Laser-Based Dynamic Compression of High-Pressure and Planetary Materials

Dr. June Wicks
JHU, Princeton University
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Measure the crystal structure of important planetary materials under dynamic (both shock and ramp) compression

NLUF Principal Investigator: T. S. Duffy (Princeton University)
Co-investigators: R. F. Smith, F. Coppapi (LLNL), J. K. Wicks (Princeton, JHU), T. Boehly (LLE)
Graduate Students: D. Kim (Princeton), S. Han (Princeton)


Publications: Wicks et al., Science Advances, 2018 -- ramp compression of Fe-Si alloys
Invited Presentations: Study of the Earth’s Deep Interior (SEDI) 2018, American Geophysical Union (AGU) 2018
Interiors of terrestrial planets

Mineral Physics Inputs
- Crystal structures
- Phase relations
- Melting behavior

Equation of state
- Thermal expansivity
- Compressibility

Transport properties
- Deformation behavior
Interiors of terrestrial planets

Super Earth (10 Earth masses)

Earth (1 Earth mass)

- MgSiO₃ olivine
- B1 MgO + MgSiO₃ Pv
- MgSiO₃ pPv
- FeNi alloy liquid
- Fe alloy liquid? hcp? fcc?

- MgO
- SiO₂

- B1 (NaCl-type)
- Post-Perovskite (pPv)
- B2 (CsCl-type)
- MgO + MgSiO₃? Fe₃P-type

- Perovskite (Pv)
- Stishovite
- CaCl₂-type
- PbO₂-type
- Pyrite
- Co3O₄
- Cotunnite

- 0 km depth
- ~6,000 km
- ~12,000 km
- ~3,000 km
- ~6,400 km

- 23 GPa
- 135 GPa
- 360 GPa
- 500 GPa
- 1300 GPa
- 4000 GPa
2018 materials:
MgO
SiO$_2$ and relevant structure analogues
SiC
The high-pressure frontier is driven by dynamic compression.
High pressures achievable using Lasers

Two classes of laser drives:
- Large laser systems (NIF, Omega).
  Multi-beam user facilities for very high pressure.
- Benchtop laser 20-J Optical laser as used in academic labs, or paired with X-ray facilities.
The B1-B2 transition: an important structural transition in simple oxides!

“... if we cannot understand MgO, we cannot understand any other oxide or silicate”
- R. E. Cohen

What we learn from analogs:

- Viscosity drop across B1-B2 boundary (Karato 2011)
- Directional dependence of transition pressure
Constraints on MgO phase diagram-- Hugoniot Calculations

![Graph showing phase diagram with pressure (GPa) on the x-axis and temperature (kK) on the y-axis. The diagram includes phases B1 and B2, and the onset of melt is marked.]

Hugoniot Measurements – Decaying shock + single shock

Bolis (2016), Miyanishi (2015), McWilliams (2012)
This study:

Laser shock compression + in situ X-ray diffraction to better constrain phase diagram

Bolis (2016), Miyanishi (2015), McWilliams (2012)
Omega Laser

- Nd:Glass laser, frequency-tripled 351 nm radiation
- Delivers 30 kJ over 1-10 ns on targets ~1 mm in size
- Energy distributed over 60 beams
- Repetition rate is ~1 shot per hour.
- Each beam focused with pointing accuracy of +/- 16 μm and timing accuracy of +/- 10 ps on target

Omega EP Laser

- 4 beams
- Long pulse mode, delivers 2.5-6.5 kJ per beam over 1-10 ns
VISAR diagnostic (Velocity Interferometry System for Any Reflector)

Samples are accelerated to velocities up to 25 km/s

VISAR Interferometer encodes Doppler shifted phase into fringe movement

Streak camera is used to resolve fringe movement in time
Streaked optical pyrometer (SOP) at the Omega Laser

Dylan Spaulding, PhD thesis 2010

For more information on calibration, see Gregor et al., Rev Sci Inst 2016.

Millot et al., Science, 2015

Jogs in the Hugoniot temperature delineate melting temperature
Two complementary shock studies of the MgO Hugoniot

**Steady shock**

- Laser Power vs Time (ns)
- Pressure vs Distance
- Temperature vs Pressure

**Decaying shock**

- Laser Power vs Time (ns)
- Pressure vs Distance
- Temperature vs Pressure
Results 1: Temperature measurement of the MgO Hugoniot
Results I: Temperature measurement of MgO Hugoniot

Three shots suggest a phase transformation at ~400 GPa

Interpret as the $B1-B2$ boundary
- consistent with phase boundary location of Boates & Bonev, PRL 2013.
- Inconsistent with the interpretation of Bolis et al., GRL 2016.
Pressure Determination using reflecting shock in quartz

Hydrocode simulations matched to Quartz shock velocity to determine MgO Pressure during x-ray probe time.
Definitive proof that this temperature excursion is associated with the B1-B2 transition.

Important implications for latent heat of transformation!
Results II: P-T points from X-ray diffraction study

B2 + liquid rather than B2 only??

DFT calculations

Mixed phase region

No peaks (liquid)

B2 + liquid rather than B2 only??

Diffraction Signal

Pressure (GPa)

B1 data

B2 data

B1 [220]

B2 [110]

B2 [100]
Next steps: implications of compression orientation, **kinetics**

Shock compression along different crystallographic directions activates different deformation mechanisms.
Proxima Centauri b
M. Kornmesser