Probing the Role of Water in Shaping Planetary Mantles

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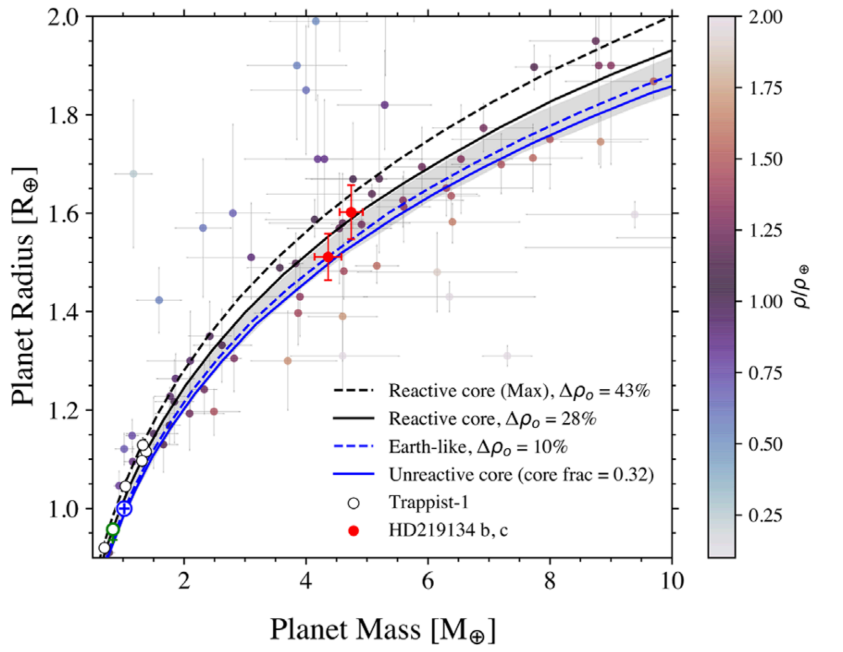
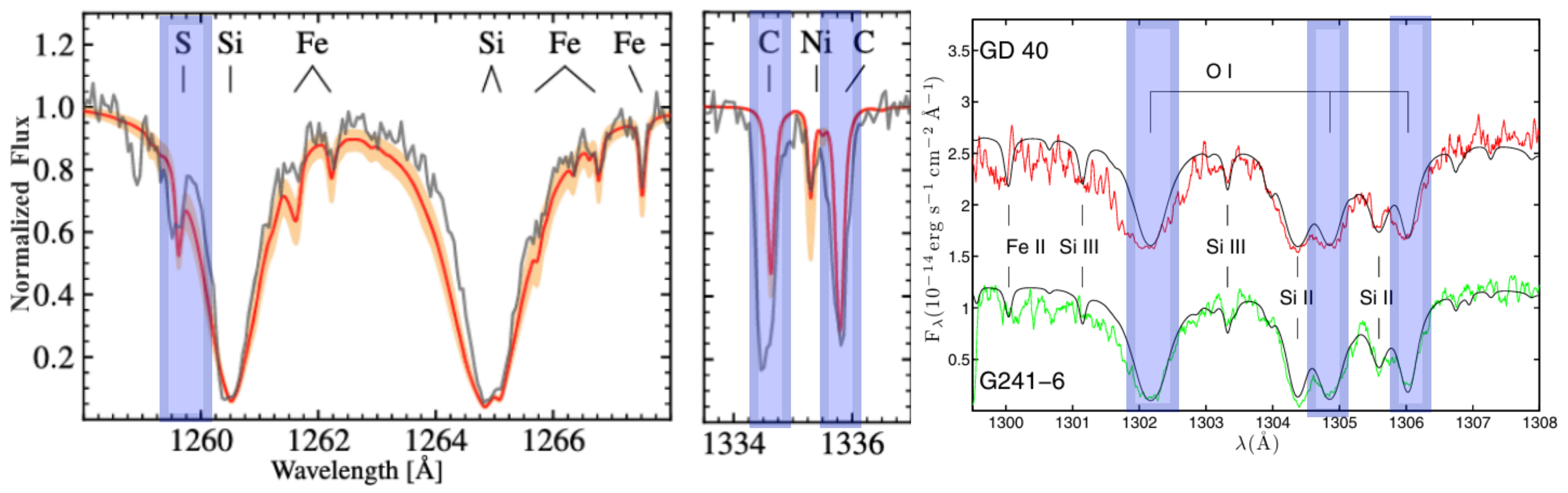
Planetary Creation and Destruction

