Formation of the Earth-Moon System: Laser Shock Studies on Janus

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NIF – JLF User Group Meeting

February, 2014

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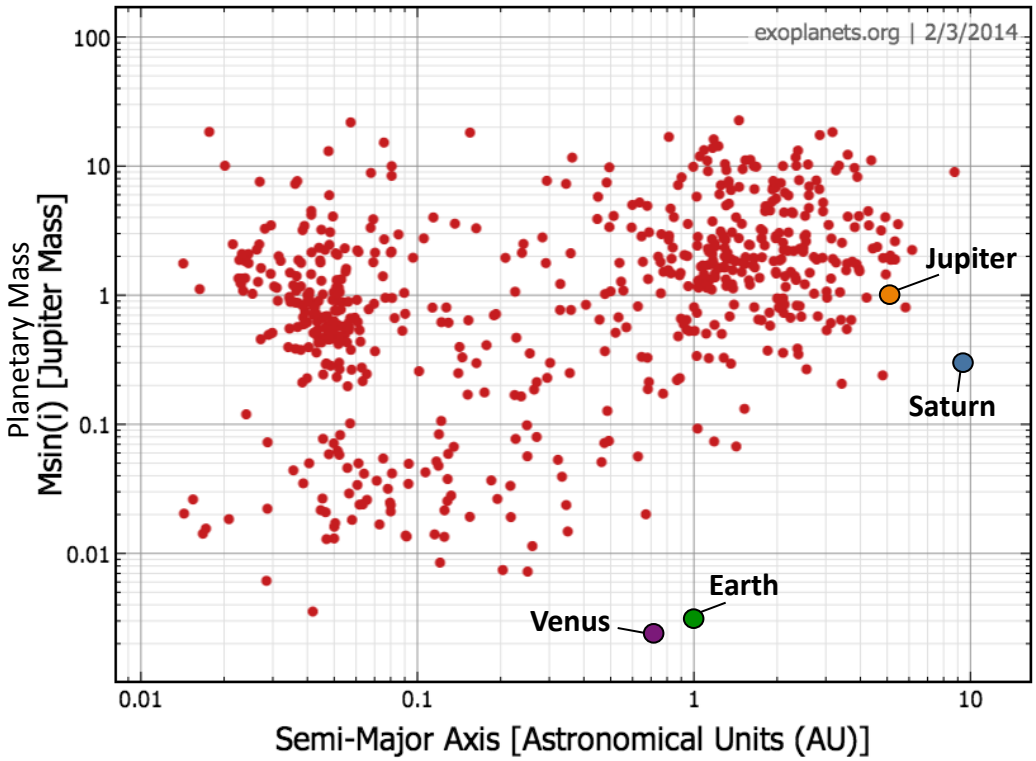
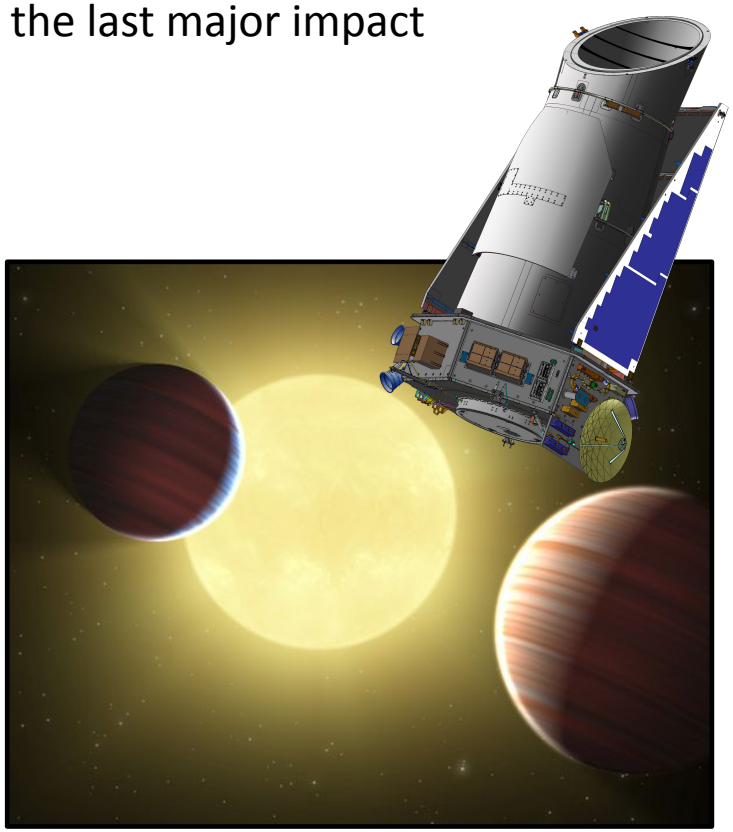
Planetary Evolution – Many Possible Outcomes

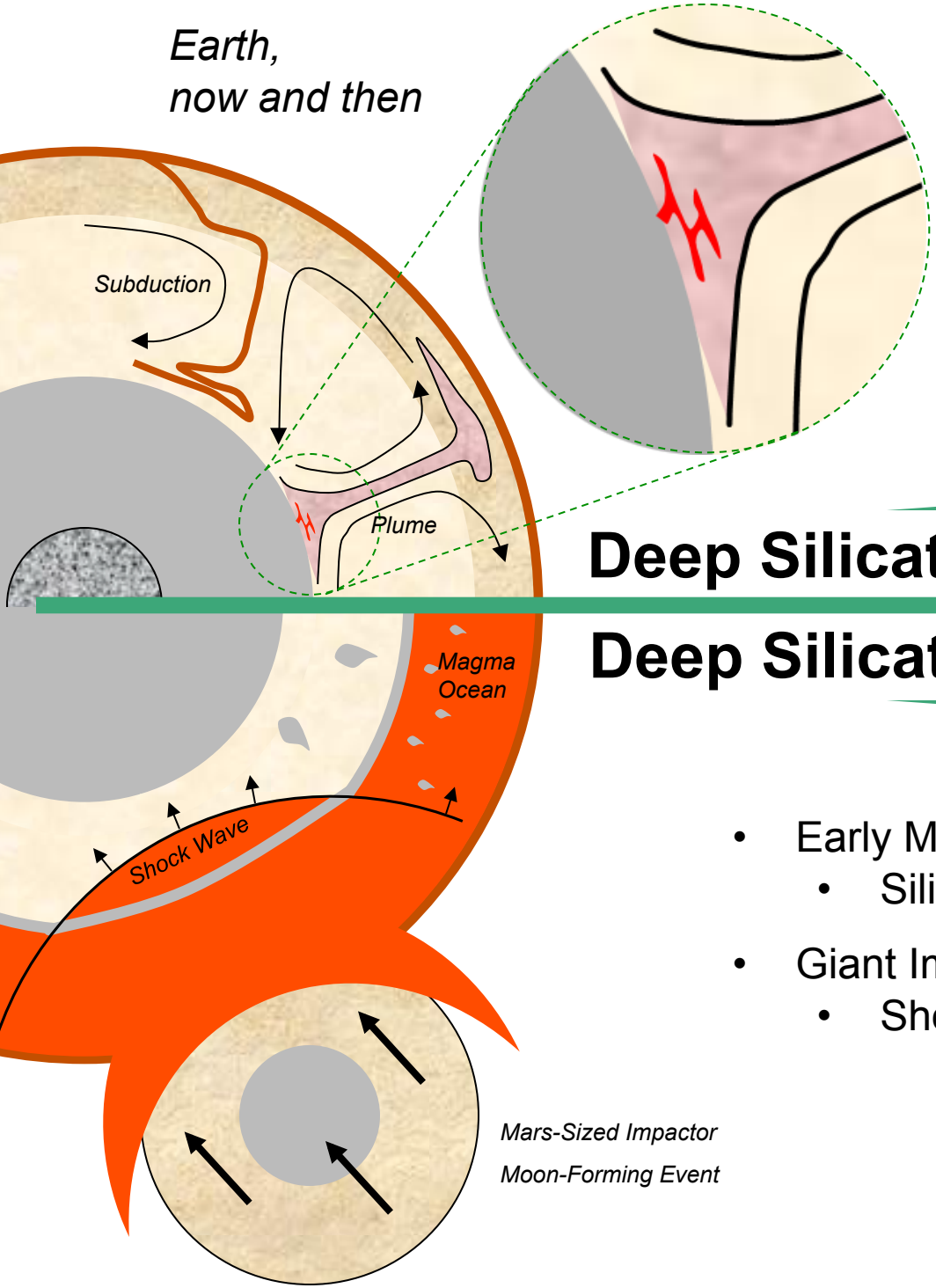
- Collisional events dominate planetary evolution, creating a rich diversity of planetary systems.
- Many planetary bodies likely display the imprint of the last major impact





kepler.nasa.gov

Earth,
now and then



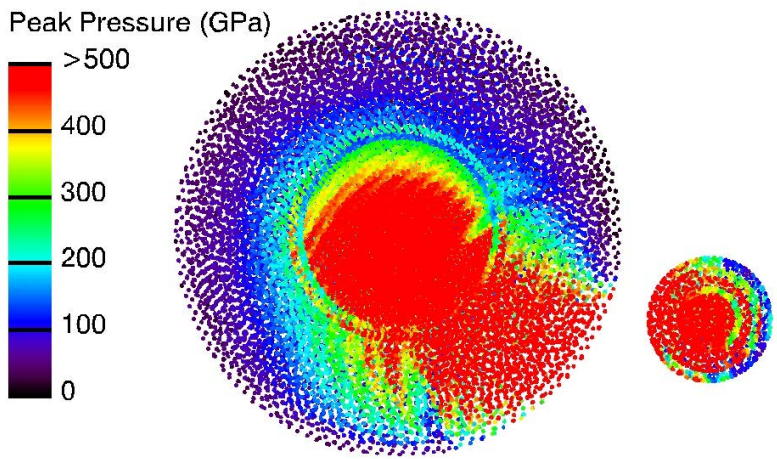
- Silicate Liquid Near Core-Mantle Boundary (D”)?
- Particularly likely at regions of high heat flow

