SAND2013-5208C

From Z to Planets

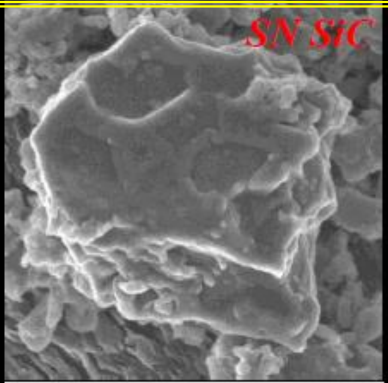
S. B. Jacobsen[1], R. G. Kraus[1], T. R. Mattsson[3], M. I. Petaev[1], D. D. Sasselov[2], S. Stewart[1], L. Zeng[2], M. P. Desjarlais[3], D. H. Dolan[3], D. G. Flicker[3], M. D. Knudson[3], R.W. Lemke[3], S. Root[3], C. T. Seagle[3], and L. Shulenburger[3]

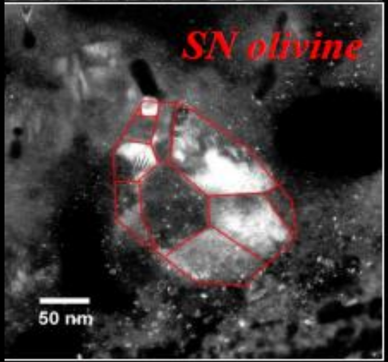
[1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138.
[2]Department of Astronomy, Harvard University, Cambridge, MA 02138.
[3]Sandia National Laboratories, Albuquerque, NM 87185-1189.

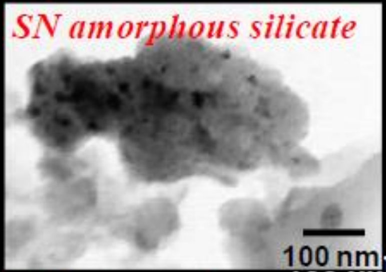
DOE/NNSA Grant # DE-AC04-94AL85000 to Harvard University

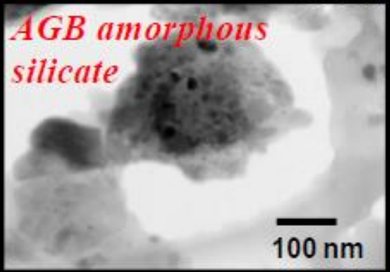
Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

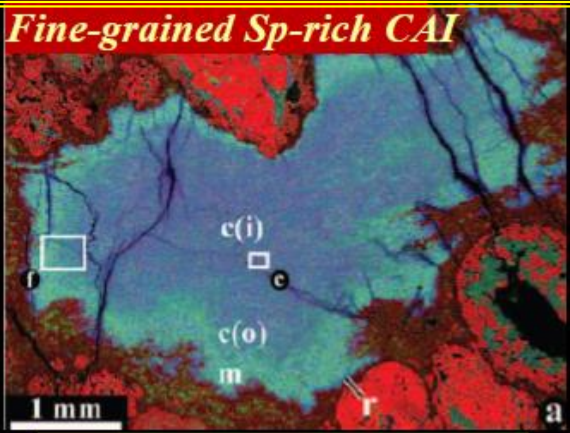
Solids evolution: StarDust → Meteorites → Planets