- Throughout a planetesimal's accretion and evolution, it experiences very energetic impacts reaching high temperatures and pressures (10^5 K and 10^3 GPa).
- The retention of primordial volatiles, like water, in the Earth's mantle[1] past any large accretionary impacts implies that there's a mechanism allowing their long-term retention in planetary interiors.
- The retention of water in planetary mantles throughout their evolution is not well incorporated into equations of state essential to models of planetary formation and structure.



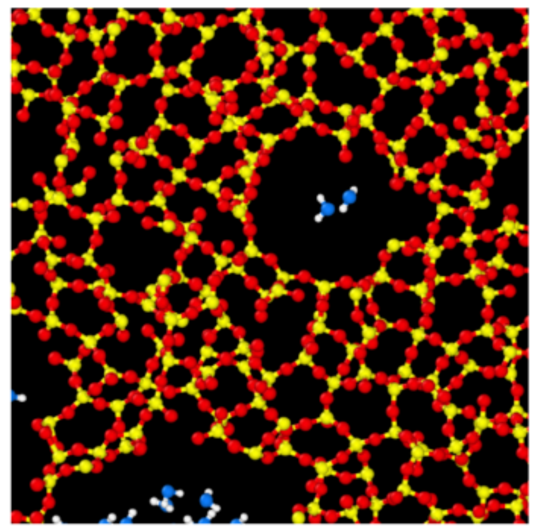
Schlichting & Young. 2022[2] — Exopanet mass-radius curves incorporating a thermochemical equilibrium planetary evolution model, which sequesters hydrogen in the planet's core, demonstrating a remarkable ability to encompass a significant fraction of low-mass rocky planets and Super-Earths.

- Observations of polluted spectra from WDs give an insight into the composition of exoplanets.
- Among the pollutants in WD spectra are volatiles such as sulfur, chlorine, carbon, and oxygen- all atomic species thought to be lost during accretion processes due to the lower than chondritic abundances in the Earth.



Hoskins et al. 2020[3] (left and middle) and Jura et al. 2012[4] (right) — WD spectra indicating volatile presence amongst other planetary remnants. Volatile species of interest are highlighted in blue.

Silicate Melts Retaining Water



Clark et al. 2023[5] — LAMMPS molecular dynamics simulation of hydrated SiO_2 melt with H_2O in voids. Silicate Si & O are yellow & red; Water H & O are blue & white respectively.

- Silicate melts lack long-range order and have variable network polyhedral ring size. Volatile species may be stored in the interstitial sites.
- Performing shock-release experiments through a range of high pressures (up to 200 GPa) and temperatures ($T > 4000$ K) replicates P-T conditions of planetary interiors throughout their lifespans.
- Shock-release experiments measure sounds speed, compressibility and other thermodynamic parameters.
- Ultimately derive equations of state (EOS) for SiO_2 melts using derived bulk modulus and compressibility.

$$P = 3K_0\eta^{2/3}\left(1-\eta^{-1/3}\right)\exp\left[\tfrac{3}{2}\left(K_0'-1\right)\left(1-\eta^{-1/3}\right)\right] \quad 1)$$

$$P = \tfrac{3}{2}K_0\left(\eta^{7/3}-\eta^{5/3}\right)\left[1+\tfrac{3}{4}\left(K_0'-4\right)\left(\eta^{2/3}-1\right)\right] \quad 2)$$