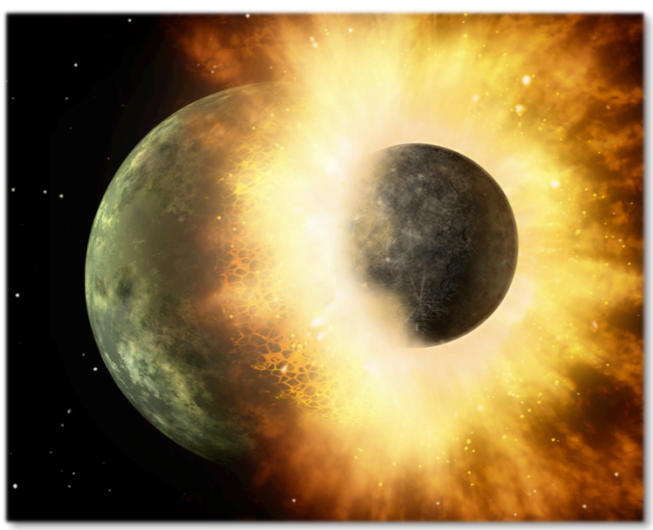
Deep Silicate Melt in the Present Earth

Deep Silicate Melt in the Ancient Earth

- Early Magma Ocean
  - Silicate Liquid at Depth
- Giant Impacts
  - Shock Melting Of Mantle

Planetary Formation in the Laboratory





Laser-driven shocks access the range of pressures and temperatures relevant to planetary formation (10's to hundreds of GPa and ~0.1 to a few eV temperatures)

Need to Understand:

Material Properties

- Phase Relations, Equations of State
- Compressibility
- Solid-Solid polymorphism

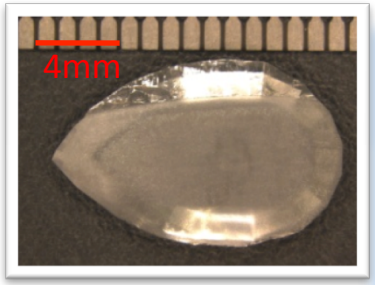
Thermodynamics and Transport Properties

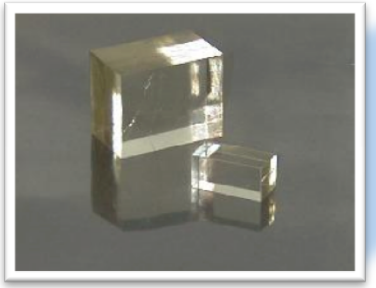
- Importance of Off Hugoniot States

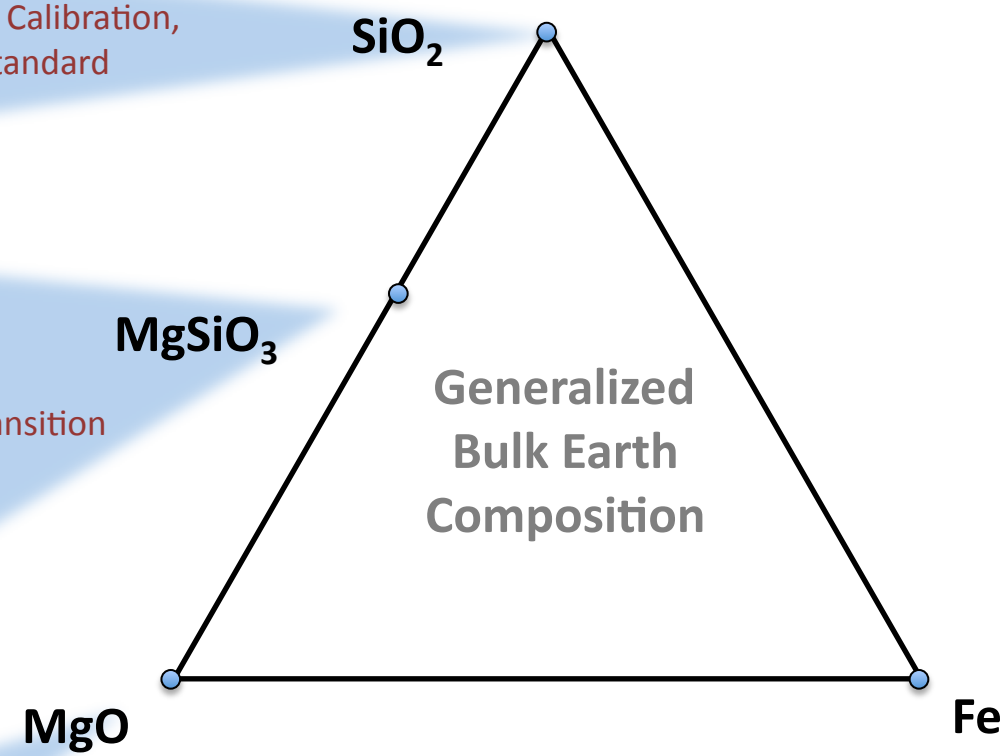
Shock-Induced Chemistry

Ultra-High Pressure Properties of Mantle Compositions

SAMPLES	MEASUREMENTS
α – Quartz Fused Silica	Temp. Calibration, EOS Standard
Natural Single Crystal	EOS Liquid Transition
Synthetic Glass	
Single Crystal	B1-B2 Melting

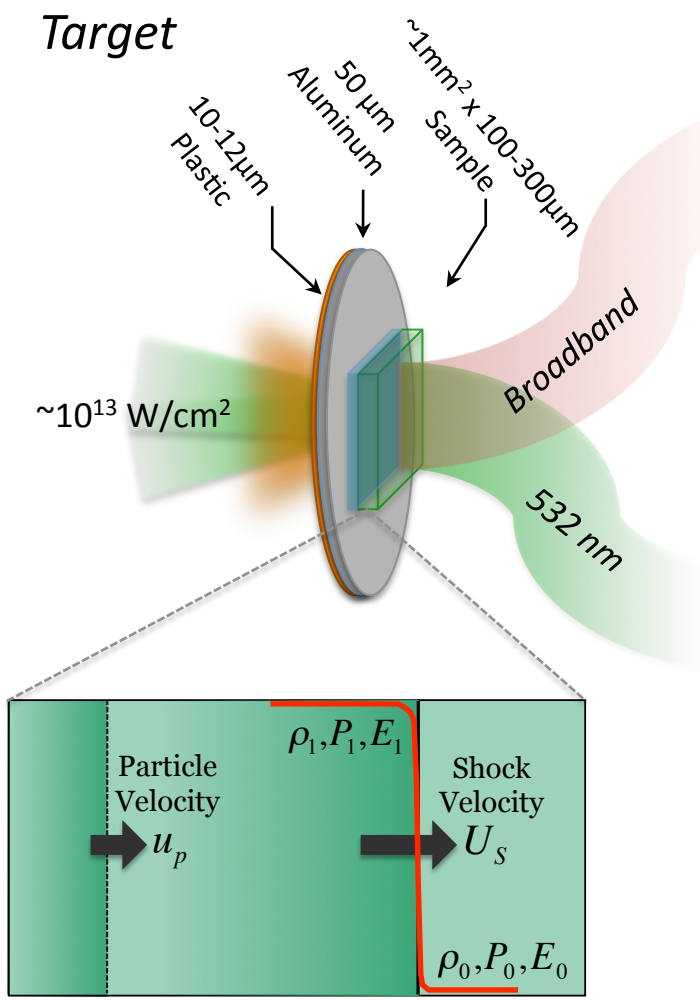






And, in many cases, can also infer thermodynamic and transport properties, including ***specific heat, conductivity***…

