Melting in Super-Earths

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Super-Earth

Gleise 832c

Wittenmyer et al. (2014)

Super-Earth

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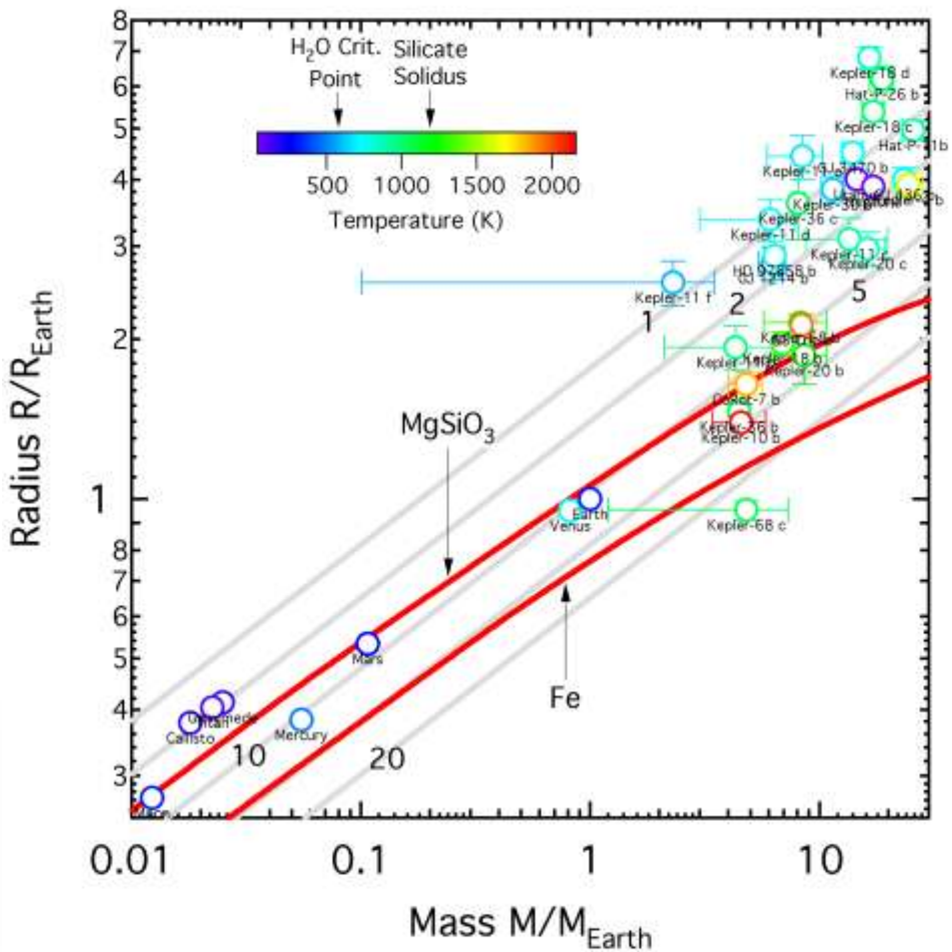
Wittenmyer et al. (2014)

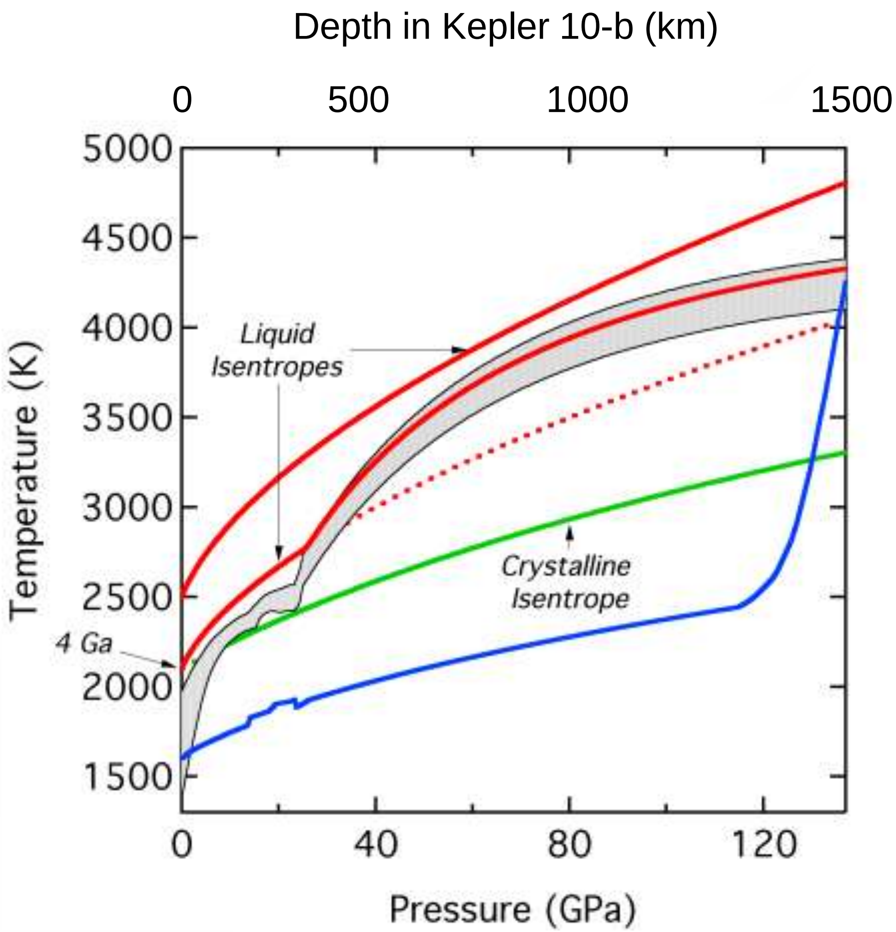
Super-Earths



$$R \propto M^{\beta}$$
$$\beta \simeq 0.27$$

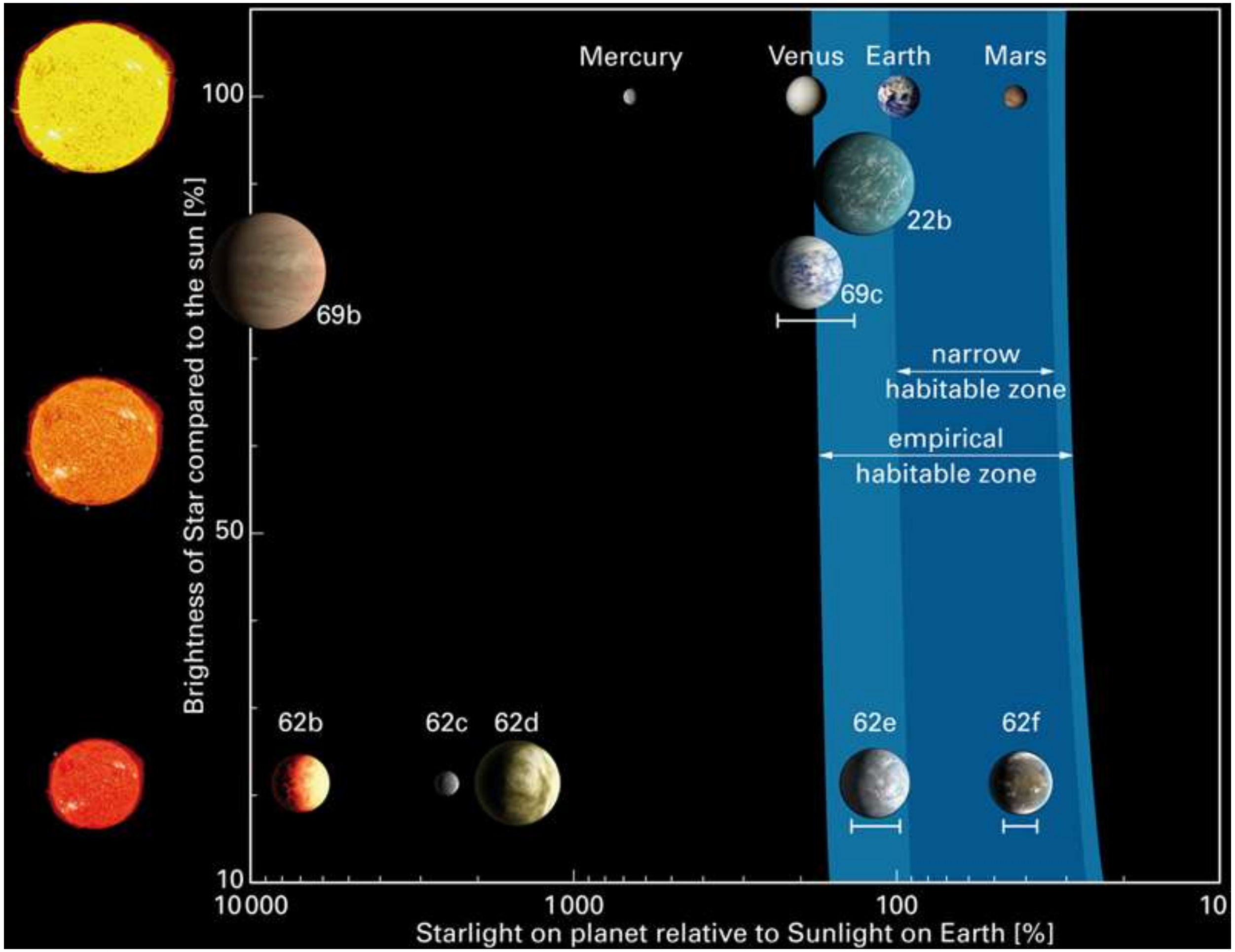
$$T_S = T_* \sqrt{\frac{R_*}{a}} \left(\frac{1 - A}{d} \right)^{1/4}$$