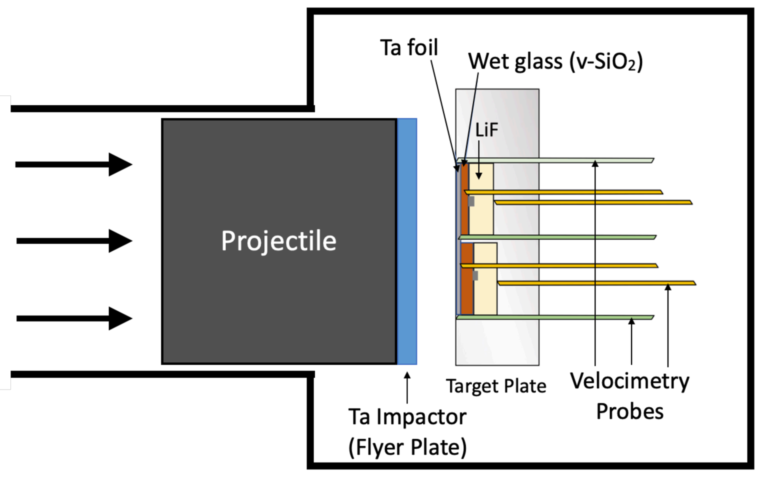
Seager et al. 2007[6]. For equations 1) and 2) K_0 is the bulk modulus of the material, K_0' is the pressure derivative of K_0, and η is the compression ratio of the material with respect to the ambient density.

RHINO Experimental Setup

We can recreate the extreme P-T conditions of planetary formation impacts and impacts throughout polluted white dwarf debris disks using two of Sandia National Laboratories' experimental platforms to create SiO_2 melts at high pressures ($P \geq \sim70$ GPa).

STAR Gas Gun

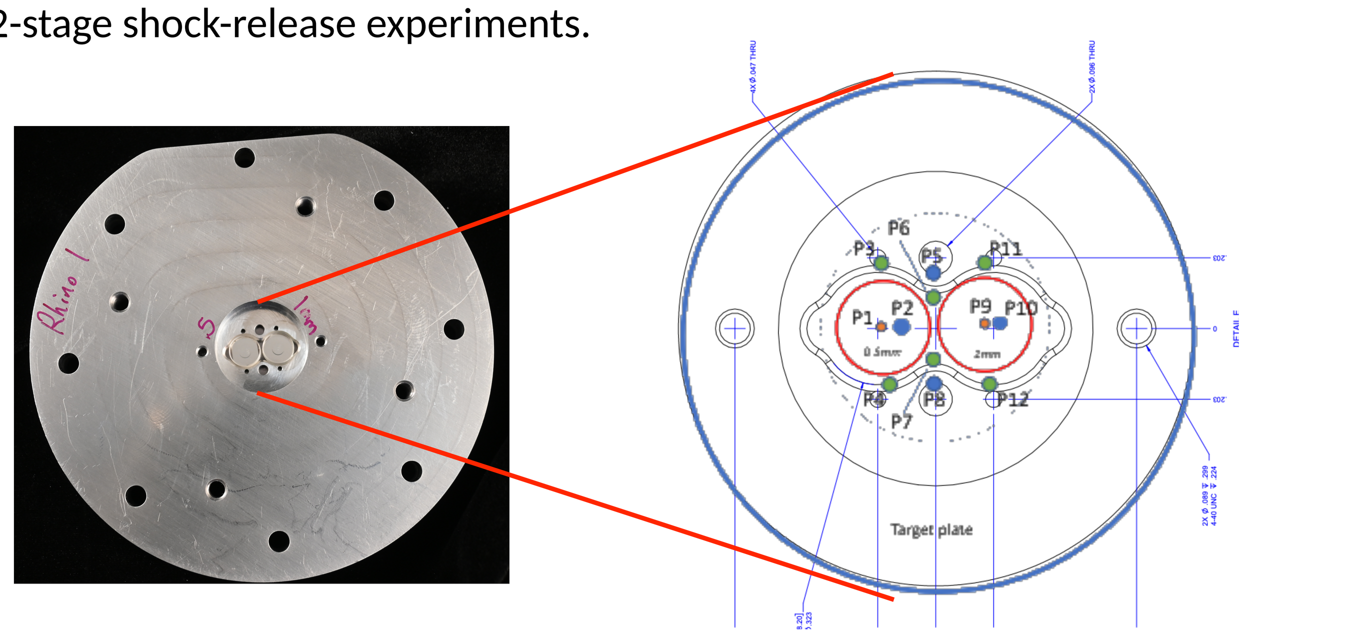
- Launches projectiles down a barrel to strike target samples of dry & damp v-SiO_2.
- Used to produce pressures ranging from 70-150 GPa.
- Can produce multiple subsequent shocks, resembling multiple impacts during planet formation and polluted white dwarf debris disks.
- Used to complement shock-ramp experiments on hydrated silica using the Z-machine.