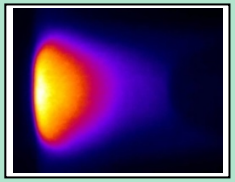
Typical Experiment and Diagnostics



Diagnostics

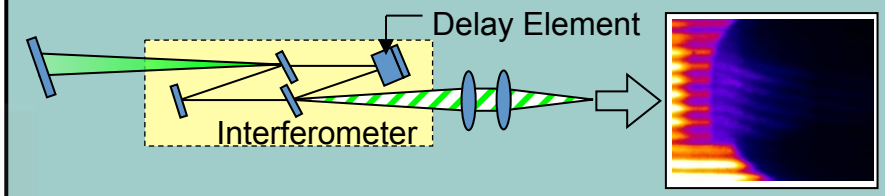
Streaked Optical Pyrometer

Records thermal emission from sample for calculation of absolute temperature



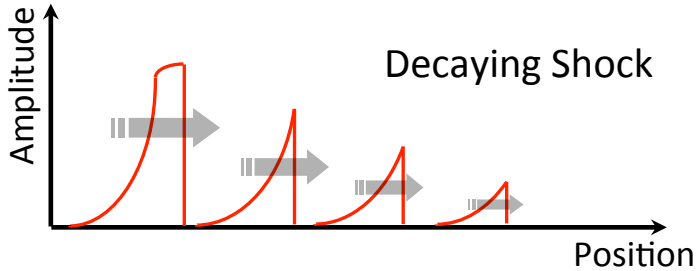
Reflectivity Monitor

Observes changes in sample optical properties



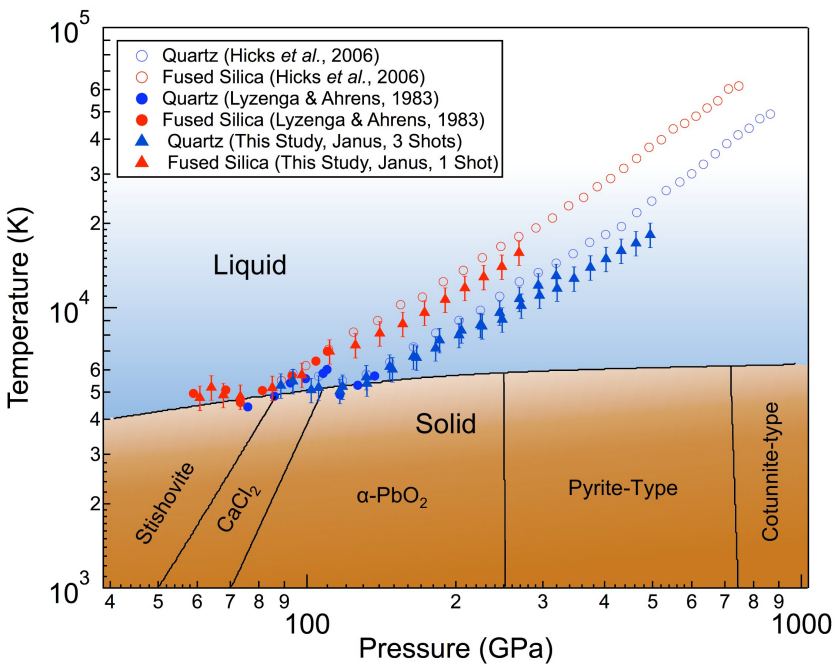
VISAR (Velocity Interferometry System for Any Reflector)

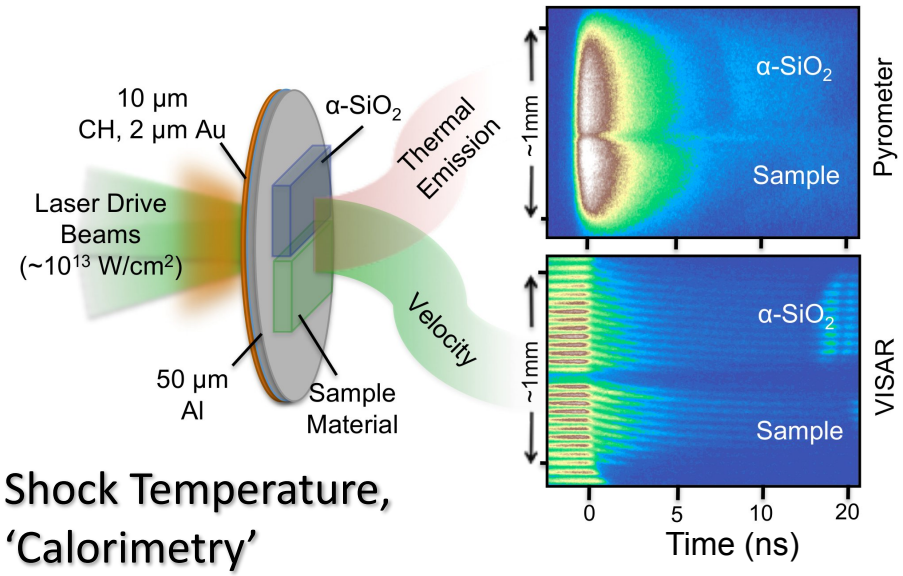
Measures Doppler shift from moving surfaces to determine shock and particle velocities



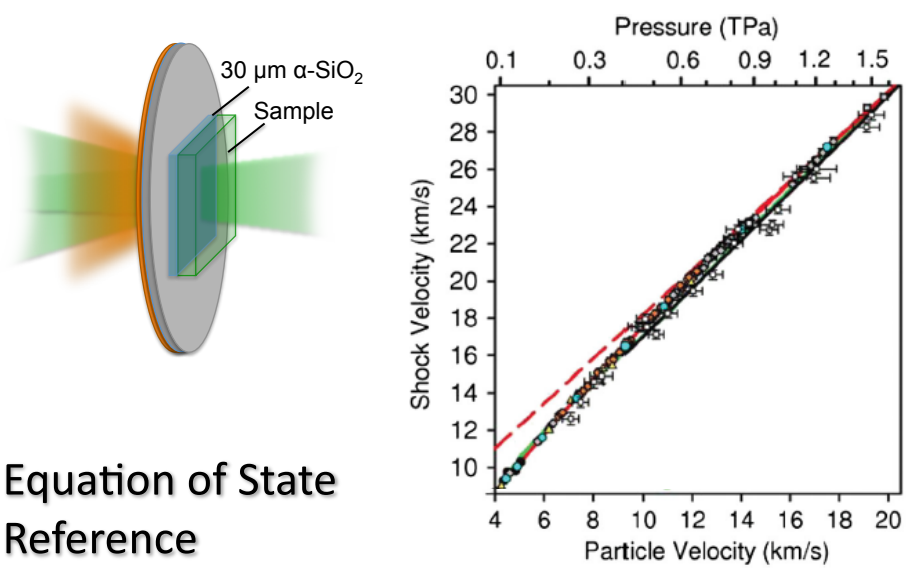
Development of Quartz As an *in-situ* Standard

- α-SiO_2 has been developed as a high pressure standard for temperature, EOS measurements
- Easier comparison of data across different campaigns





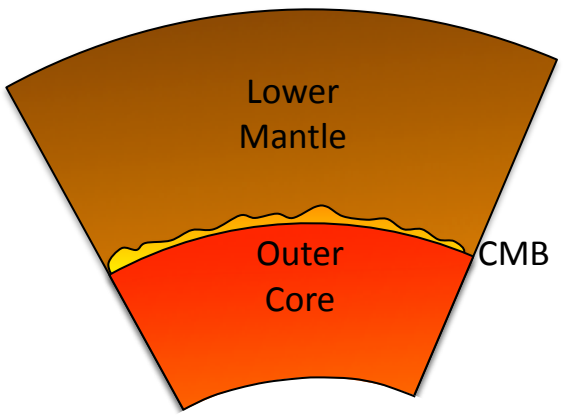
Shock Temperature, 'Calorimetry'

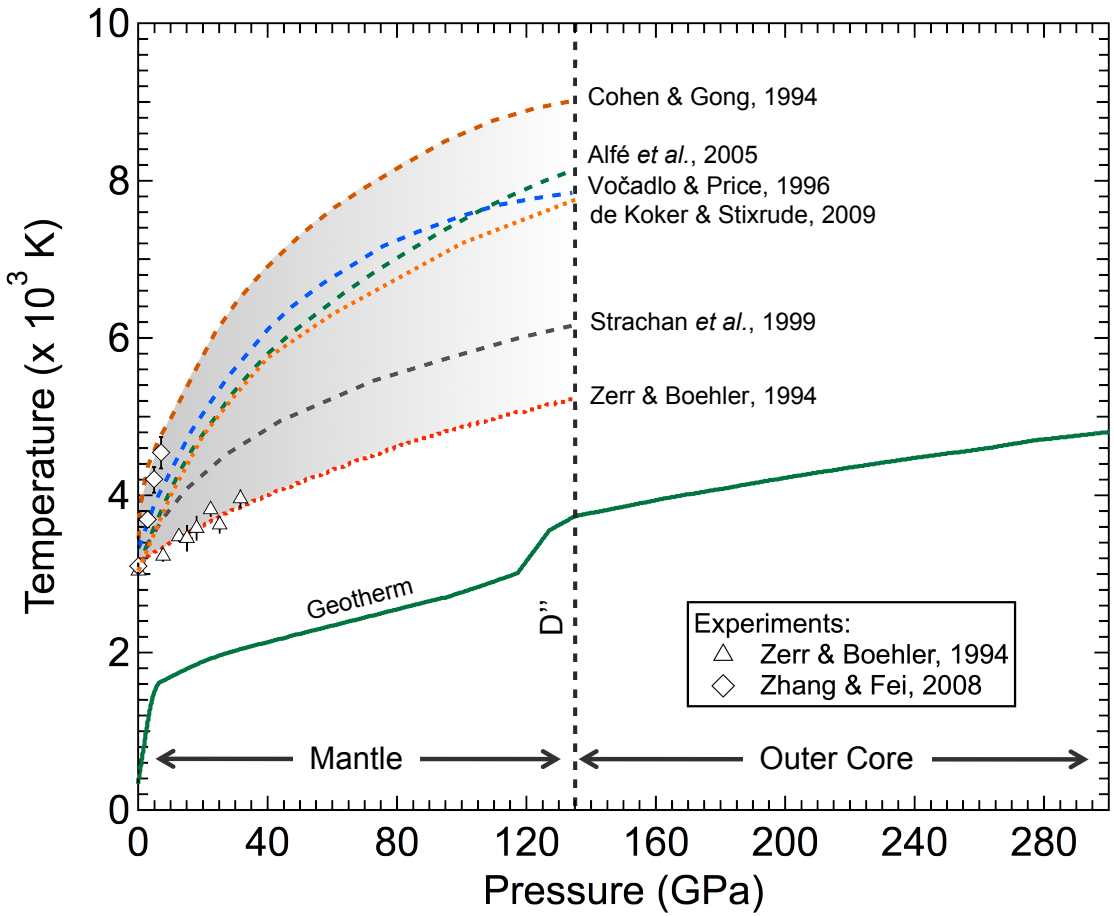


Equation of State Reference

Shock Compression of Single-Crystal MgO

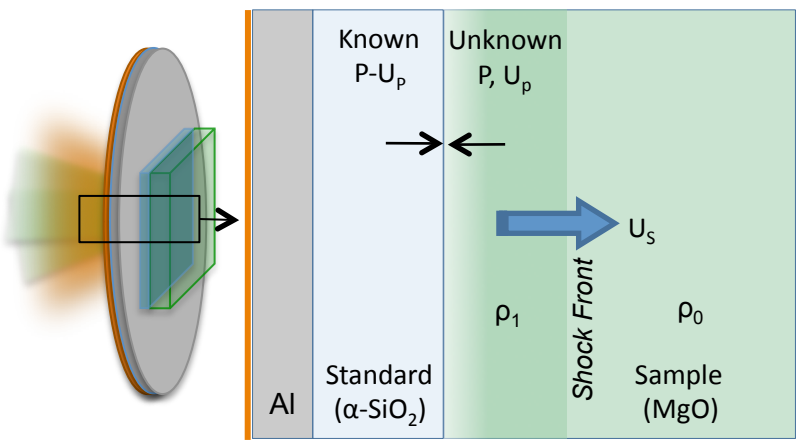
R. Stewart McWilliams, D. K. Spaulding, J. H. Eggert, P. M. Celliers, D. G. Hicks, R. F. Smith, G. W. Collins, R. Jeanloz, **Phase Transformations and Metallization of Magnesium Oxide at High Pressure and Temperature** , *Science*, 2012.