Deep Melting



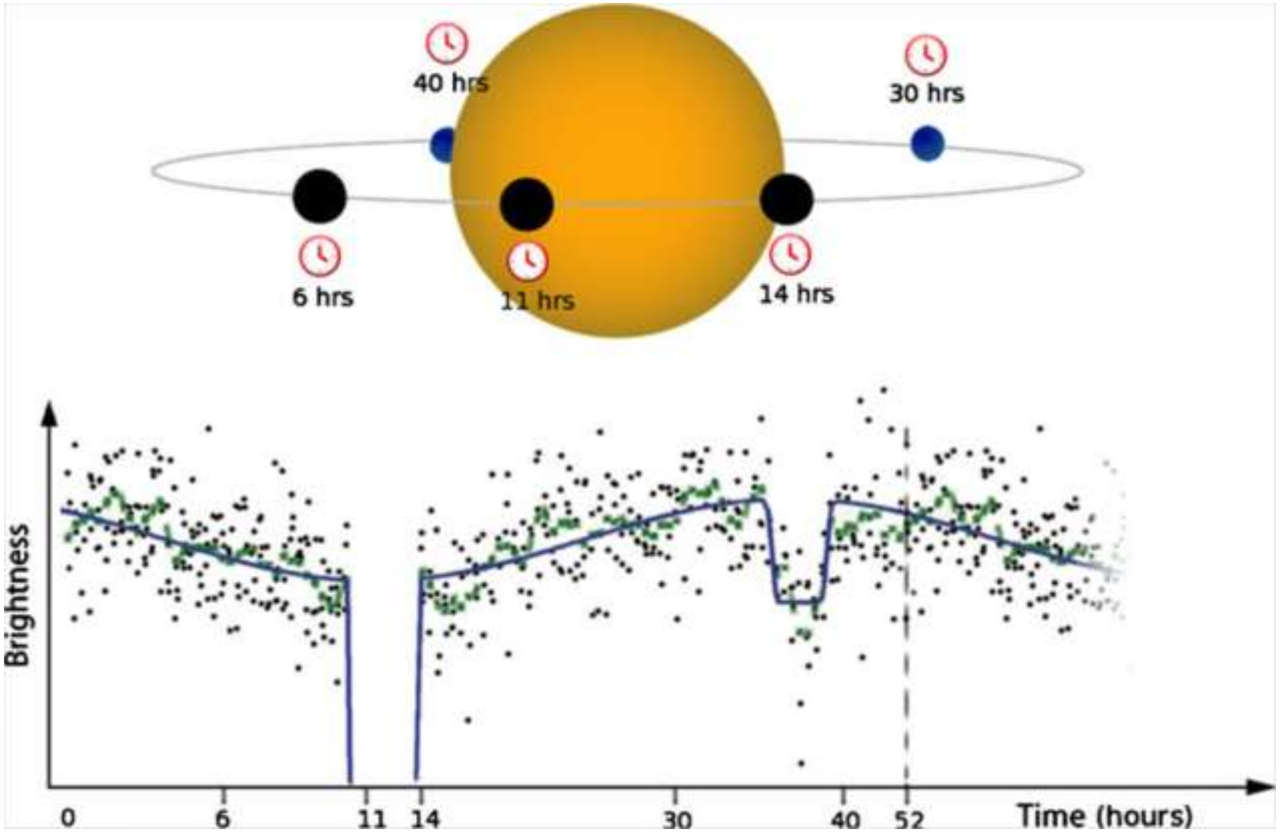
Stixrude et al. (2009) EPSL

Habitable Super-Earths



Borucki et al. (2013) Science

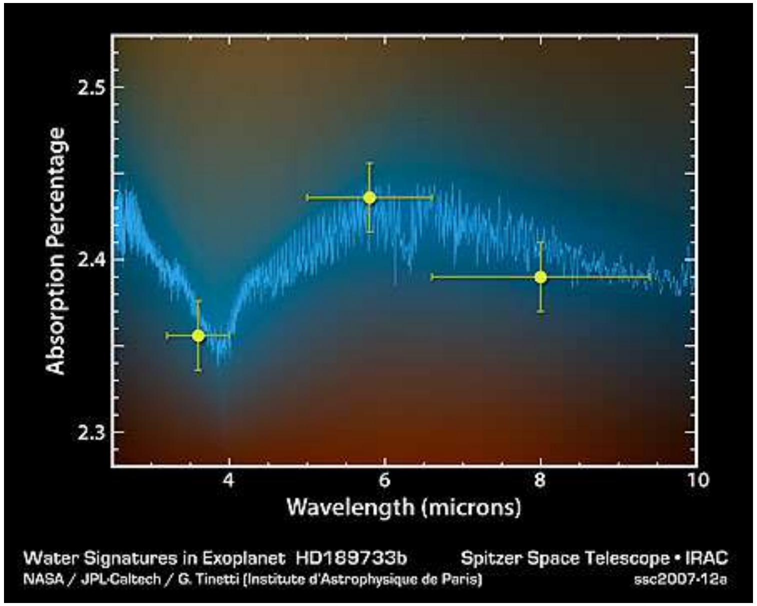
Observations

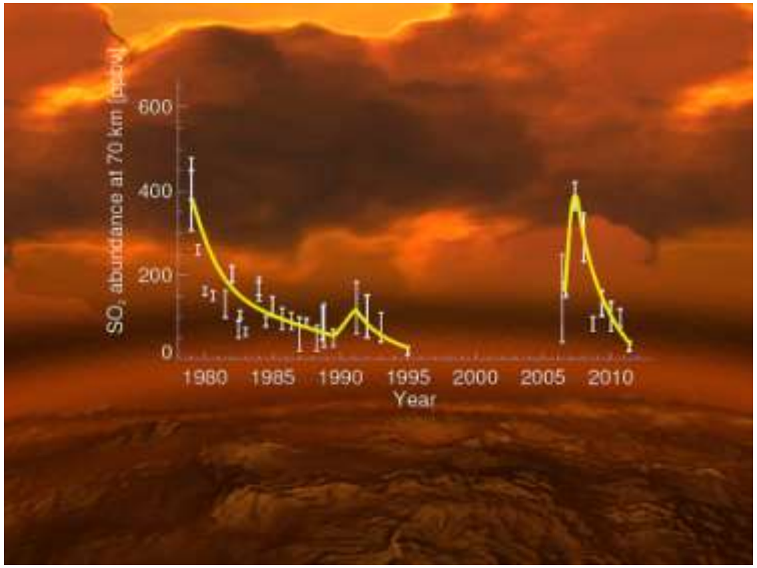


Tinetti et al. (2012) Exp. Astro.