Simplified model of the end of the gas gun barrel and the target chamber. The sample (SiO_2) and target window (LiF) are set in the target plate.

Target Plate

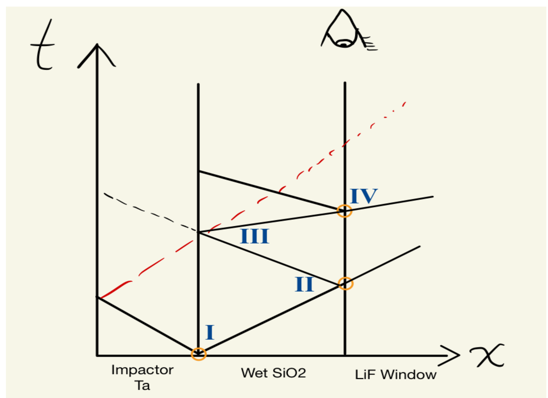
- Two silica samples are set within a target plate to compare results derived from each shock.
- Probes are located throughout the plate and samples to collect VISAR and PDV data of the impact and resulting shock states.
- Six 2-stage shock-release experiments.



RHINO dual-sample target setup with VISAR probes being green, PDV blue, and Romulan (VISAR & PDV) probes being orange.

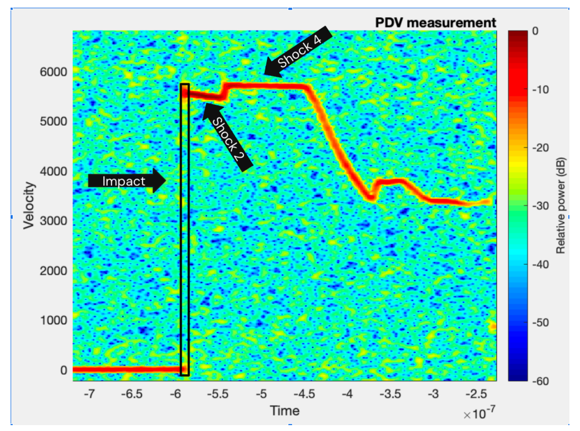
Data Collection and Analysis

- VISAR (Velocity Interferometer System for Any Reflector) and PDV (Photon Doppler Velocimetry) data are collected for each sample in the two-stage shock states of the water-doped SiO_2.
- Analysis of the shock states allows for the characterization of the effects of water on SiO_2 melts at these high P-T conditions.
- Errors in the VISAR probes and PDV probes in two shots.
- The first shock state at the Ta-SiO_2 interface provides a shock velocity alongside the particle velocity and stress using the Rankine-Hugoniot equation.