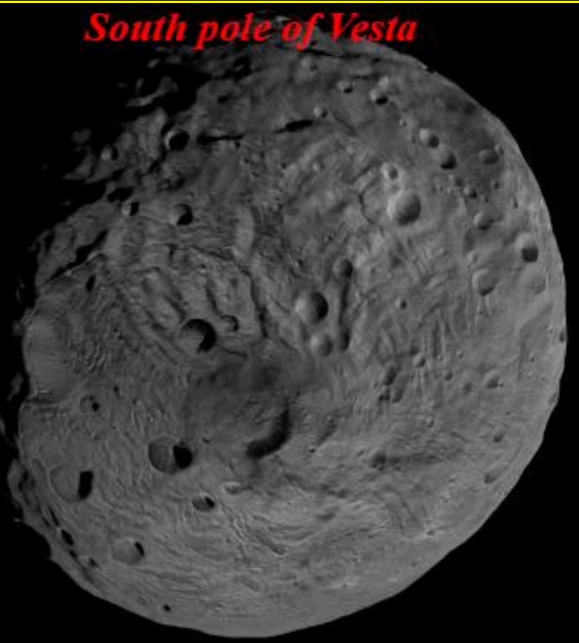




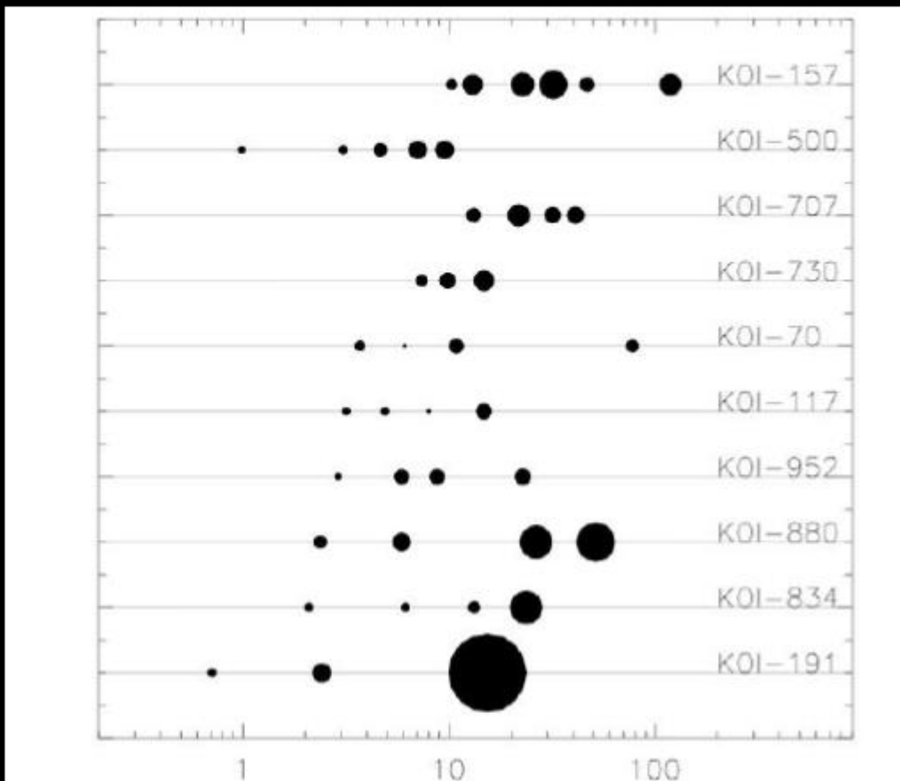








The Kepler mission multi-planet transiting systems

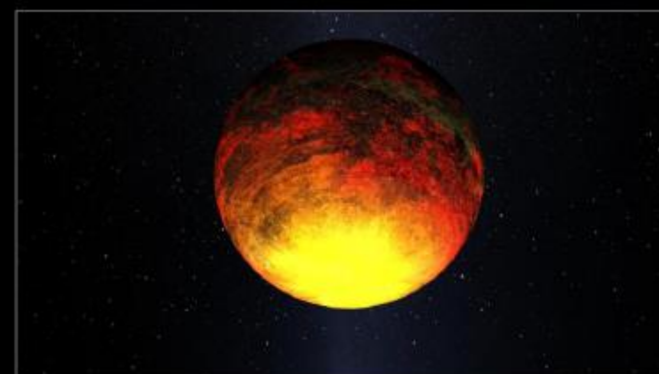


Period (days)

Fabricky and Kepler Team (2011)

Kepler's First Rocky Planet: Kepler-10b

Kepler is giving us new knowledge about the frequency of near Earth-size planets.



Products

- Graduate student 1: Richard Kraus (finished PhD in May 2013)
- Graduate student 2: Li Zeng (will finish in 2014?)
- Paper I: Shock Thermodynamics of Iron and Impact Vaporization of Planetesimal Cores by Richard G. Kraus, Seth Root, Raymond W. Lemke, Sarah T. Stewart, Stein B. Jacobsen, and Thomas R. Mattsson (submitted to Nature)
- Paper II: The effect of temperature evolution on the interior structure of solid planets by Li Zeng and Dimitar Sasselov (in preparation)
- Web-based tool for planet structure (Li Zeng)
- Poster at 2012 fall AGU: Shock-Induced Melting and Vaporization of MgO by Multi-Mbar Shock and Release Experiments by Richard G. Kraus, Seth Root, Raymond W. Lemke, Daniel H. Dolan, Christopher T. Seagle, Marcus D. Knudson, Luke Shulenburger, Michael P. Desjarlais, Sarah T. Stewart1, Stein B. Jacobsen, Dawn G. Flicker, and Thomas R. Mattsson.
- Papers on Fe, MgO and thermodynamic calculations of planetary chemistry during Galactic evolution will be coming within the next year.

Formation and Interior Structure of Earth-like Planets

Planet models

- Onion shell model
- Chemical differentiation model
- Collisional stripping model

Exoplanets

- ***Mass – radius*** plot is the only information to constrain the structure and composition of exoplanets.
- How well can we use the data to answer the 'composition' question?