Silicate Melting

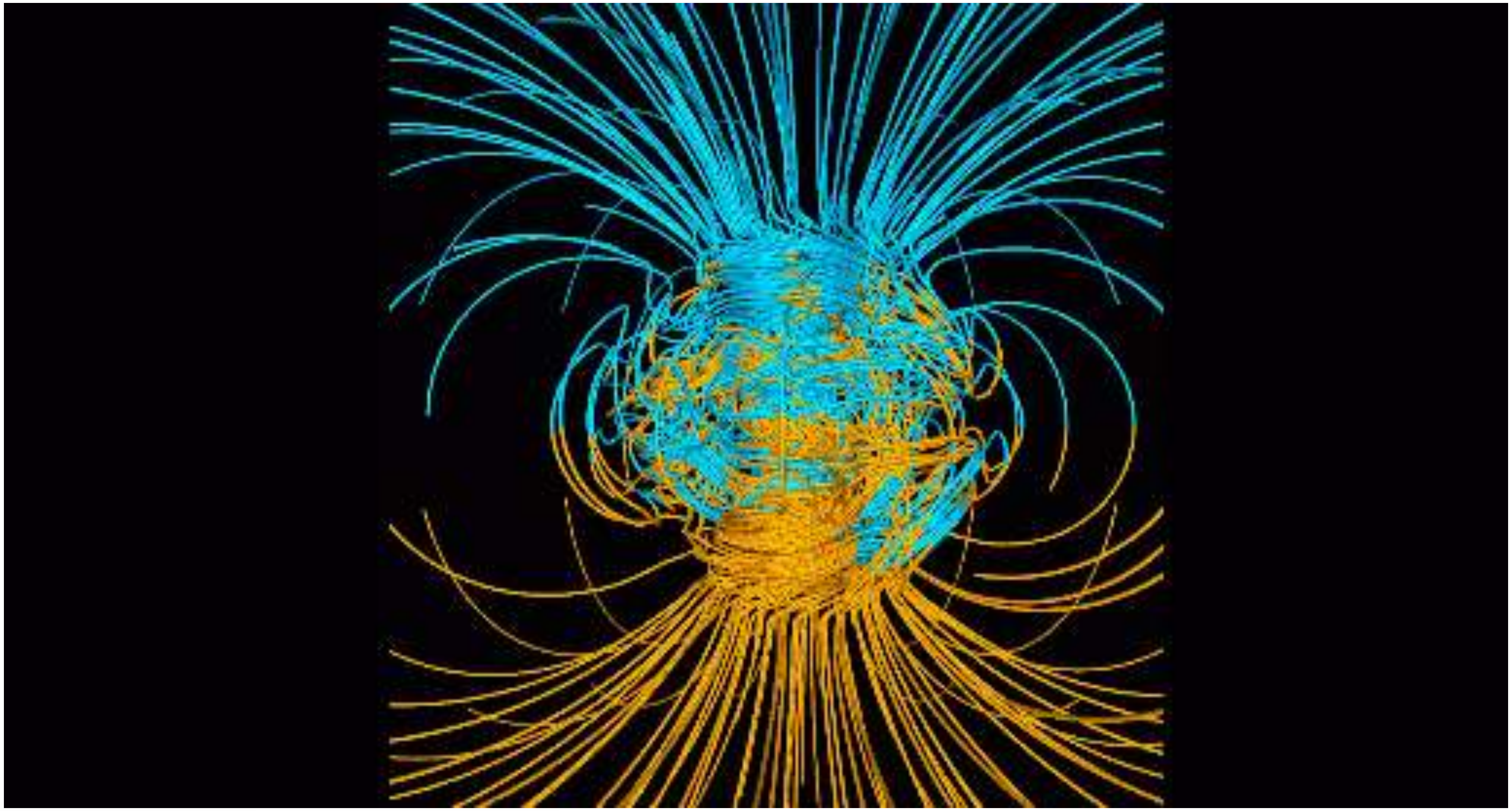
Atmospheric Spectroscopy





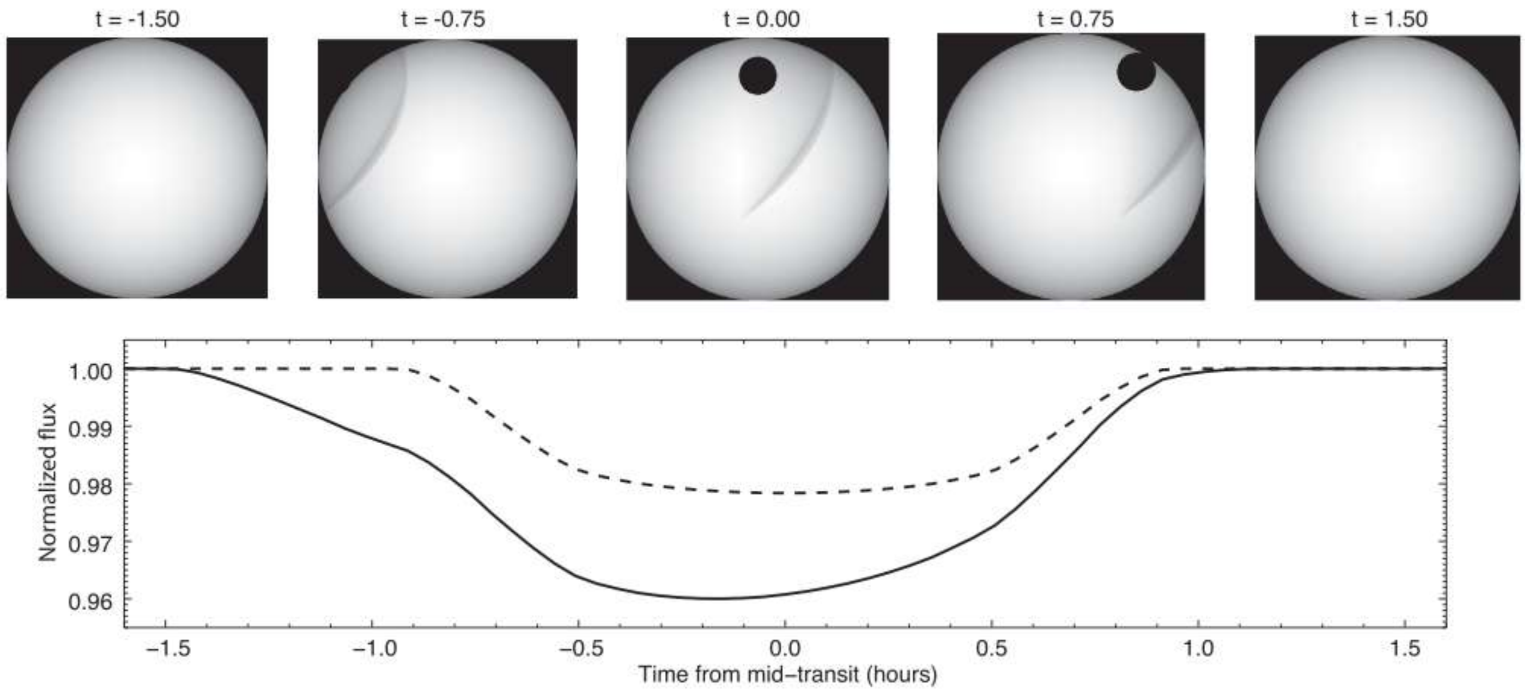
Tinetti et al. (2007) Nature
Marcq et al. (2012) Nat. Geosci.

Iron Melting



Glatzmaier & Roberts (1995) Nature

Exoplanet magnetic fields



Llama et al. (2013) MNRAS

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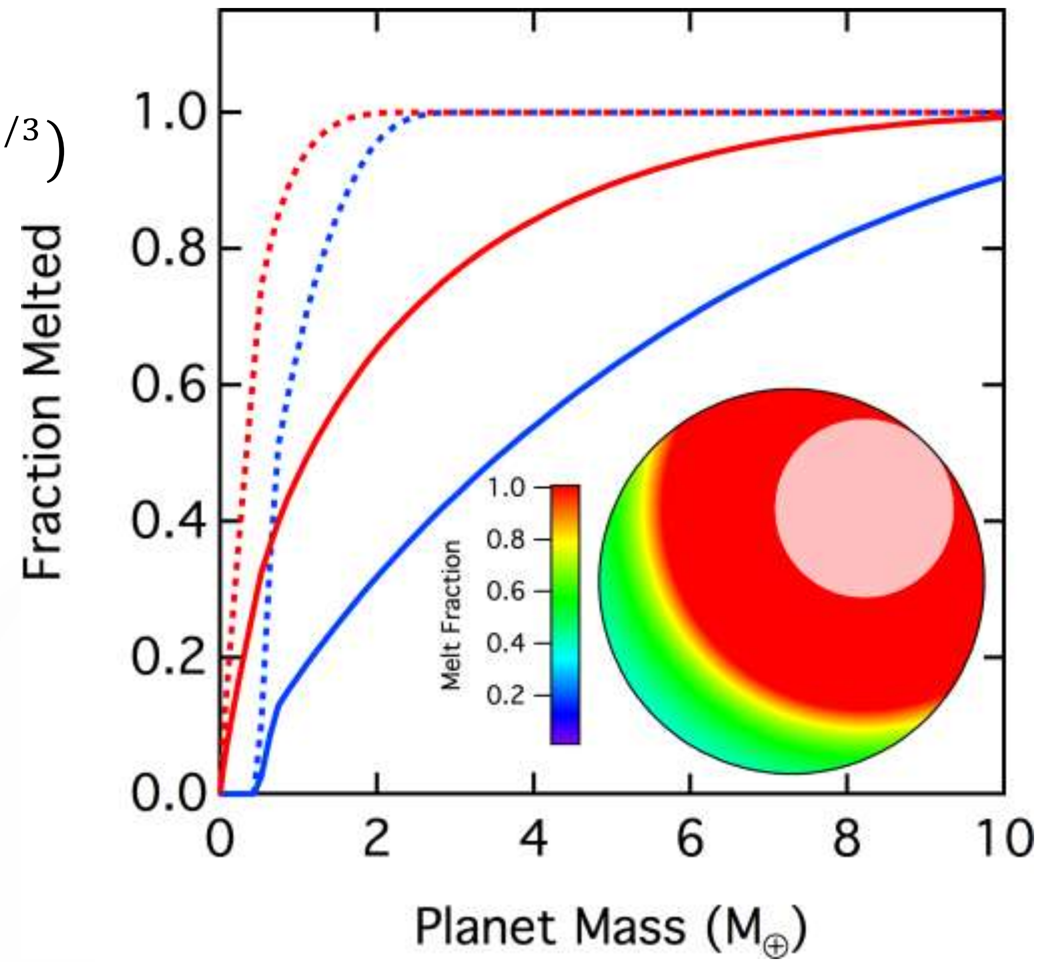
Wittenmyer et al. (2014)