$$P = \rho_{Ta}[A_{Ta} + b_{Ta}(u_I - u_P)] * (u_I - u_P)$$

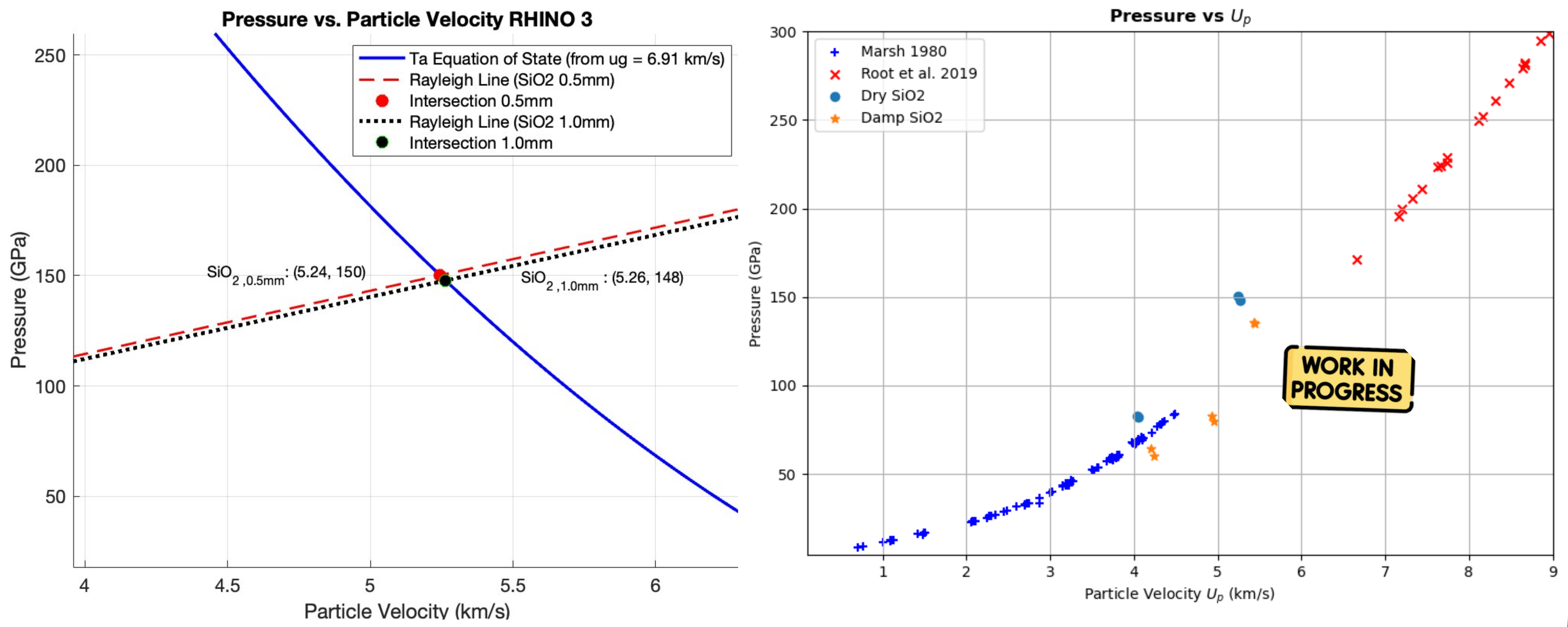
$$P = \rho_{SiO_2} * u_S * u_P$$



Example of a velocity curve in PDV showing the two stages and shock states

Results

- Solving for the intersection of the Ta EoS and the Rayleigh line yields somewhat consistent results between the 0.5 and 1 mm thick SiO_2 samples.
- Preliminary results indicate that the damp SiO_2 may have a trend of producing a higher particle velocity for a given shock velocity.
- Differences in results between the .5 & 1 mm samples indicate issues with the experimental setup or unexpected behavior that is not being analyzed properly.



Impedance matching example using Ta hugoniot EoS from Marsh 1980[7] and pressure and U_p plot using fused silica hugoniot data from Marsh 1980[7] and Root et al, 2019[8].

Future Work

- Exploring a different experimental design to prevent VISAR and PDV failure and reduce data spread.
- The RHINO data helps fill in a data gap, complementing shock-ramp experiments on the Z-machine.
- Expanding the range of pressures being explored will help provide a clearer trend and elucidate the true effect of water on SiO_2 at high pressures.
- Given the volume fraction of the solar system's rocky planets and the water content of extrasolar rocky bodies[9], the effect of water can help further our understanding of the structure and evolution of rocky exoplanets.

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