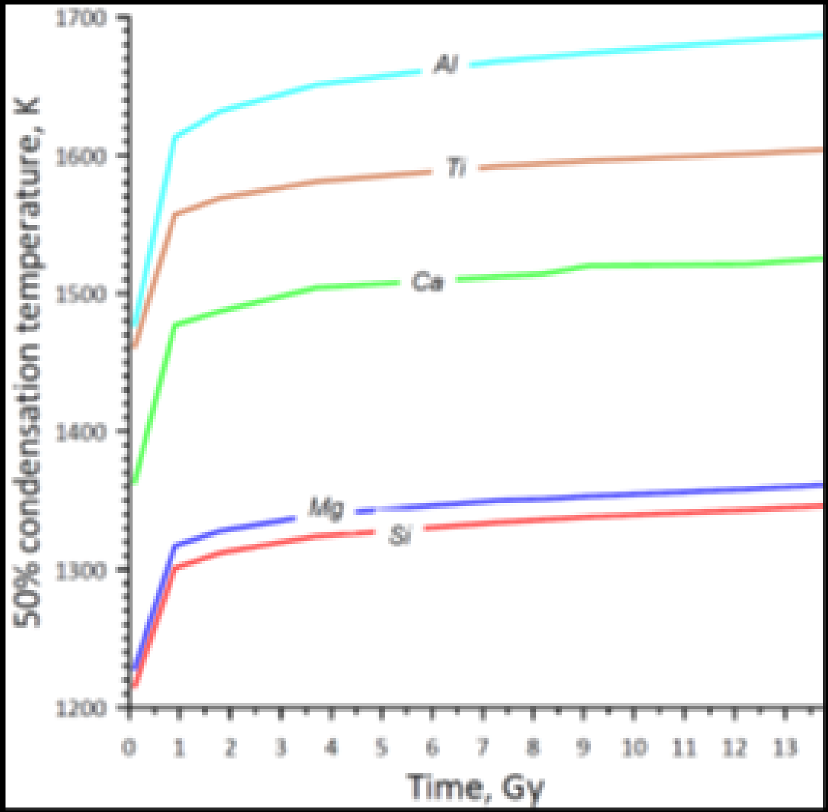
We need

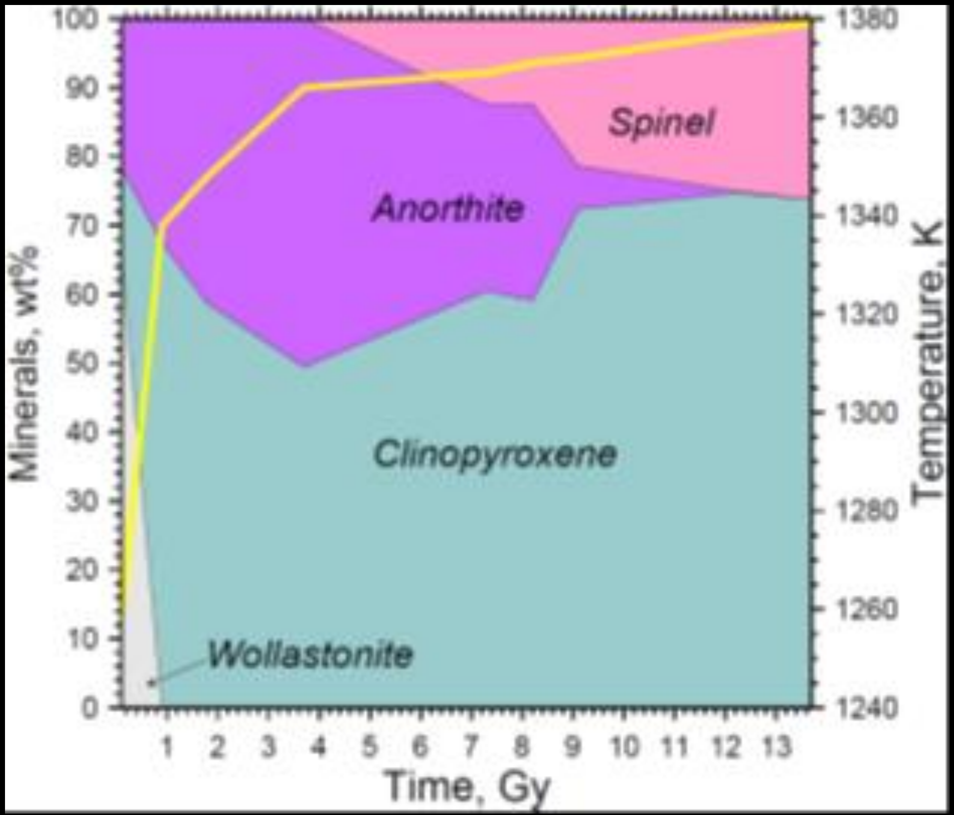
- Precise EOS (w/Z) for:
  - MgO, SiO_2, $MgSiO_3$, Fe, Fe-alloy
- For P-T conditions up 10 Earth-mass planets

Current questions

- ***What is causing the extensive chemical equilibration in large planets?***
- ***How can we understand late veneers that make planets habitable?***

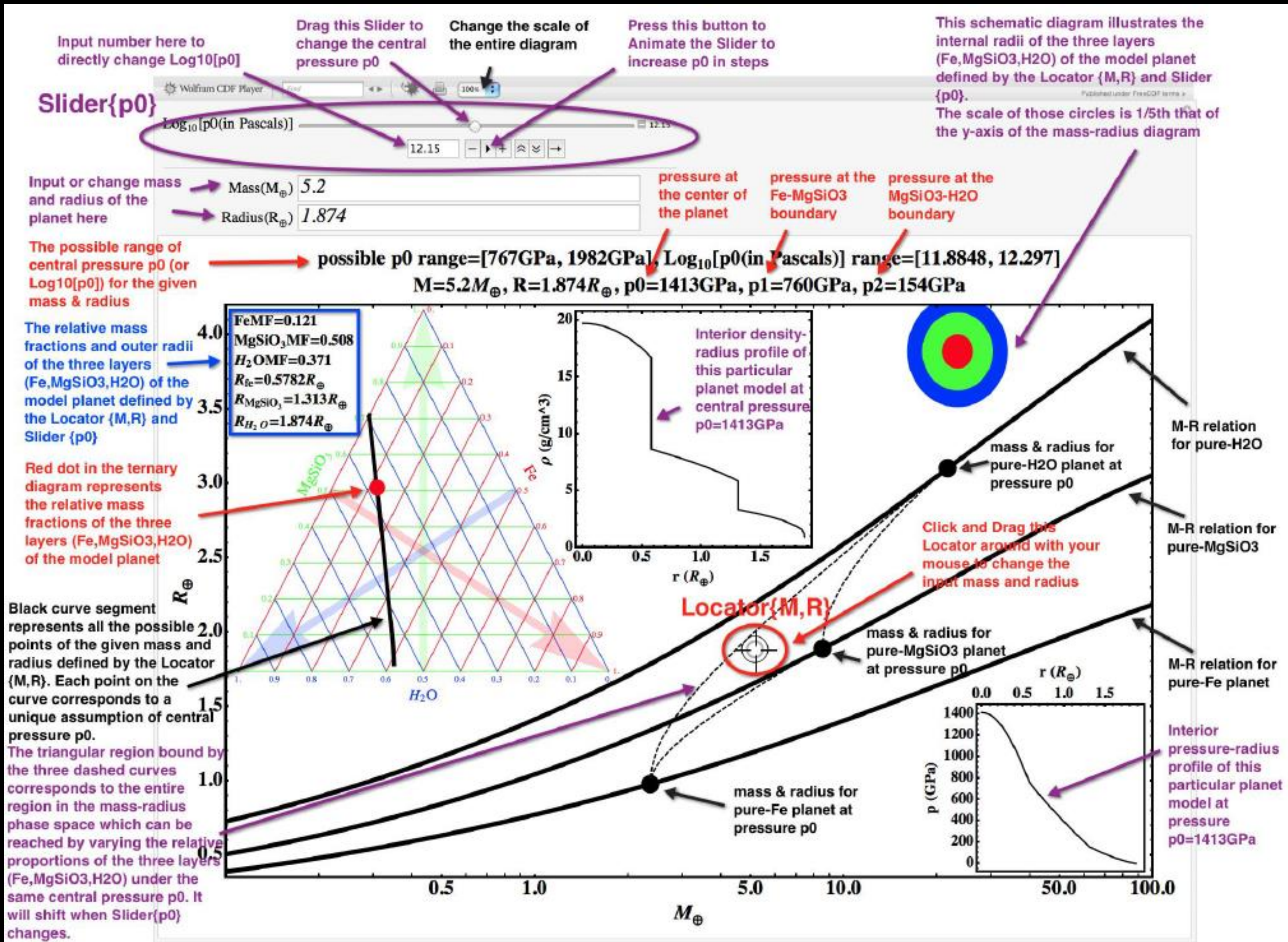
Chemical Evolution of Earth-like Planets in our Galaxy