Accretional Heating

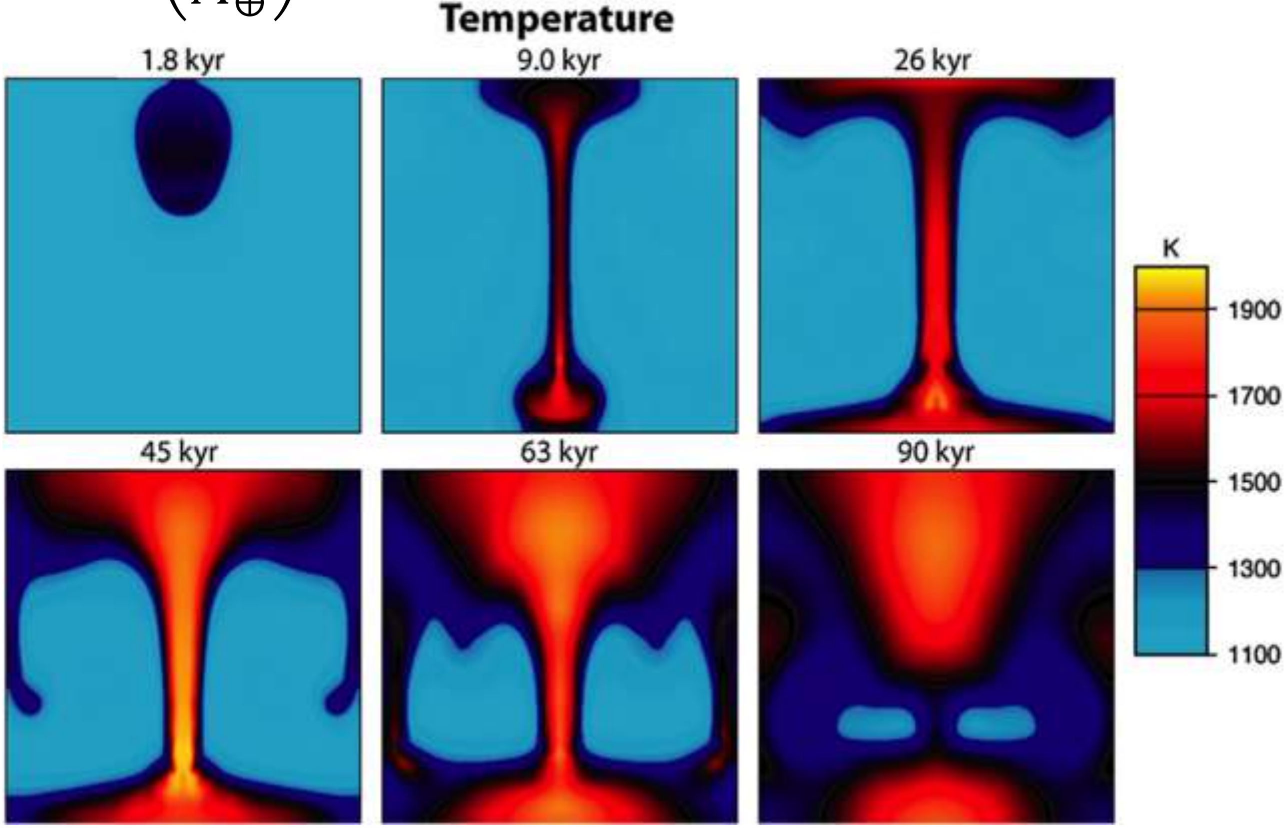
$$T_P = T_S + \frac{1}{5c'}\left(\frac{M_i}{M_P}\right)\left(GM_P^{2/3}\right)$$