MgO Hugoniot Equation of State from Impedance Matching

Hugoniot Equation of State (EOS) is determined by simple impedance matching with an α-SiO_2 standard.

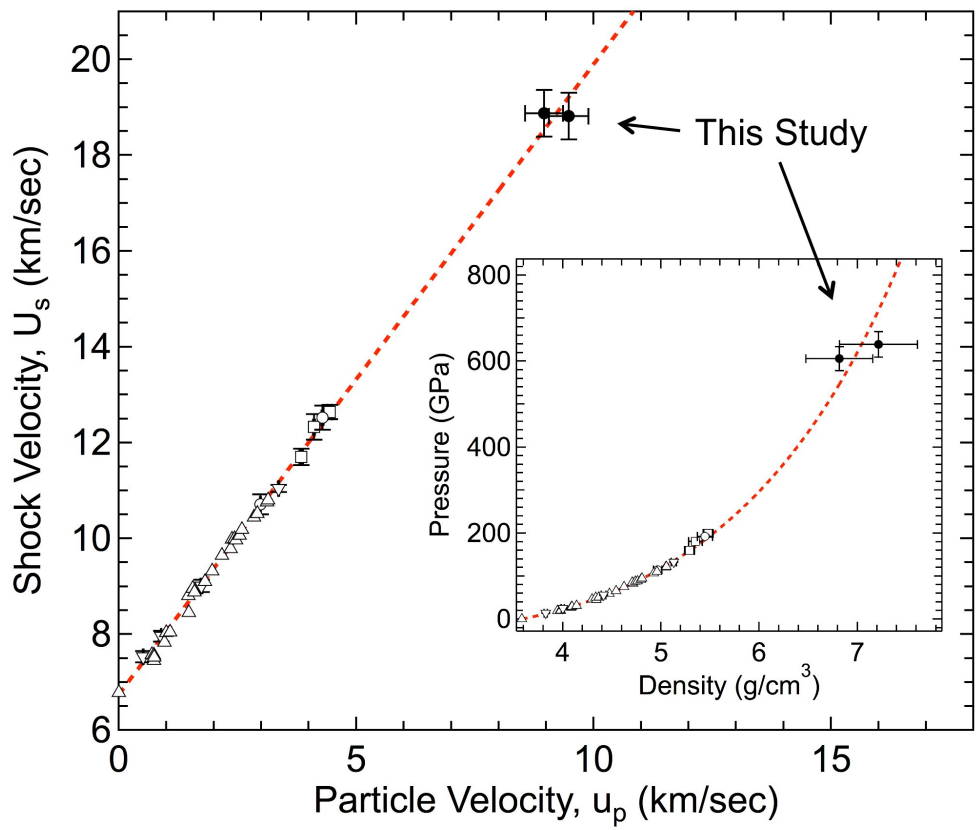


$$\rho_0 U_S = \rho_1 (U_S - u_P)$$

$$P_1 = \rho_0 U_S u_p$$

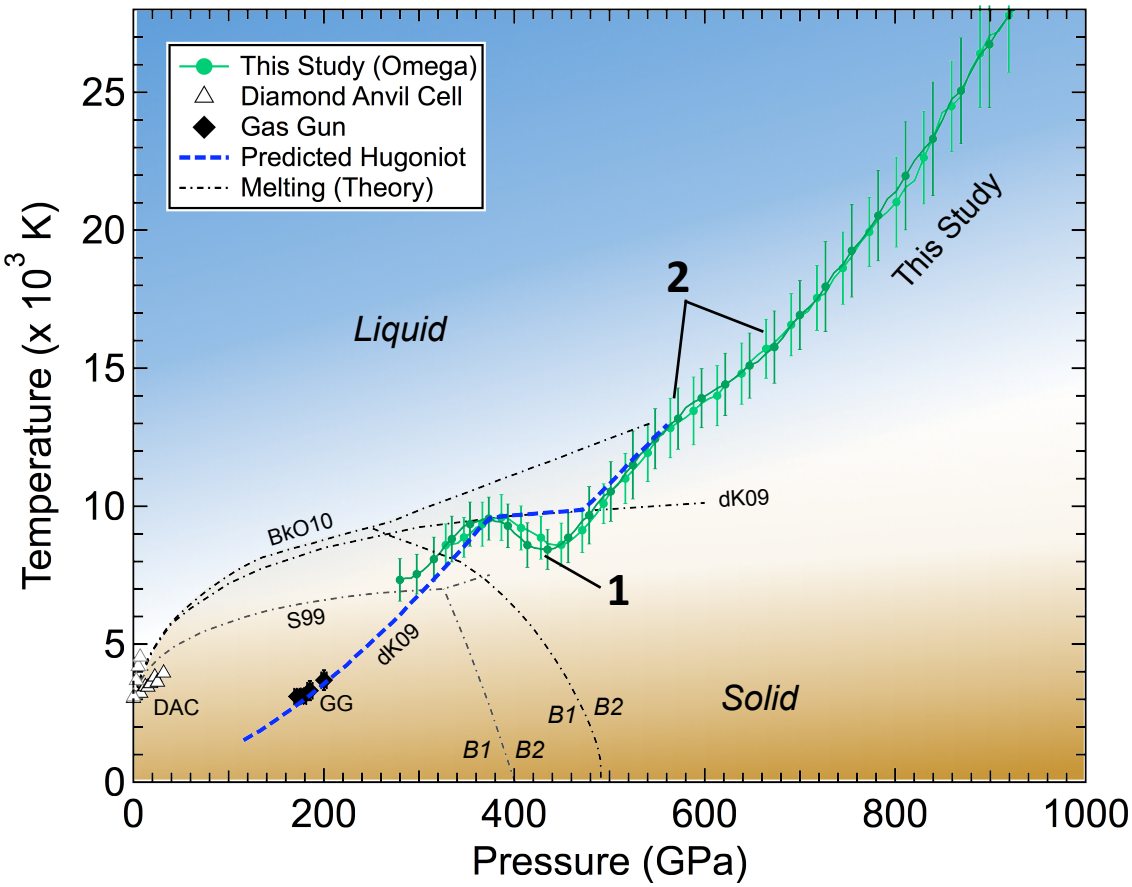
$$(E_1 - E_0) = \frac{1}{2} P_1 (V_0 - V_1)$$

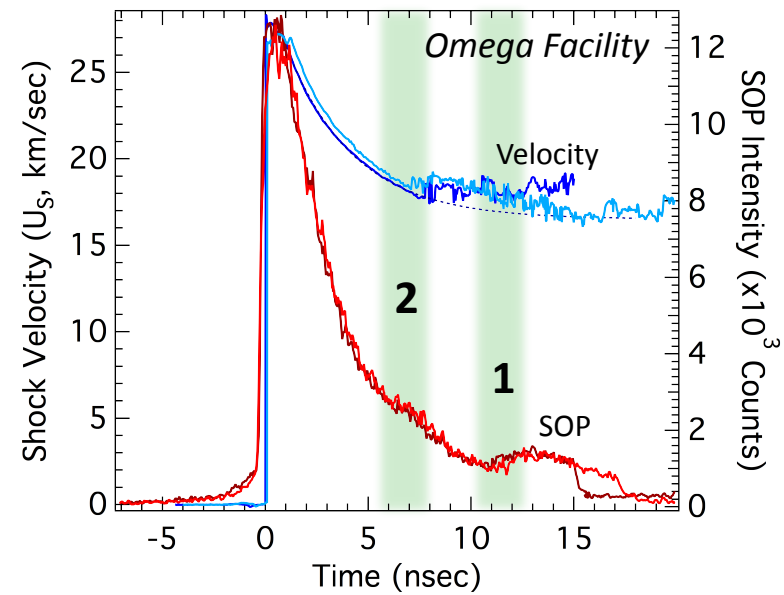
$U_s = (6.743 \pm 0.070) + (1.316 \pm .017)U_p$

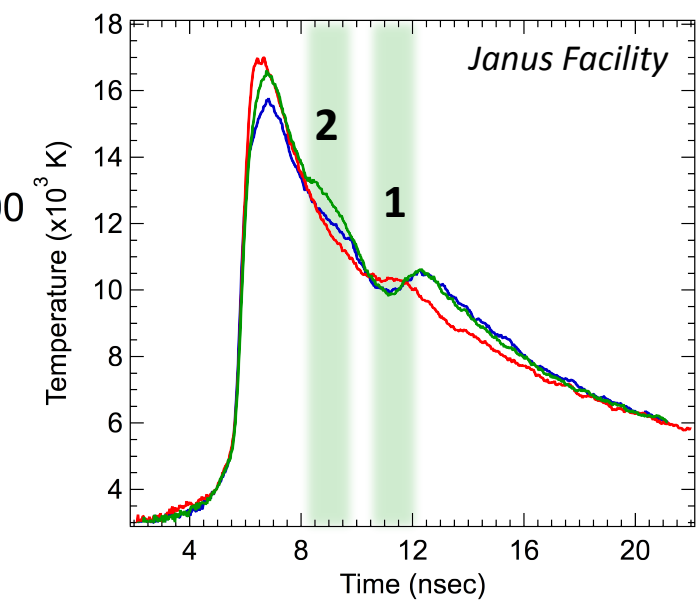


Marsh (1980), Vassiliou *et al*. (1981), Svendsen & Ahrens (1987), Duffy *et al*. (1995), Zhang *et al*. (2008)