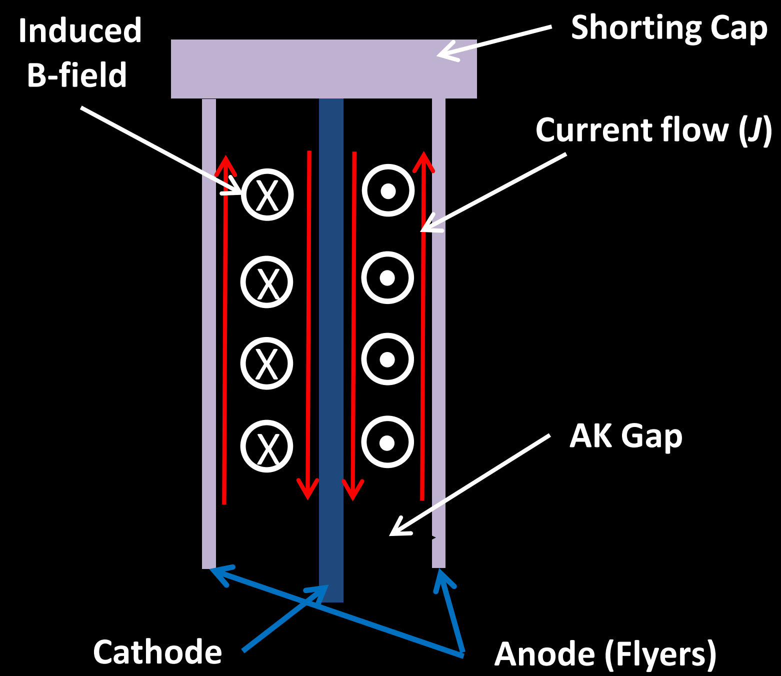


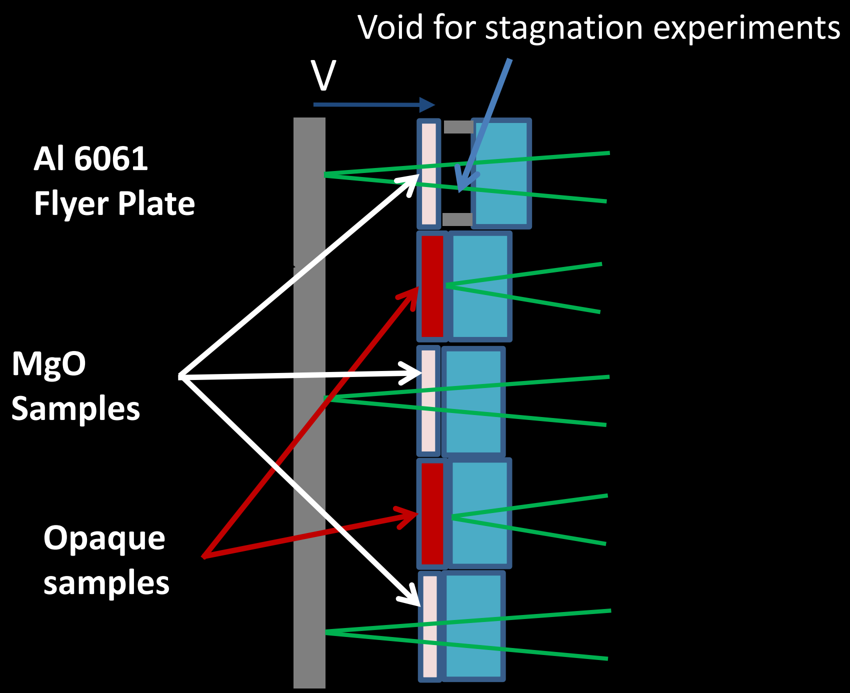
Left panel: 50% condensation temperatures of the elements Mg, Al, Si, Ca and Ti during the evolution of our Galaxy. Time 0 is the Big Bang and 9.1 Gy is the time of formation of our solar system. **Right panel:** Mineralogy of the refractory component (CAIs) during the evolution of our Galaxy. The temperature of each assemblage is 1 K above the condensation temperature of metal or olivine whichever condenses first.