Stixrude (2014) Phil. Trans.; Tonks & Melosh (1993) JGR

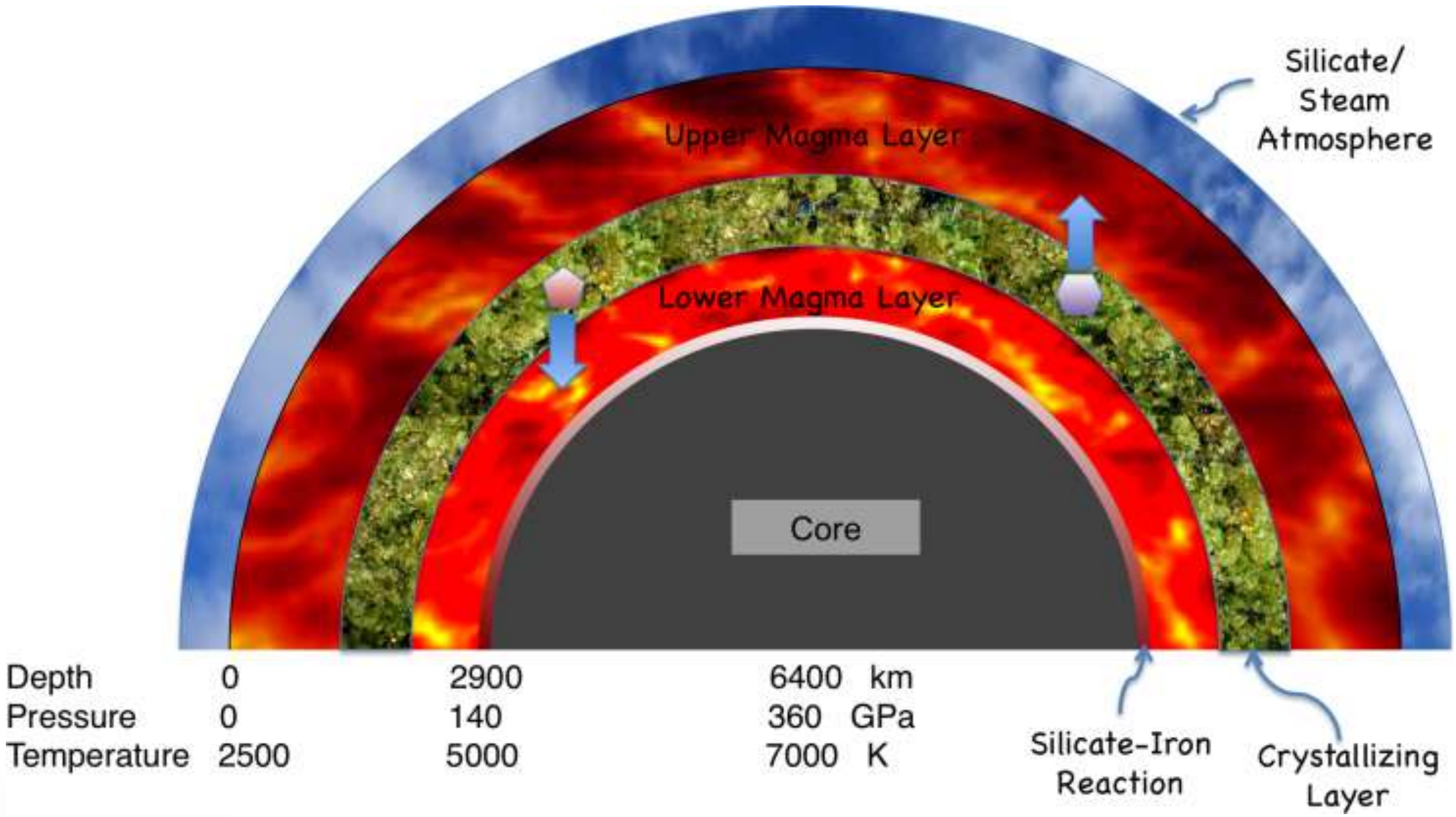
Gravitational Heating

$$\Delta T_P \approx 2300\,K\left(\frac{M_P}{M_\oplus}\right)^{1-\beta}$$



Ricard et al. (2009) EPSL

Molten Planet



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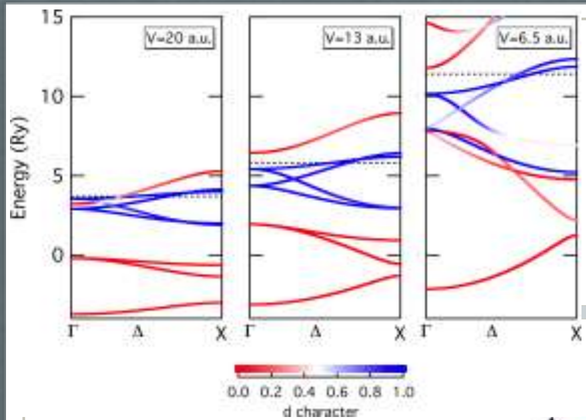
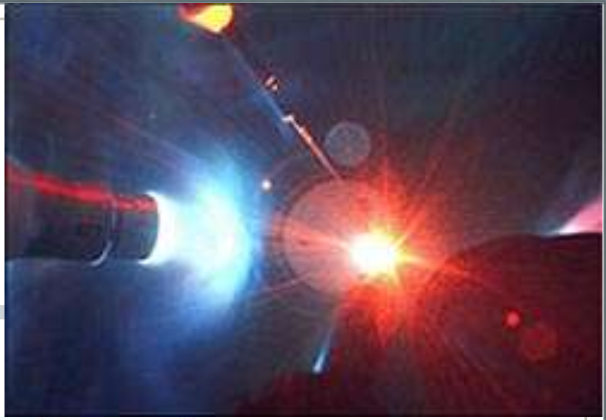
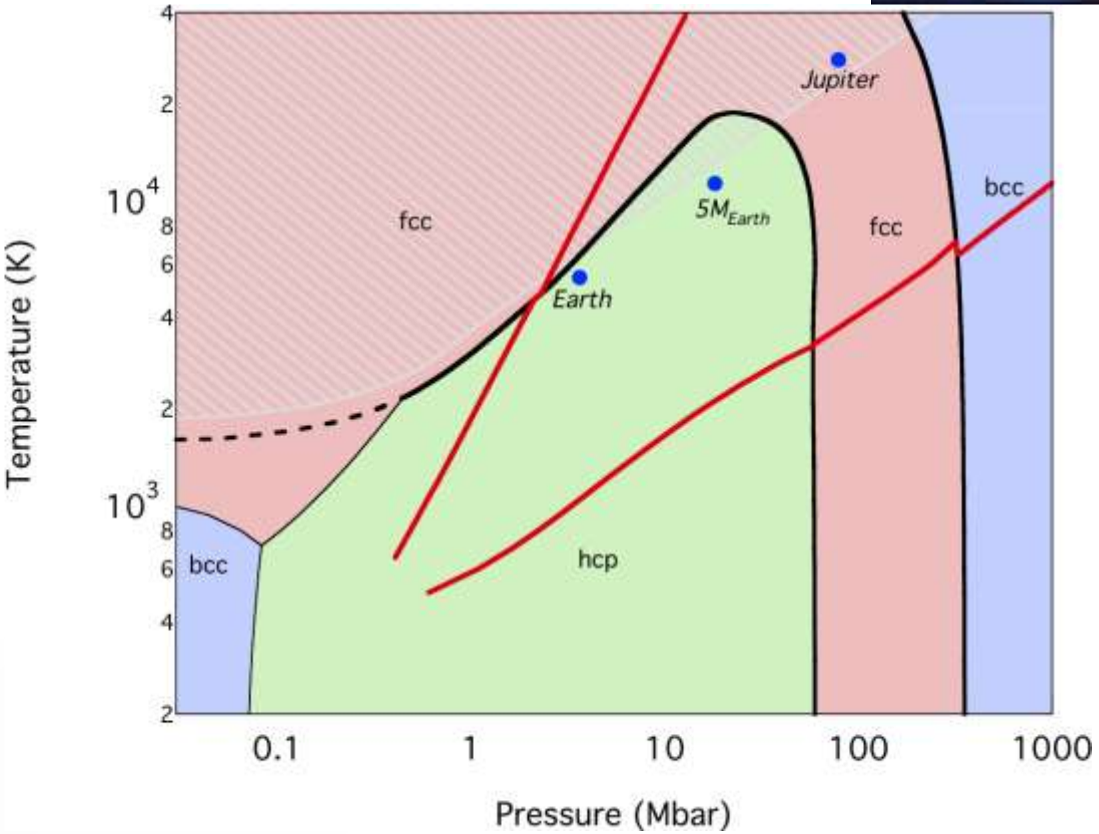
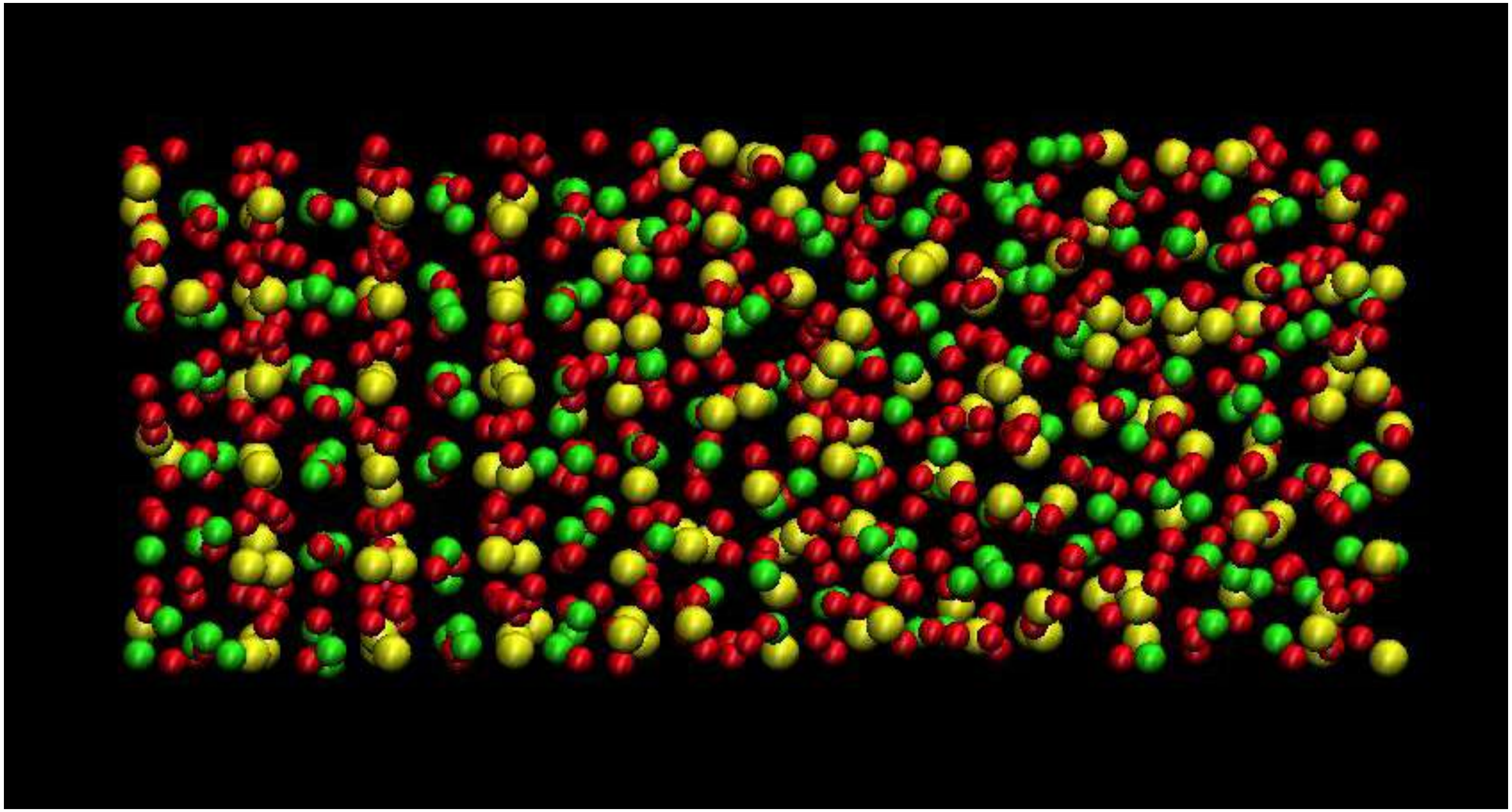






Stixrude (2012) PRL
Jeanloz et al. (2007) PNAS

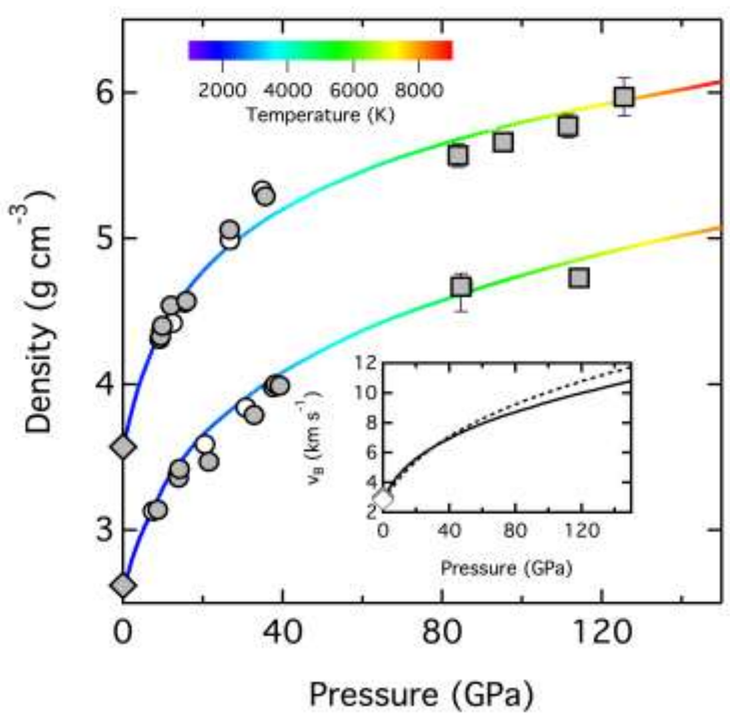
First Principles Molecular Dynamics



John Brodholt, UCL

Density Functional Theory

- Predictive power
  - No free parameters
  - No *a priori* assumptions regarding shape of charge density or nature of bonding
- Scope
  - Entire pressure-temperature range of planets (and stars)
  - Entire periodic table
- Accuracy
  - Tested via comparison with experimental data

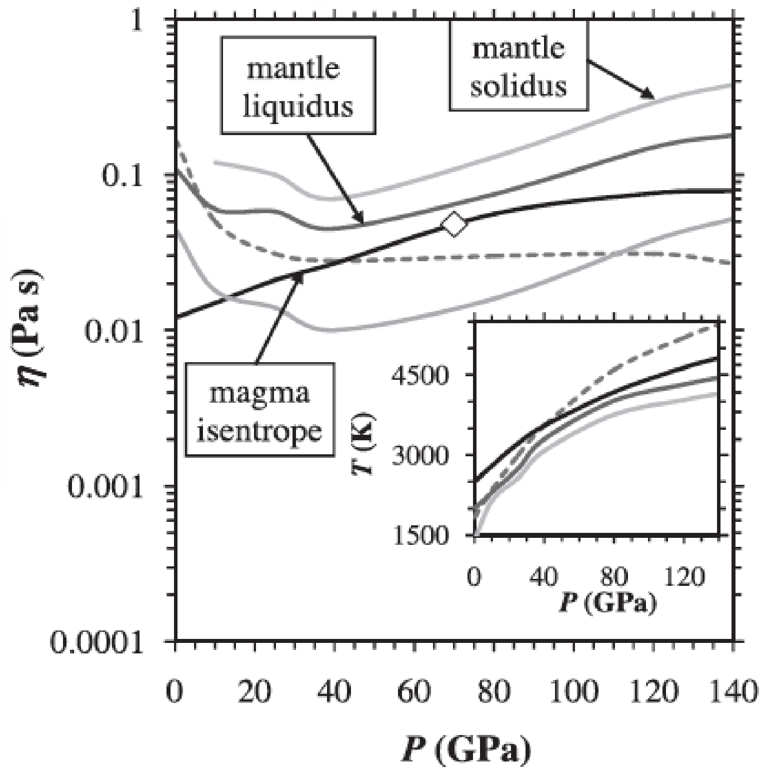


Sun et al. (2011) GCA

Karki et al. (2012) Am. Min.