MgO (single-crystal) – Pyrometry as a Shock 'Calorimeter'

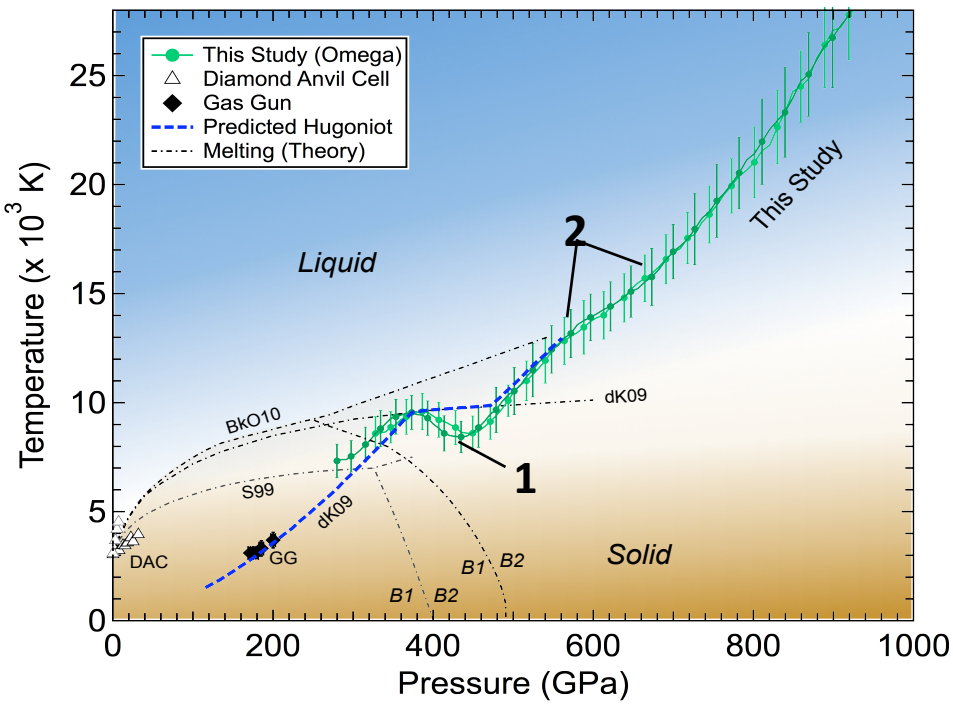


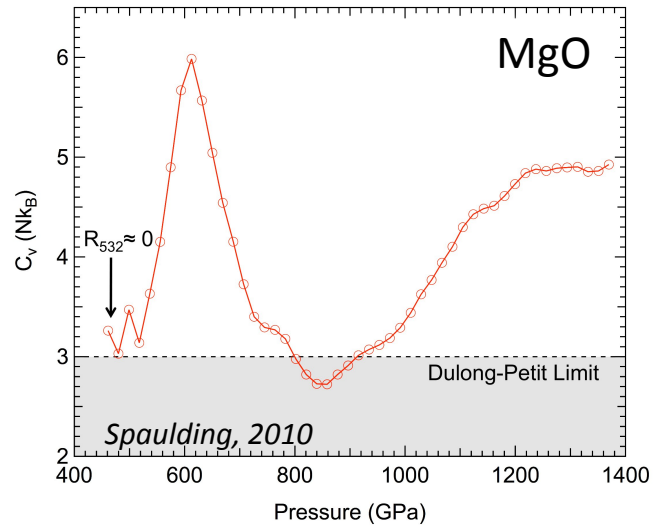


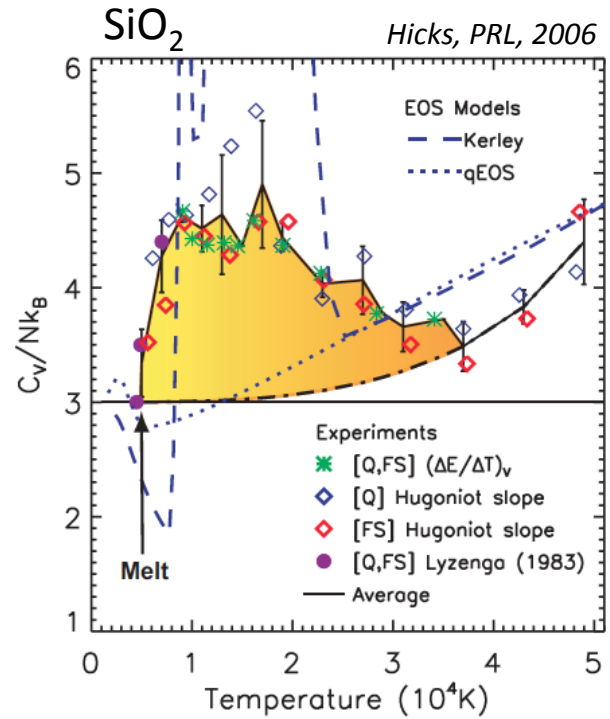


Pyrometry is a sensitive probe of the energetics of the sample across phase transitions and to potential changes in electronic structure and bonding.

Streaked Pyrometry as a Shock 'Calorimeter'







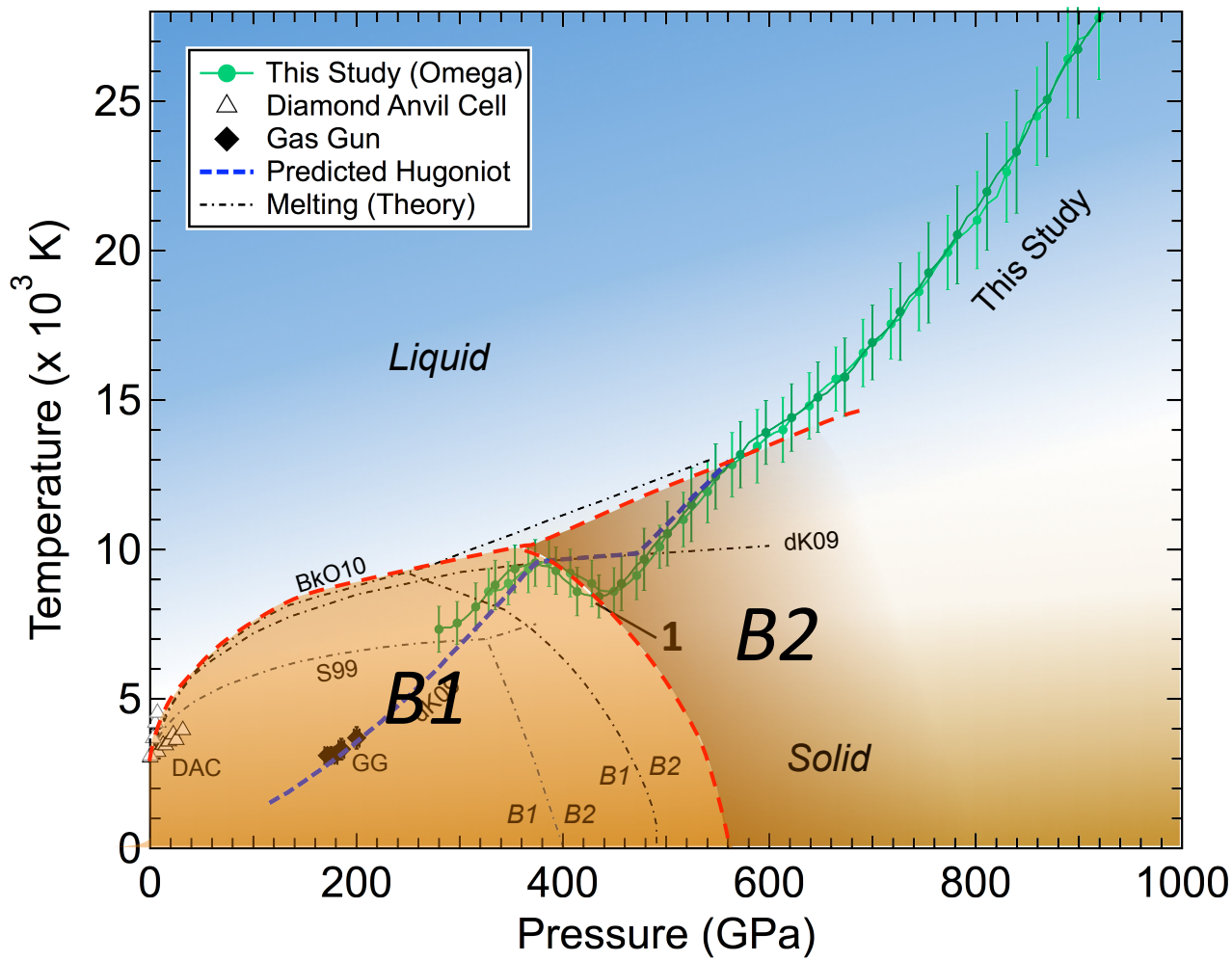
- Specific heat is estimated from the slope of the Hugoniot temperature

$$C_v = \left(\frac{\Delta E_H - \Delta E_S}{\Delta T_H - \Delta T_S}\right) \approx \left(\left.\frac{\partial E}{\partial V}\right|_H + P\right) \Big/ \left(\left.\frac{\partial T}{\partial V}\right|_H + \gamma \frac{T}{V}\right)$$