Web-based Interactive Tool for Planet Structure



Z: Experimental Setup





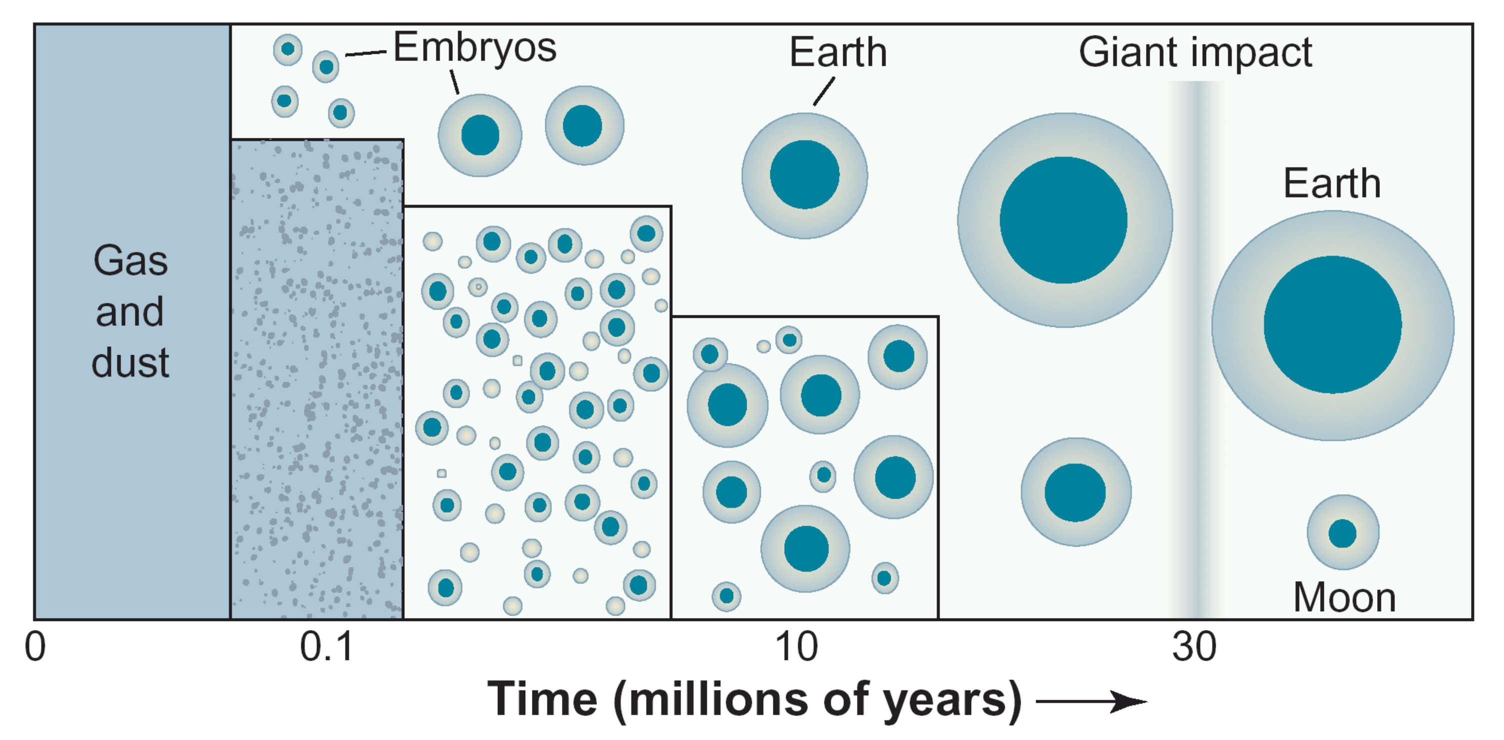
- Current pulse loops through shorting cap inducing a *B* – field.
- Resulting *J x B* force accelerates anodes (flyers) outward up to 40 km/s
- Asymmetric AK Gaps result in two different flyer velocities (two Hugoniot points per experiment

- Multiple samples per experiment
- VISAR used to measure flyer velocity
- Pyrometry for temperature measurements

Z: Experiments

- We have performed 5 dedicated experiments so far at Z with 2 ride alongs
- The impact velocity range has been from 14 to 26 km/s.
- Each experiment has two target panels, so you can think of 5 dedicated experiments as really 10 different impact experiments, where 3 of those have been on iron and 7 have been on MgO.
- To date, the role of shock-induced vaporization of iron cores during planet formation has not been assessed, which is likely a result of the poorly constrained thermal equation of state of iron and the high value estimated for the shock pressure required to initiate vaporization upon decompression, 887 GPa.
- Here we present a new determination of the entropy on the iron Hugoniot and thereby the shock pressure required to vaporize iron.