Viscosity

- Increases by factor of ~10 from surface to base of mantle
- Silicate liquids remain mobile throughout mantle
- Vigorous convection



$MgSiO_3 \pm H_2O$

Karki & Stixrude (2010) Science

Magma Ocean Dynamics

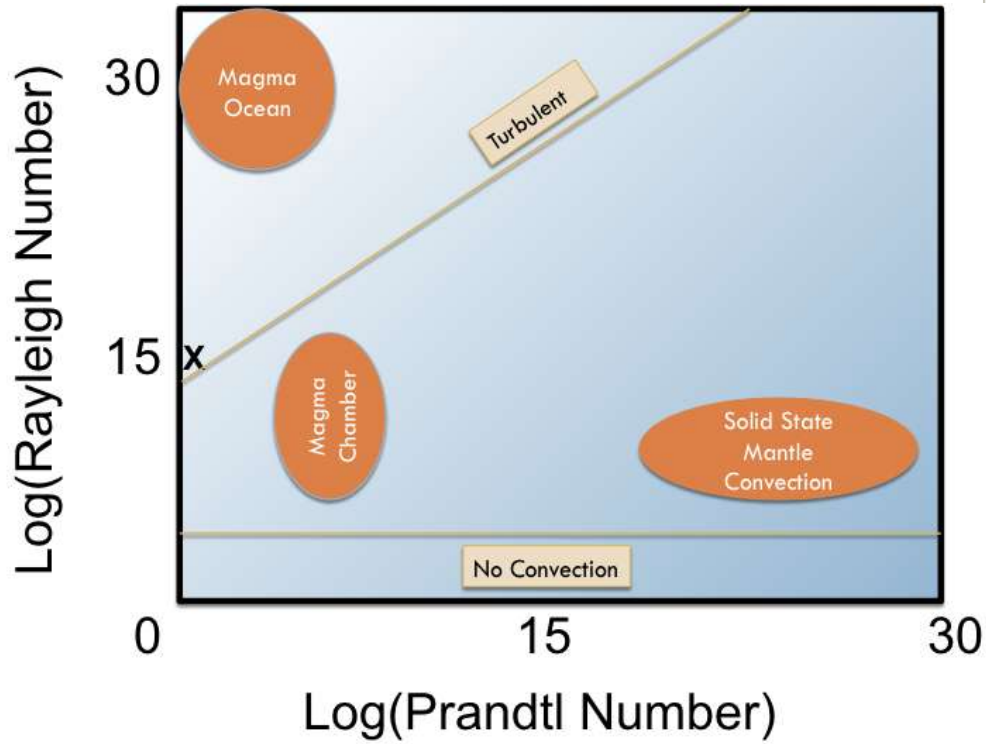
Flow is super-turbulent

Heat flux exceeds incoming stellar

$$Ra = \frac{\alpha\rho g (T_M - T_S) L^3}{\kappa\eta} \approx 6 \times 10^{30}$$

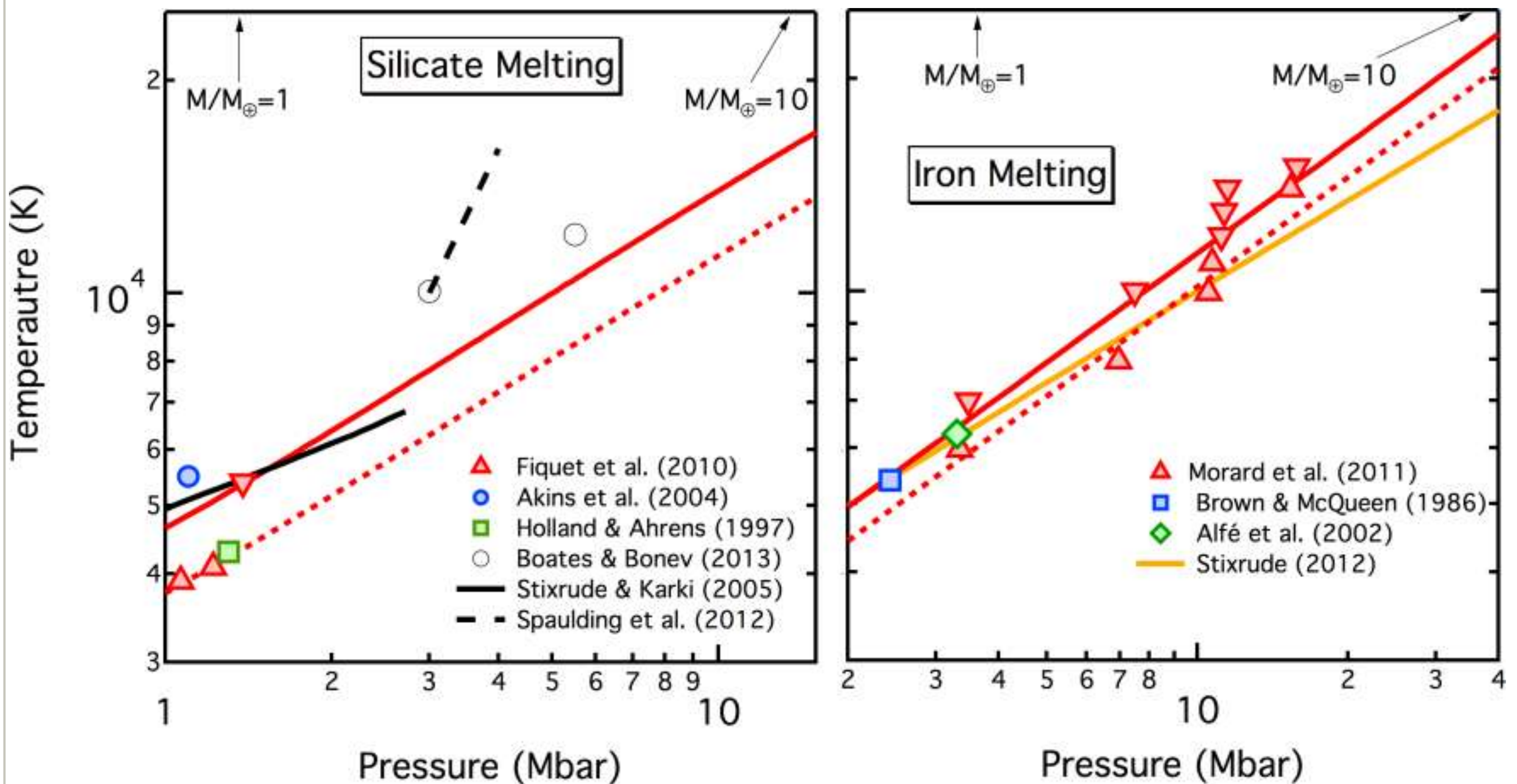
$$Pr = \frac{\eta}{\rho\kappa} \approx 60$$

$$F = 0.22 \frac{k(T_M - T_S)}{L} Ra^{2/7} Pr^{-1/7} \approx 6 \times 10^4 \text{ W m}^{-2}$$



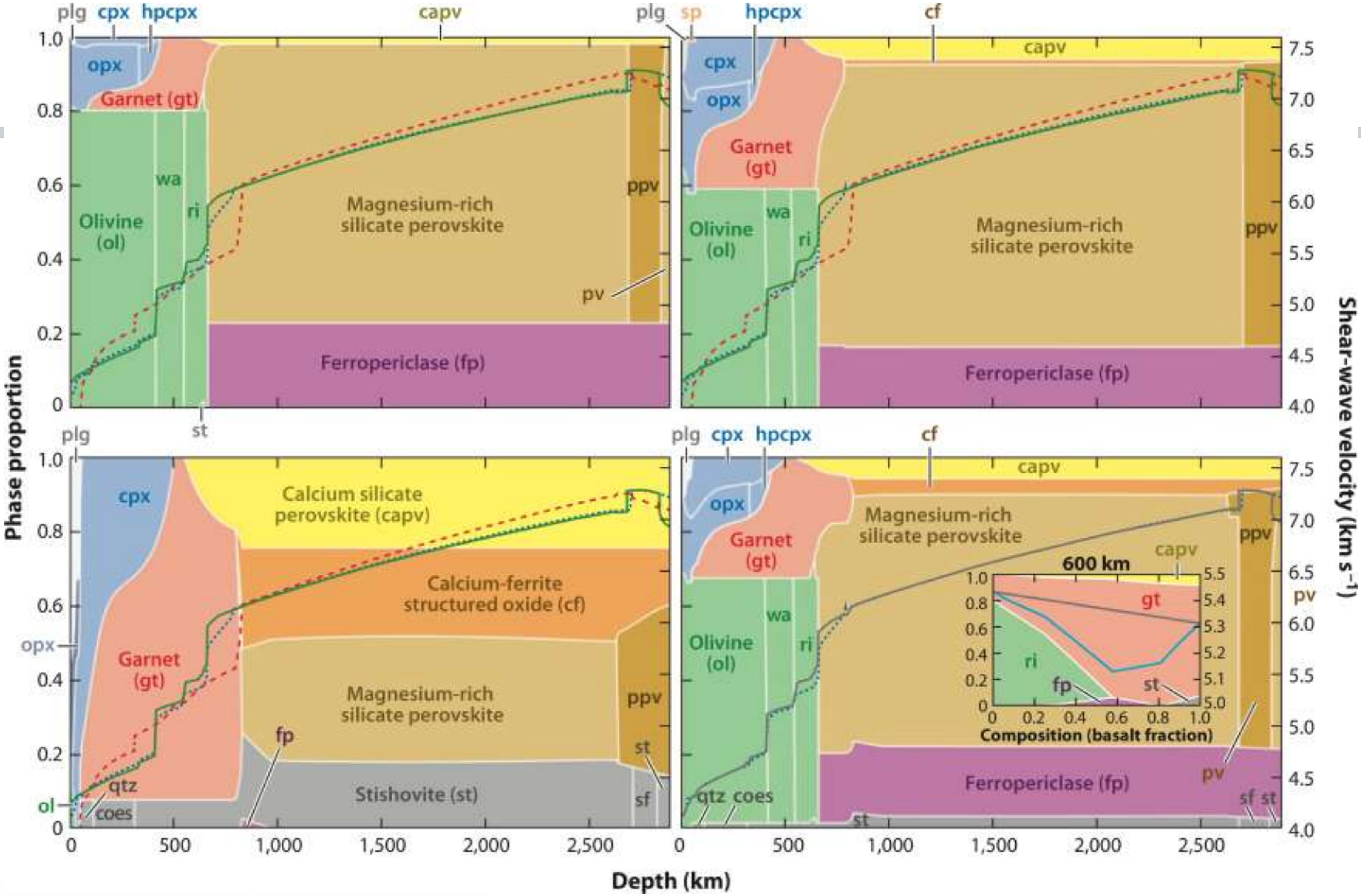
Karki & Stixrude (2010) Science

Planetary Melting



Stixrude (2014) Phil. Trans.