Phase Diagram and Implications for Melt, B1-B2 Transition

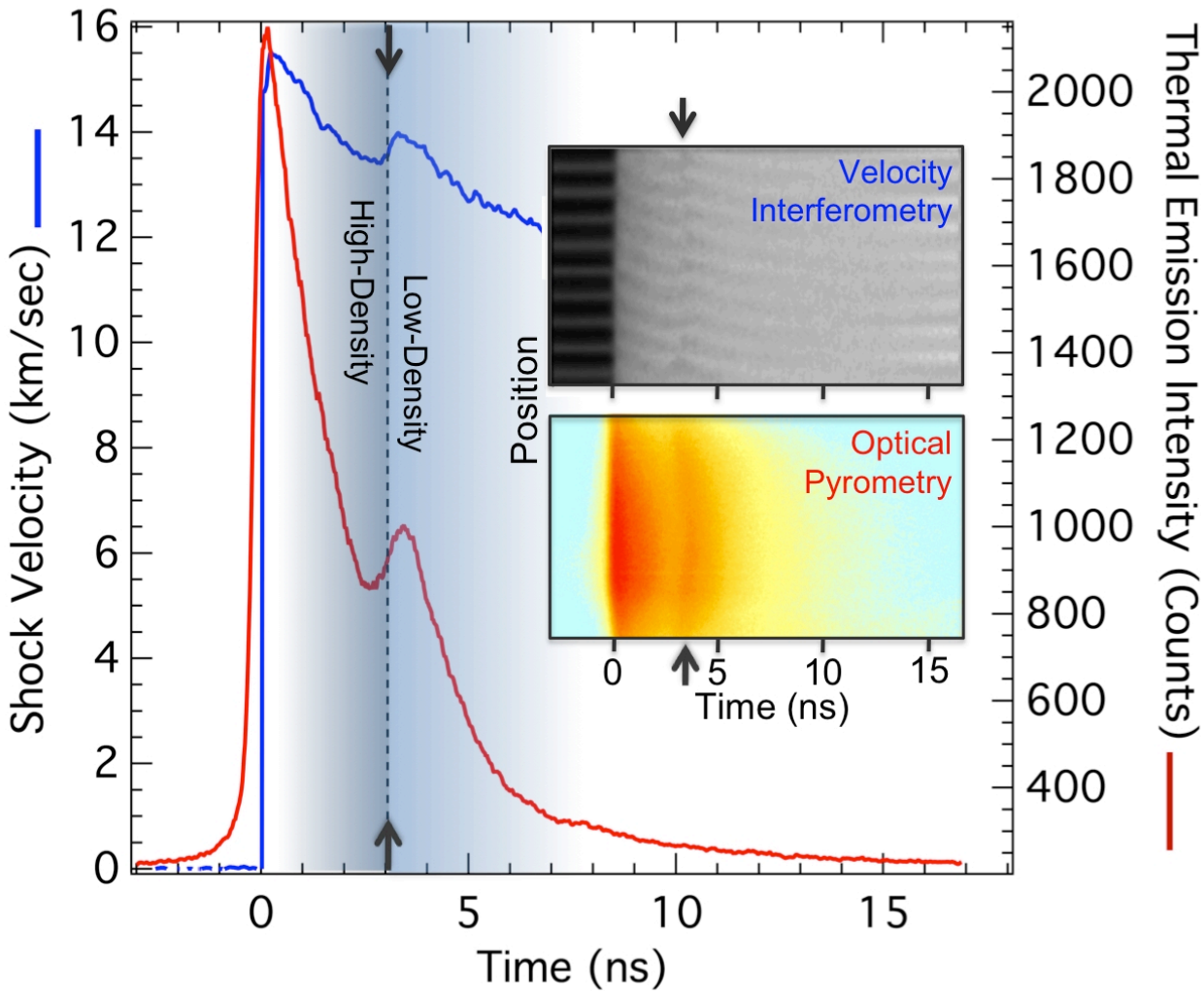
- Results are consistent with the highest predicted melting curves, suggesting MgO melts at more than twice the temperature of the CMB

- B1-B2 transition recently confirmed with in-situ diffraction (Coppari et al., 2013)



Shock Compression of $MgSiO_3$: Single-Crystal and Glass

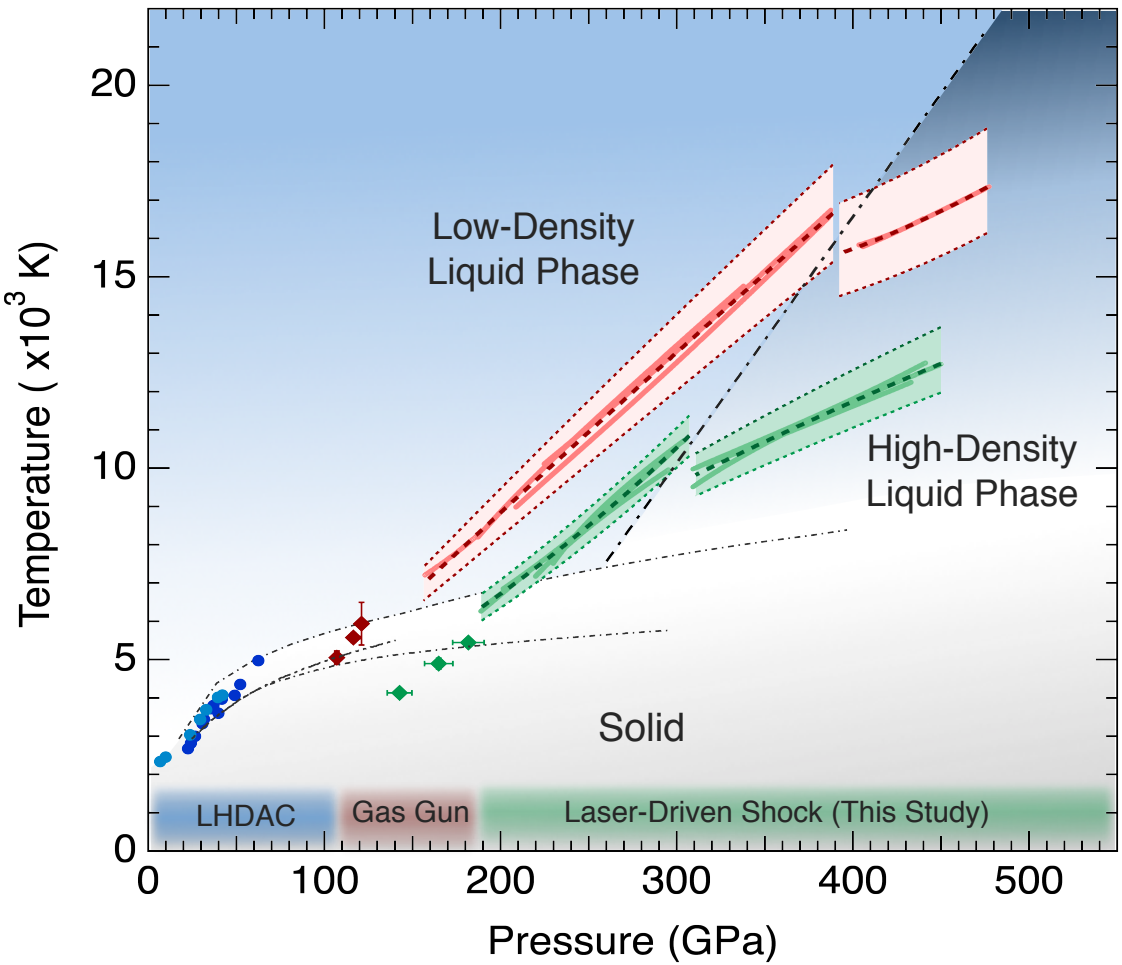
D. K. Spaulding, R. S. McWilliams, R. Jeanloz, J. H. Eggert, P. M. Celliers, D. G. Hicks, G. W. Collins, R. F. Smith, **Evidence for a Phase Transition in Silicate Melt at Extreme Pressure and Temperature Conditions,** *Physical Review Letters* **108** (2012).



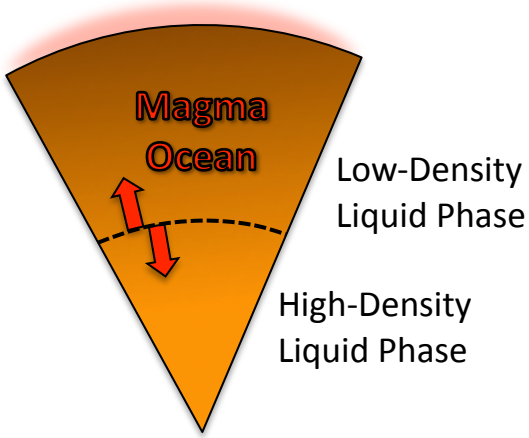
- First observations of a simultaneous change in *velocity* accompanying the increase in thermal emission
- Identical signatures observed in both starting materials (independent of drive)
- Discontinuity in U_S suggests a volume change

$MgSiO_3$ Phase Diagram – First Observations of an Apparent Liquid-Liquid Phase Transition in a Silicate Material

$MgSiO_3$ undergoes a transition between liquid states distinguished by density and entropy.



From the low-pressure to the high-pressure phase:
$\Delta V = -6.25 \pm 2.2\%$ and
$\Delta S = -2.9 \pm 0.6$ J/K · mol of atoms



$MgSiO_3$ - Alternative Interpretations?