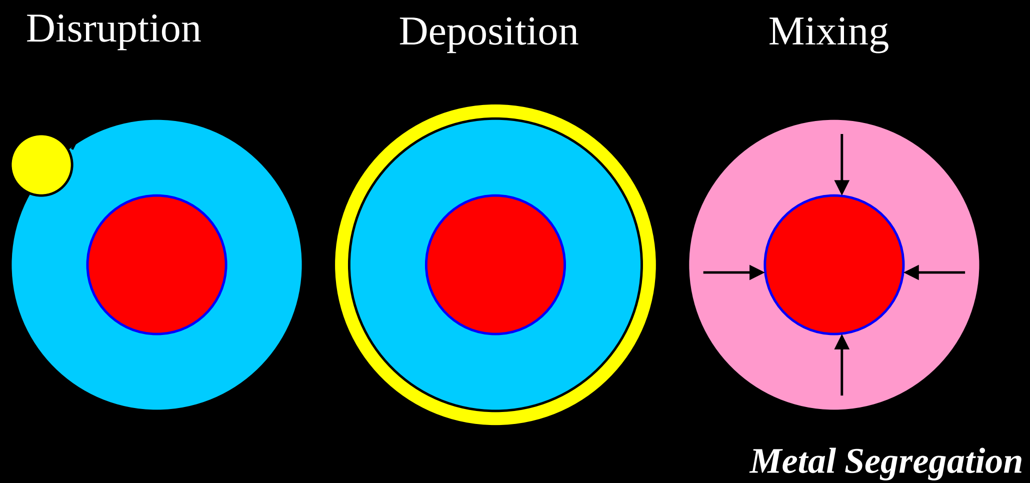
Motivation 1: The Formation of Earth



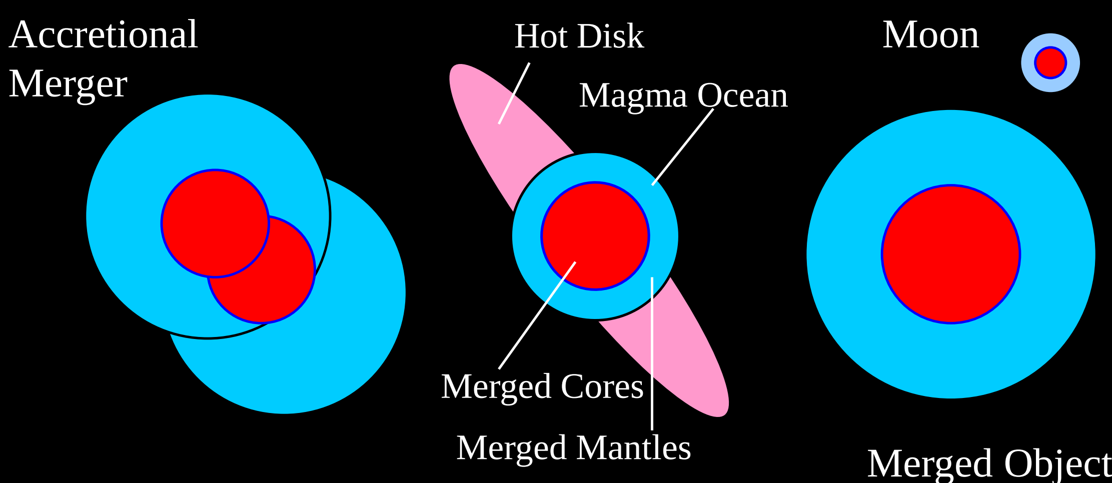
The first new solid grains formed from the gas and dust in the Solar Nebula some 4567 million years ago. Within 100,000 years, the first embryos of the terrestrial planets had formed by planetesimal accretion. Understanding the behavior of the iron metal cores and silicate mantles during this process is extremely important for interpreting the record of this process found in meteorites and terrestrial planet materials.

Motivation 1: The Formation of Earth

Fully Equilibrative Accretion:



Core-penetrative Accretion:



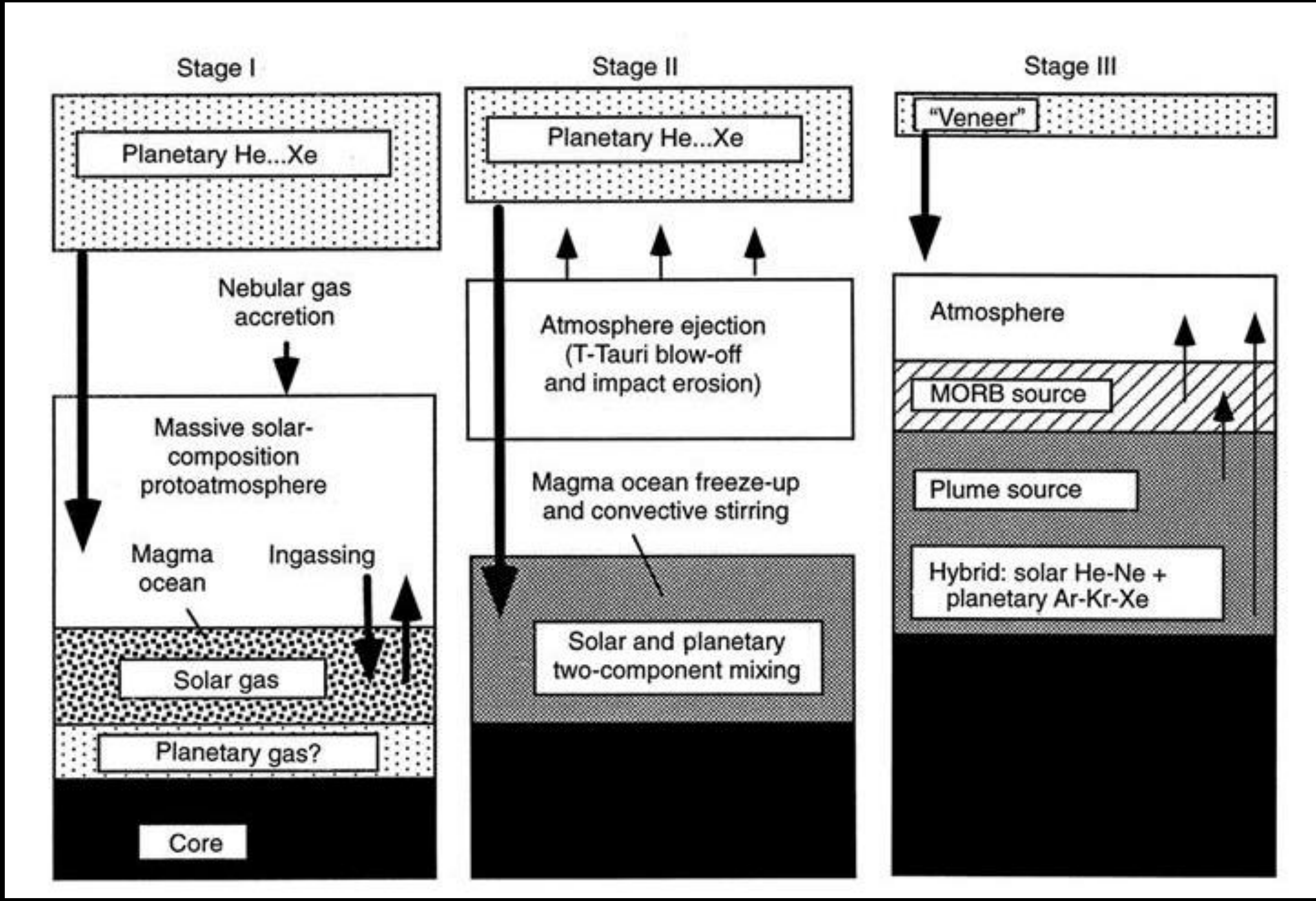
Tthe degree of mixing and chemical equilibration between the iron cores of planetesimals and the mantle of the growing Earth strongly affects our understanding of the timing of Earth's core formation and the origin of the unexpectedly large concentration of highly siderophile elements (HSEs) in Earth's mantle.