HeFESTo



Stixrude & Lithgow-Bertelloni (2005 GJI; 2012 AREPS)

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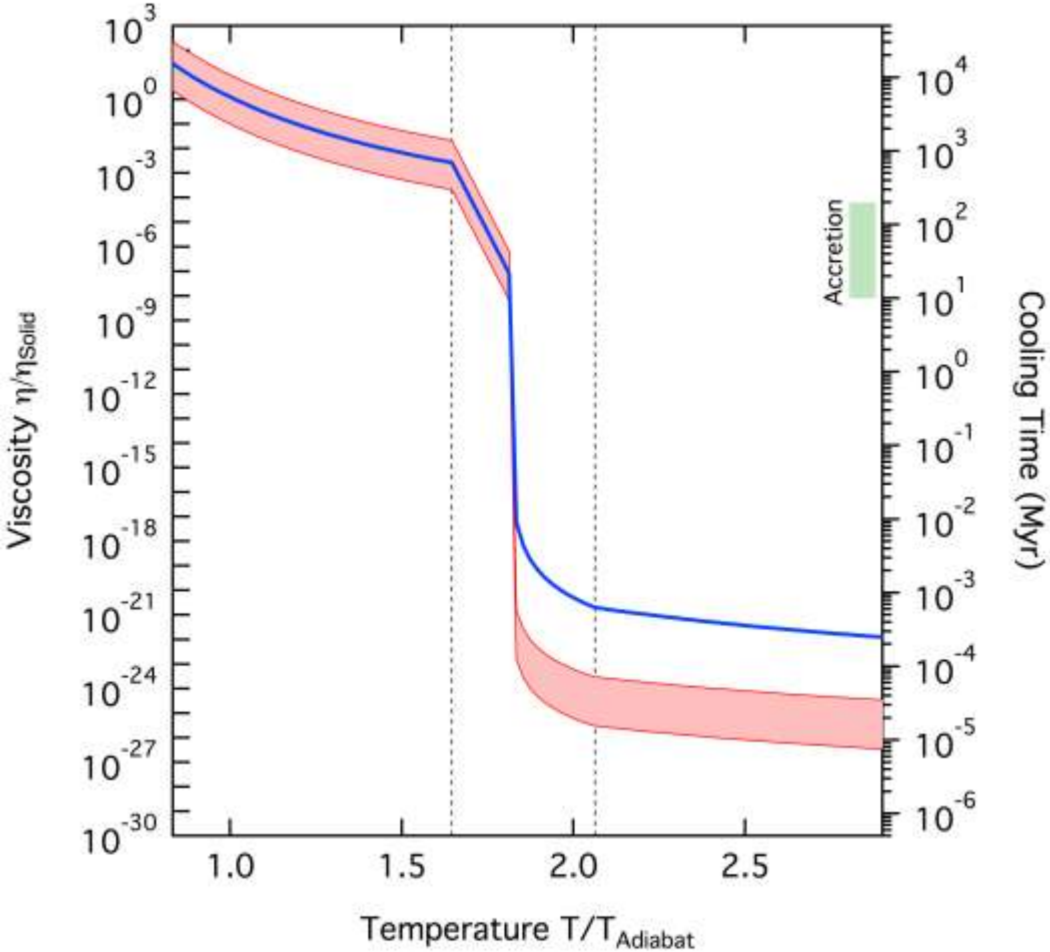
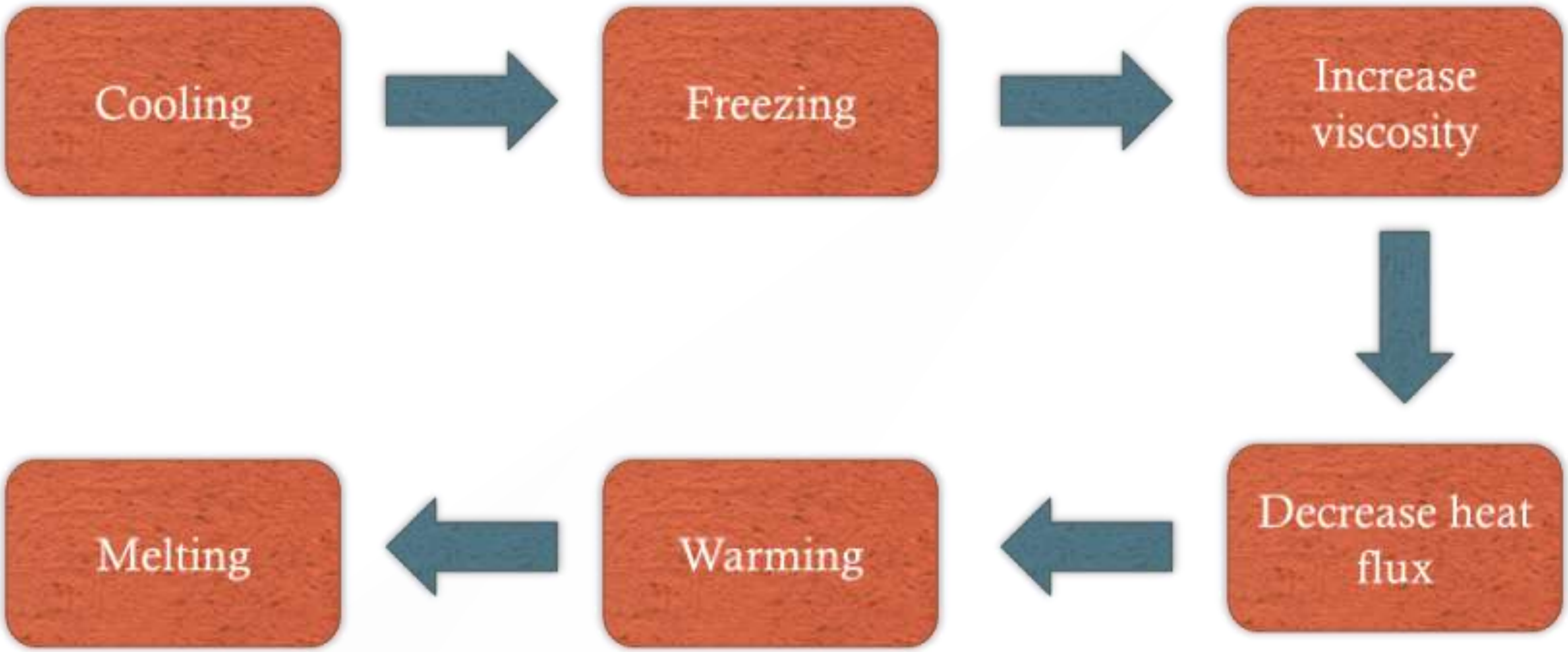
Wittenmyer et al. (2014)

$$\tau = 3.9\ \mathrm{Gyr}\left(\frac{M_P}{M_\oplus}\right)^{1-2\beta}\left(\frac{\eta_0 e^{-\alpha\phi}}{1\times10^{21}\ \mathrm{Pa\ s}}\right)^{1/3}\left(\frac{T_P - T_S}{1300\ \mathrm{K}}\right)^{-1/3}$$