Difficult to approach theoretically due to high temperature conditions

- Melting?

  Glass observations are at ~16kK, 4 Mbar (~2 x diamond melt)

- Dissociation?

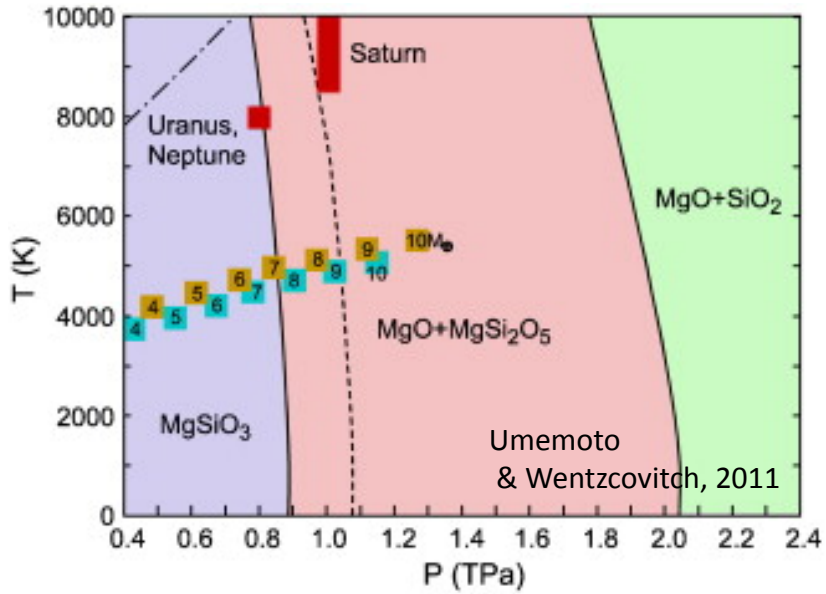
  Presumed Clapeyron slope suggests *decrease* in entropy with increasing pressure, inconsistent with predictions

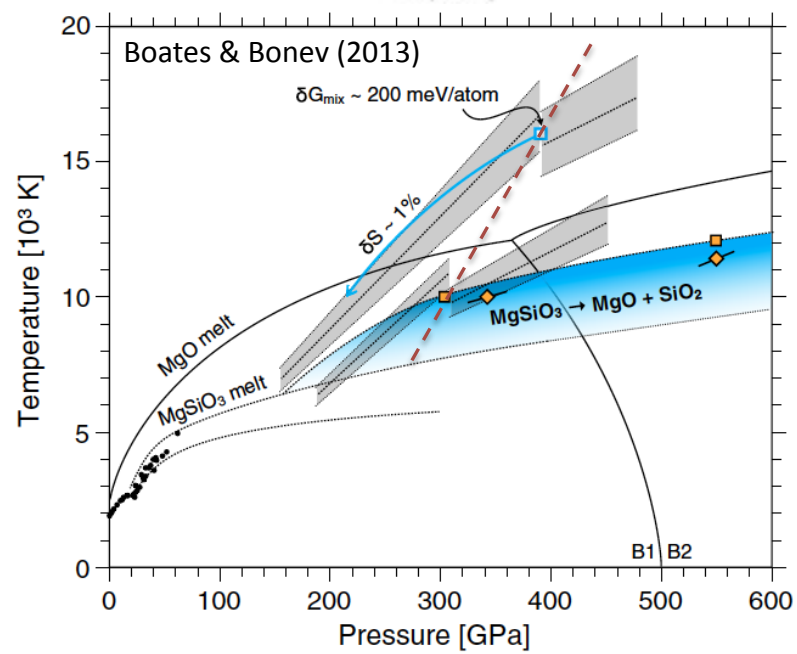
- Glass Transition?

  Requires lower temperatures

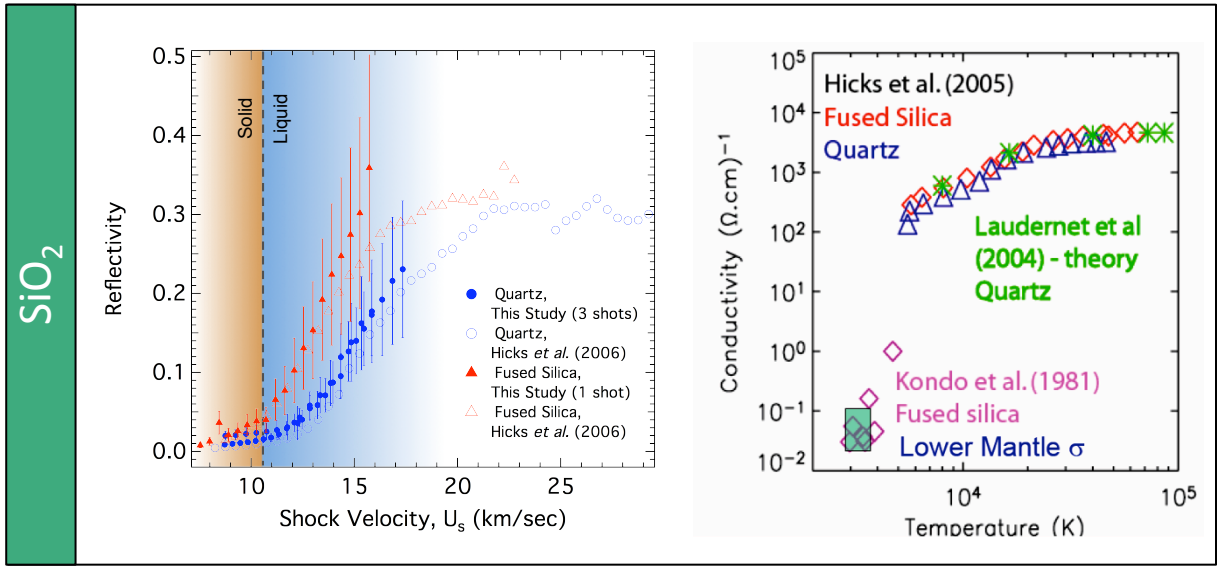
  Not seen in other decaying shock experiments (e.g. diamond, fused-silica, MgO, molecular systems)

Also see, Militzer, 2012; Zhao, 2014

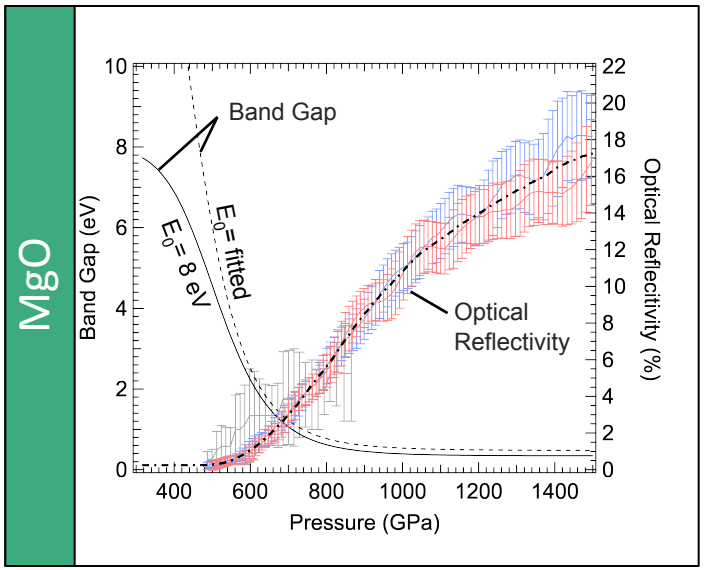


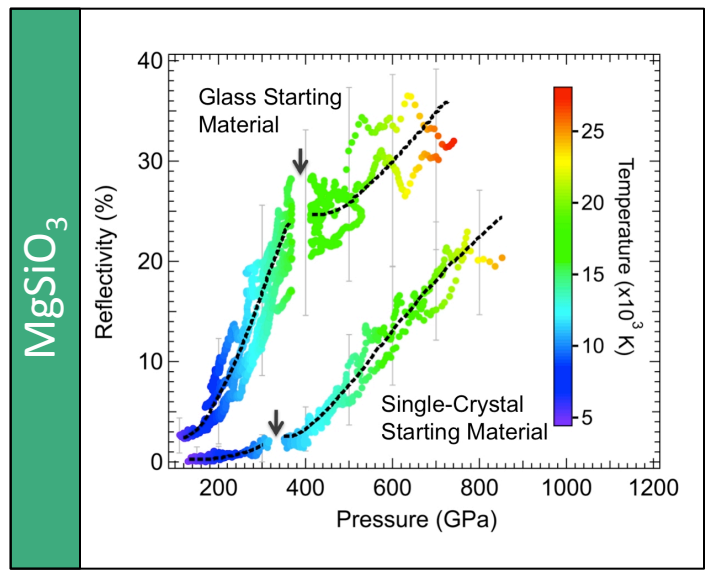


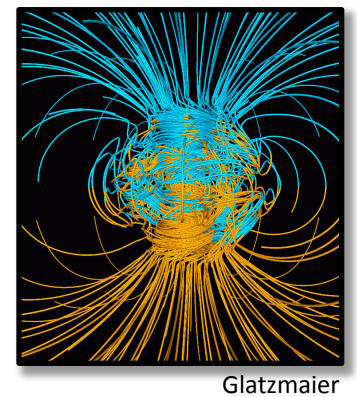
Metallic-like Conductivities at Multi-Mbar Pressures



SiO_2, MgO, $MgSiO_3$ behave like poor metals in the liquid state and may contribute to magnetic dynamo generation when molten.