Motivation II: Early Atmosphere and Late Veneer (Noble Gas Evidence)

Stage I :proto-Earth grows large enough to accrete a massive H_2-He protoatmosphere directly from the nebular gas.

This supports a global magma ocean into which solar gases dissolve and through which metal rains out to form the proto-core.

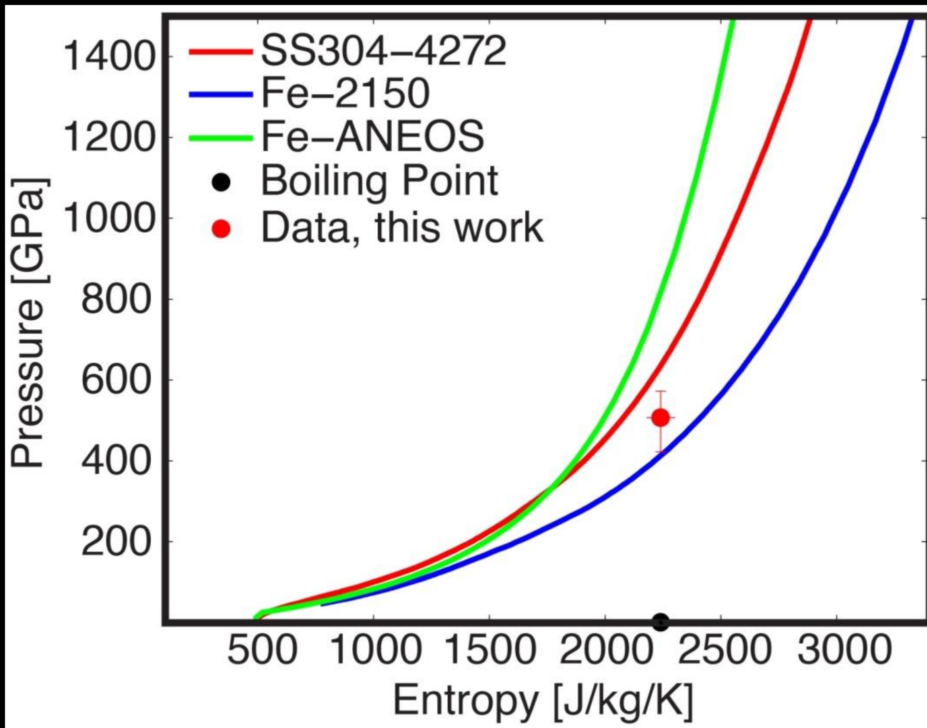
Stage III began when the solar UV luminosity decreased to a level allowing an atmosphere to be retained and grown by mantle degassing and accretion of volatile-rich matter ("late veneer").

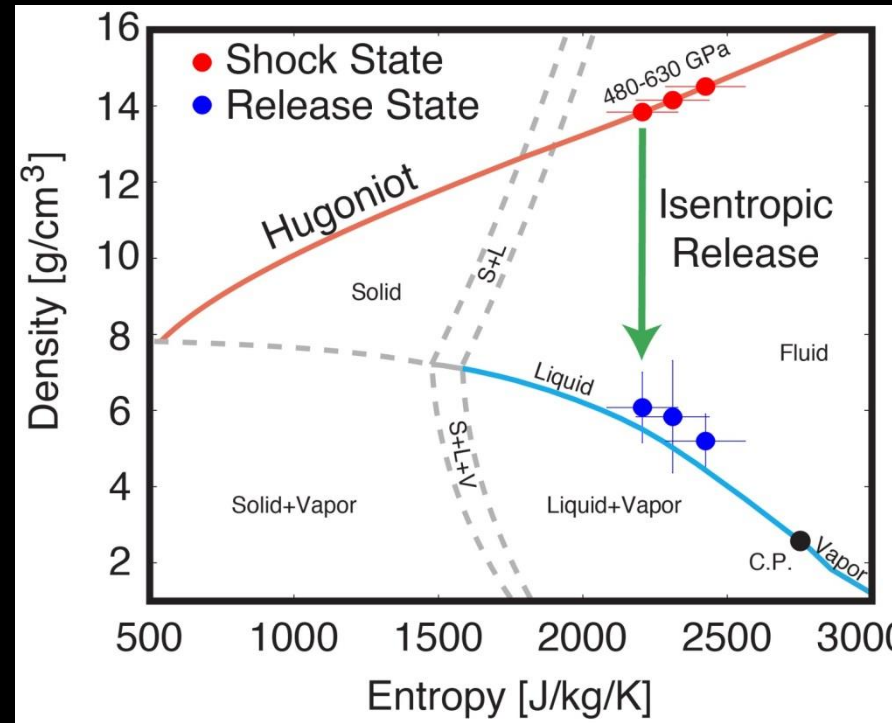


< 5-10 Myr ~ 30-150 Myr

Late veneers make planets habitable so testing this model is extremely important?

