NIF, will allow the exploration of solids to TPa conditions. The general idea is to tailor the laser pulseshape to gently compress the sample so as to not form a shock. This technique was used to compress diamond to TPa conditions at the Omega laser facility. Figure 1 shows the highest pressure solid stress density ever studied in the laboratory and the work is

submitted to Physical Review Letters.[1] Ramp compression techniques can also be used to determine when high pressure phases change with increasing pressure or temperature. We also showed that ramp compressing solids through solid-solid or liquid-solid phase transitions are clearly mapped with ramp compression techniques and the phase transition kinetics can be explored under the rapid laser ramp compression capabilities. This work was showcased in Physical Review letters (this was a cover article shown in Fig. 2) which showed ramp compressing bismuth we discovered a new and perhaps general behavior of how the kinetics of phase transitions effects how materials transform from one phase to another under rapid compression.[2]

Fig. 2 Phase transition kinetics of Bi PRL

In addition to ramp compressing solids we also invented, developed, fielded, and published the first results describing how low Z materials can be compressed to ultra-high densities by combining precompression with static diamond anvil cells and laser generated shock waves. This led to an article featured in Physical Review Letters which describes the equation of state of helium shock compressed to a liquid metal.[3] Figure 3 shows the compressibility for dense helium versus pressure at an initial density of 0.123g/cc. As helium turns into a metal like conductor it becomes more compressible. These techniques have been implemented in designs to be used on the NIF that will compress hydrogen perhaps into a superconducting, superfluid, or Wigner crystal state.

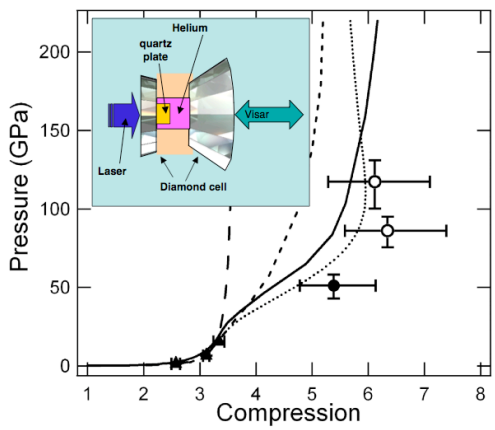

Fig. 3. Compressibility of helium at the insulator to conducing transition from recent PRL.

We also developed advanced shock compression techniques that allow equation of state measurements with accuracies comparable to gas gun experiments albeit at significantly higher pressures. These ultra-high pressure shock measurements focused on carbon because the high-pressure properties of carbon are integral to evolutionary models for planets and experiment designs to achieve controlled intertially confined fusion on NIF. Figure 4 shows new Hugoniot equation of state data for shock

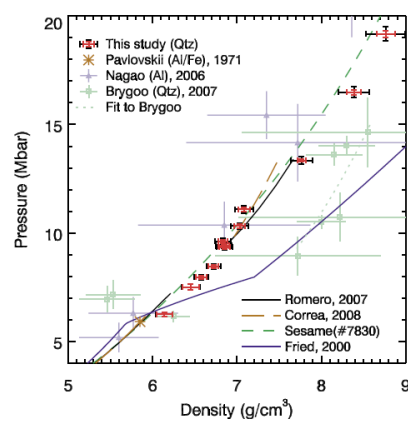

Fig. 4. New diamond Hugoniot data (red points) compared to previous data (blue, greed, brown points, and model calculations (lines).

compressed diamond (red points) compared to previous data (green, blue, brown points). These new data show that improvements in laser shock data have improved accuracies in density measurements by a factor of 3 to 10. Data also suggest an increase in density upon the onset of melting at ~6 Mbar (600 GPa) and another change in slope at pressures larger than 11 Mbar suggesting the Hugoniot separates from the melt curve coexistance line near that pressure.[4] The level of accuracy shown in Fig. 4, puts significant constraints on new ab-initio models, condensed matter theory, and planet evolutionary models. Moreover, these techniques are being implemented into NIF experiments for achieving perhaps Gigabar (100 teraPascals) pressures.

In addition to accurate Hugoniot measurements, we measured the temperature of shock compressed diamond from 6 Mbar to 40 Mbar (4,000 GPa). These data were used to map the carbon melt curve from 6 to 11 Mbar, which is by far the highest-pressure melt curve ever measured.[5] The melt temperature decreases from 9200 to 8400 K with increasing pressure over this range. Figure 5 shows the temperatures for shock compressed diamond together with theoretically calculated phase boundaries. Specific heat estimates between 1,100 and 2,500 GPa, determined from these temperature and shock Hugoniot data were used to discover a new polymeric structure in dense fluid carbon. This together with optical reflectivity data, reveal carbon in the 1,000 GPa regime, melts to a denser polymeric-metallic fluid. These results combined with structural models for Uranus and Neptune indicate that pure carbon present deep inside these planets is in the form of solid diamond. This work has recently been submitted to Nature.

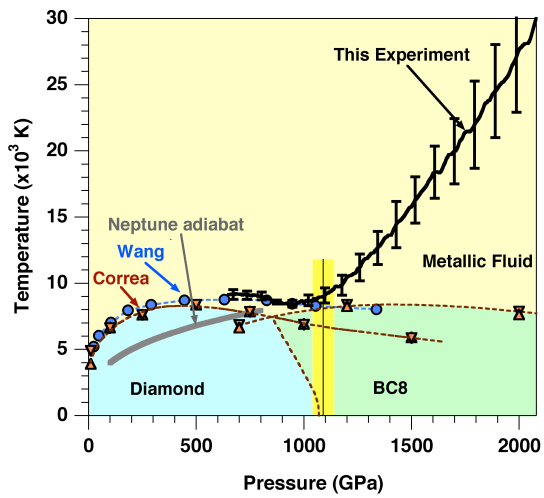

Fig. 5. Temperature data (black line) together with calculated phase boundaries from Correa and Wang. Also shown ins a calculated isentrope for Neptune. Data from 1100 GPa (11 Mbar) to 600 GPa (6 Mbar) follow the melt curve and show a negative dP/dT for the melt curve. Above, 1100 GPa (11 Mbar) temperatures are for the fluid phase.

Finally, these results have attracted significant attention in the condensed matter, plasma physics, and planetary science communities. We had ~10 invited talks showcasing this work, held a Town Hall Meeting at the American Physical Society Condensed Matter meeting last year and organized a special session at the AAAS annual meeting.

[1] D. K. Bradley, J. H. Eggert, R. F. Smith et al., *Phys. Rev. Lett.* **102**, 075503 (2009).

[2] RF Smith, JH Eggert, MD Saculla et al., *Phys. Rev. Lett.* **101**, 065701 (2008).

[3] J. Eggert et al. PRL 100,124503(2008).
[4] D. Hicks et al. Phys. Rev. B 78, 174102(2008).
[5] J. Eggert et al. Submitted to Physics Nature (2009).