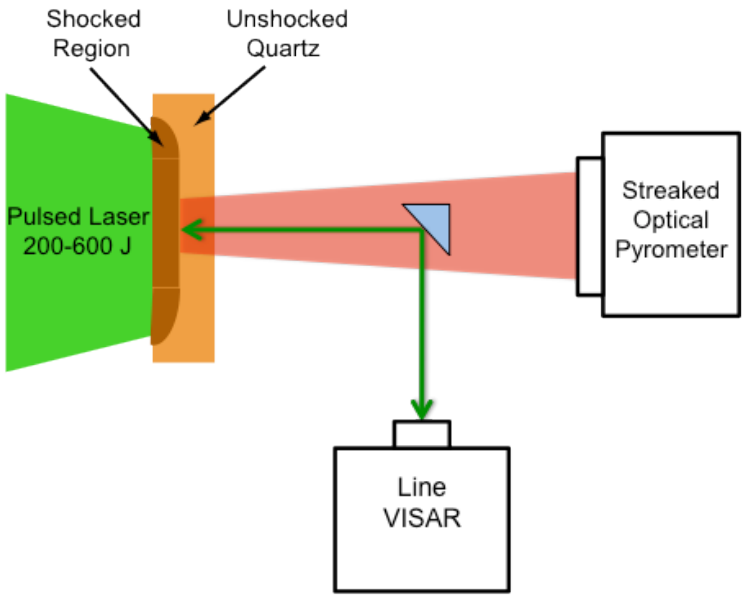


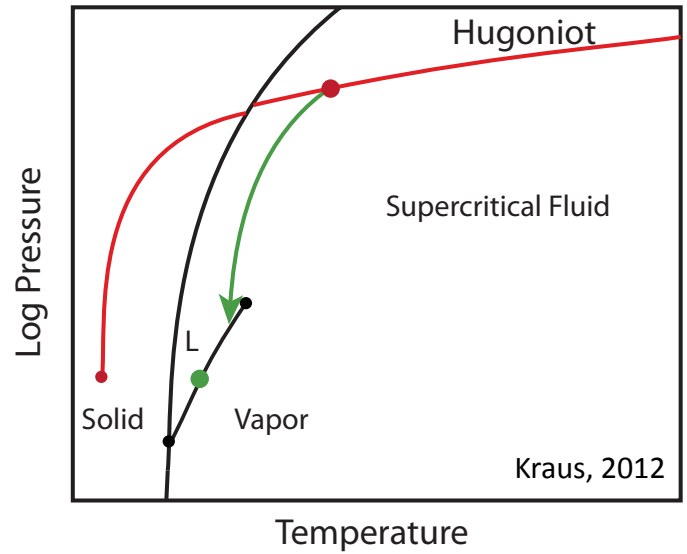


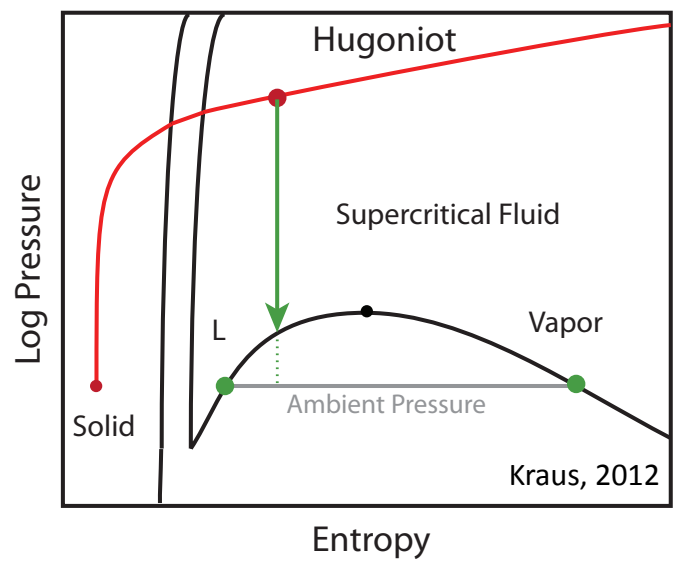
Glatzmaier

SiO_2 – Measuring the Liquid Vapor Curve at Janus

Shock and release experiments access off-Hugoniot states that are critical for understanding the thermodynamics of giant impact events.





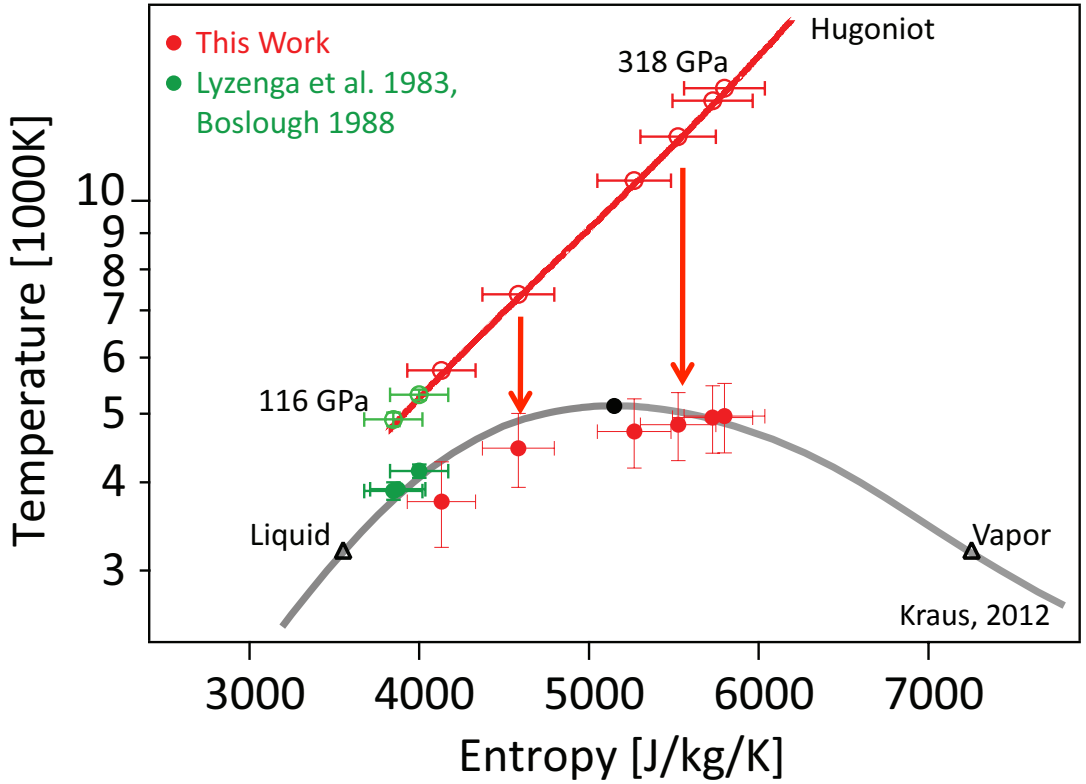


R. G. Kraus, S. T. Stewart, D. C. Swift, C. A. Bolme, R. Smith, S. Hamel, B.D. Hammel, D. K. Spaulding, D. G. Hicks, J. H. Eggert, and G. W. Collins. **Shock Vaporization of Silica and the Thermodynamics of Planetary Impact Events**, *J. Geophysical Research*, 2012.

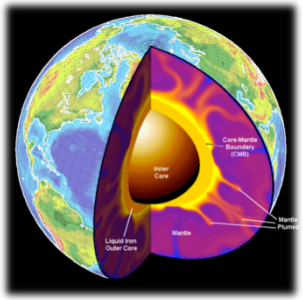
SiO_2 – Measuring the Liquid Vapor Curve at Janus

Post-shock temperatures are buffered by the liquid-vapor dome, allowing identification of the critical point through multiple shock and release experiments.

Vapor is important for properly modeling impact events! → Important to extend this method to other planetary constituents

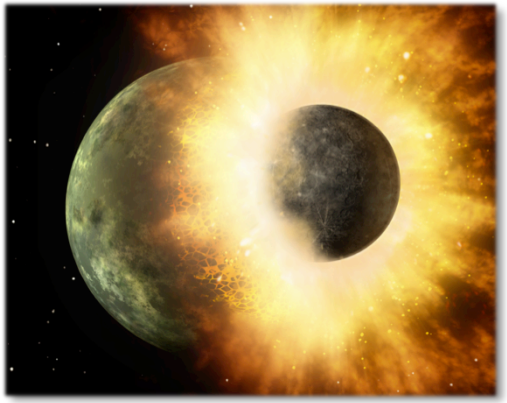


Summary



- Experiments have revealed predicted as well as unexpected phase changes in the fundamental constituents of the Earth's interior.

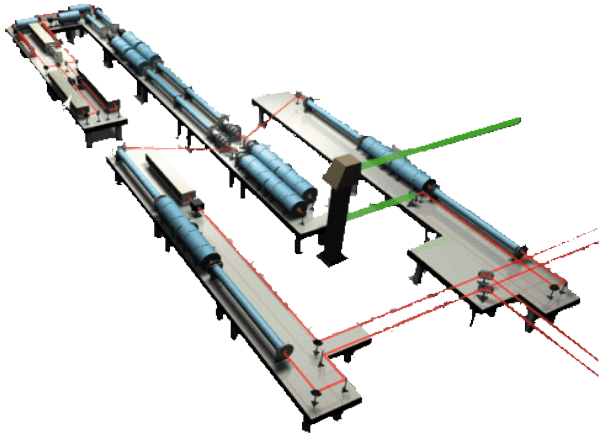
- Shock and release experiments are valuable for exploring off-Hugoniot states relevent to melt and vaporization in giant impact events.



- Planned experiments will further examine the potential for related shock-induced chemistry

Suggestions for Discussion – JLF Improvements and Infrastructure

- Energy stability and reliability

- Additional staff may be helpful so that at least one person can assist on a given platform, particularly early in an experimental campaign.

- Diagnostic 'protection' and dedicated diagnostic representatives.