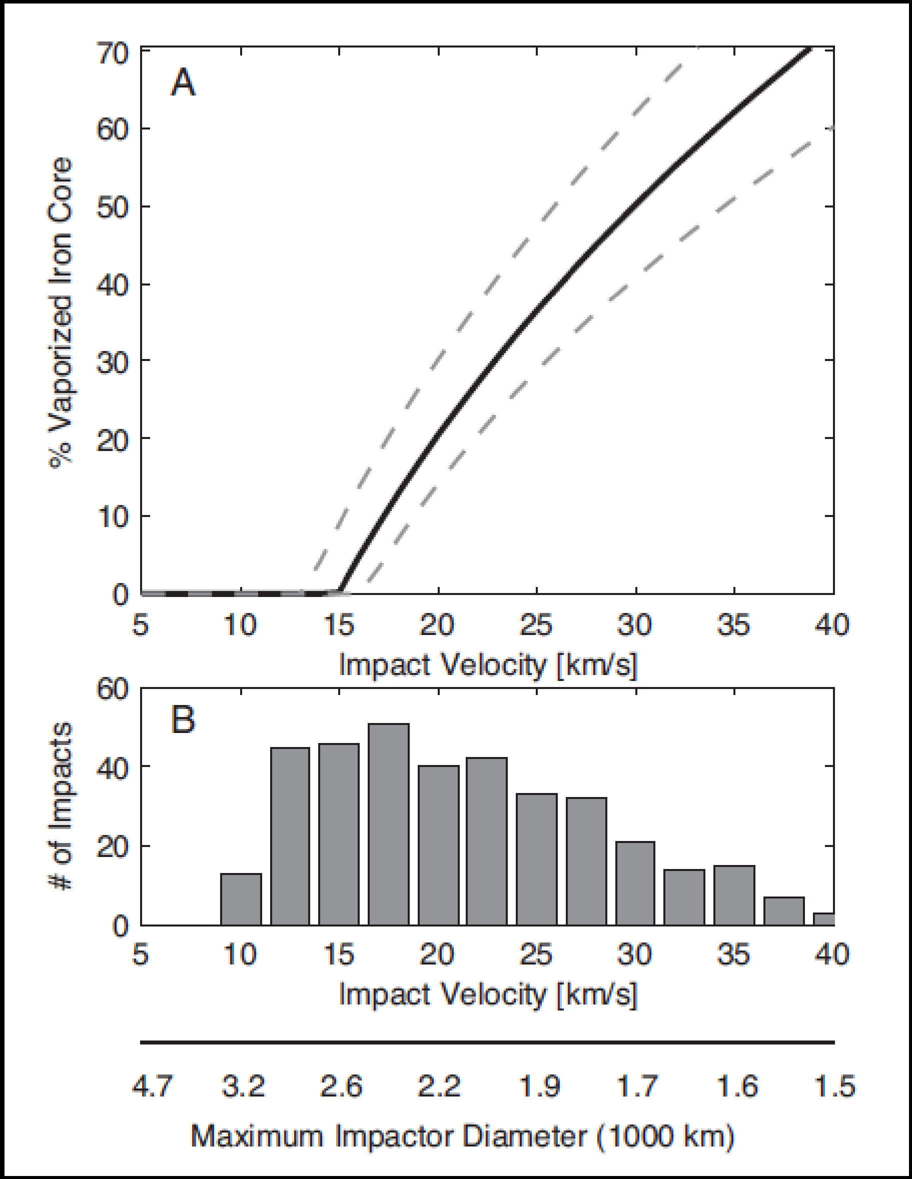
Fe experimental results





Entropy on the iron Hugoniot. Comparison of the SESAME 2150 EOS for iron, the ANEOS EOS for iron, and our data point for the entropy on the iron Hugoniot. Also shown is the entropy at the 1-bar boiling point. We find that the shock pressure to vaporize iron is 507(+65,-85) GPa, which is significantly lower than the previous theoretical estimate and readily achieved during the high velocity impacts at the end stages of accretion.

Iron Vaporization during Planet Formation



A. Vaporization fraction of iron cores as a function of impact velocity for 300 K initial temperature with 1 confidence interval. For an initial temperature of 1500 K, the core begins to vaporize at 13 km/s.

B. Histogram of impact velocities onto Earth-mass planets from N-body simulations of planet formation. Most impactors onto the Earth and Moon achieve partial vaporization of their cores. At each impact velocity, bodies larger than the estimated maximum impactor diameter may penetrate through Earth's mantle to the core. Partial vaporization aids the dispersal of the cores of impactors smaller than this size limit.

Implications of Iron Vaporization during Planet Formation

- Vaporization of planetesimal cores by an impact–generated shock will increase dispersal of accreting core material over the surface of the growing Earth, substantially enhancing chemical equilibration between the accreting cores and the Earth's mantle.

- Vaporization of planetesimal cores will also decrease the accretion efficiency of HSE's onto the Moon relative to the Earth, providing an explanation for the comparatively low concentration of HSE's in the lunar mantle.