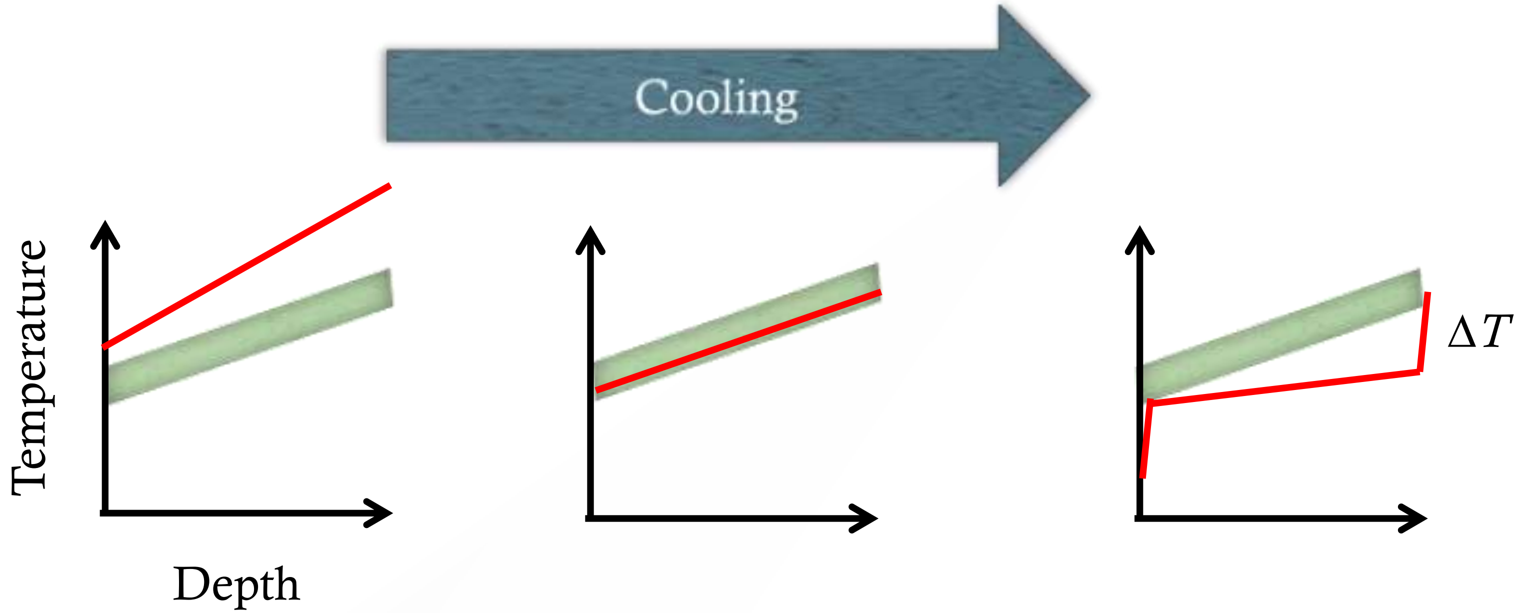


Stixrude (2014) Phil. Trans.

Thermal Regulation

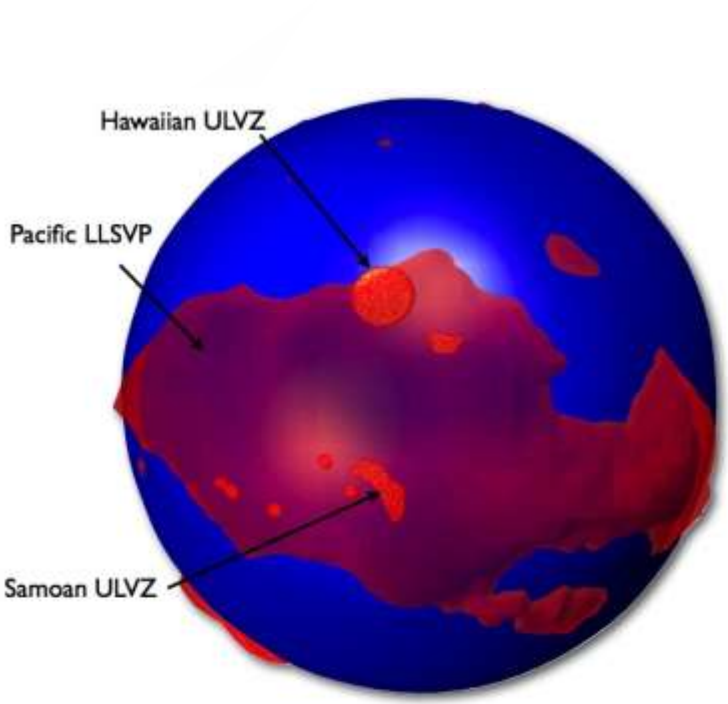


Thermal evolution with melting

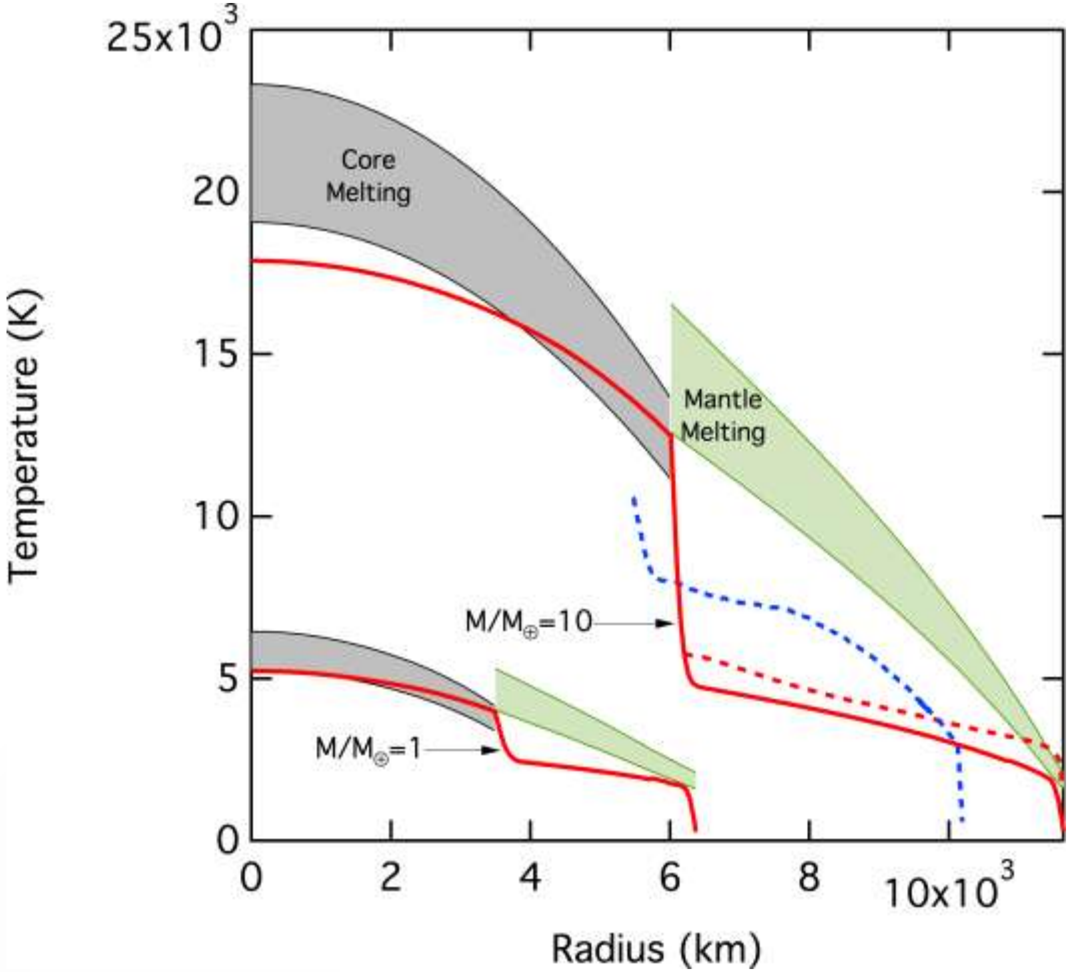


$$\Delta T = \left(\frac{\eta}{\rho^2 \alpha g c k^2}\right)^{1/4} F^{3/4}$$

Boundary Layer Melting



Super-Geotherms



Stixrude (2014) Phil. Trans.

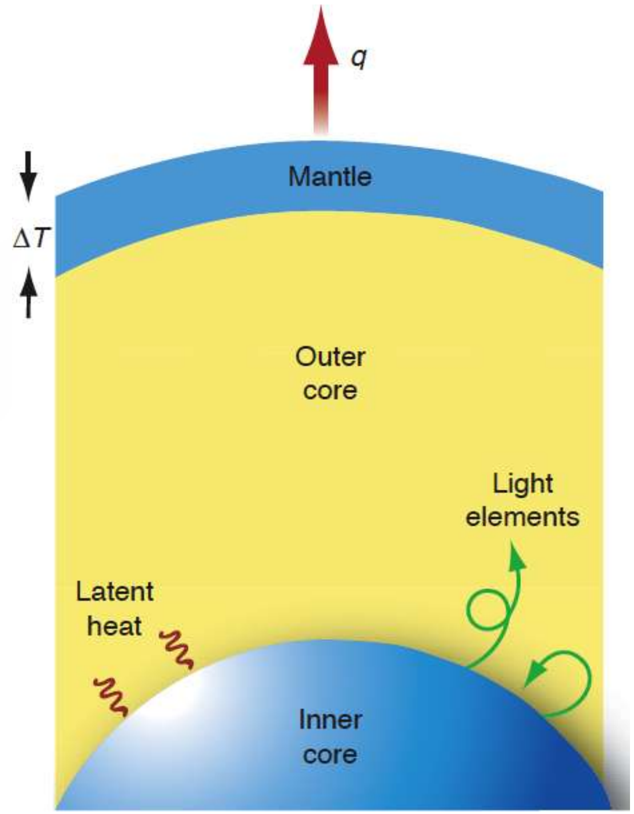
Super-Earth

Gleise 832c

Wittenmyer et al. (2014)

Super Earth Magnetic Fields

- Cooling is an important, perhaps essential energy source for a dynamo
- Freezing inner core releases latent heat and gravitational energy
- Heat flux exceeds heat conducted down the core adiabat



Buffett (2003) Nature

Super-Earth Magnetic Fields

$$F_{\text{CMB}} \approx 80 \text{ mW m}^{-2} \frac{M_P}{M_\oplus}$$

is greater than

$$F_{\text{cond}} \approx 2k \frac{T_C}{R_C} \ln \frac{T_0}{T_C} = 60 \text{ mW m}^{-2} \left(\frac{M_P}{M_\oplus}\right)^{1-\beta}$$

Stixrude (2014) Phil. Trans.

Conclusions

- Super-Earths began in a completely molten state
- Melt survives in upper and lower mantle boundary layers
- Volcanic activity increases with planetary mass
- Magnetic field strength increases with planetary mass
- Observable constraints on super-Earth melting are plausible