The Initial State of the Moon Forming Disk and the Mantle of the Earth

Miki Nakajima and David Stevenson

California Institute of Technology email: mnakajima@caltech.edu

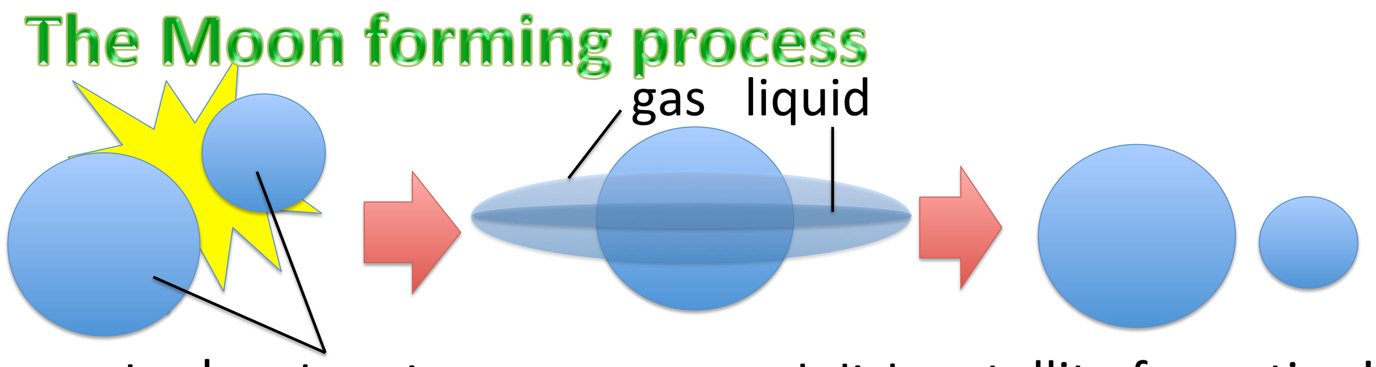
P-14

Abstract

According to the giant impact hypothesis, a Mars size body hit the proto-Earth. The impact generated a debris disk around the proto-Earth, from which the Moon was accreted. A big challenge of this model is that the isotope similarities between the mantles of the Earth and the Moon cannot be explained. Pahlevan & Stevenson (2007) proposed that isotope can be exchanged between the disk and the mantle through the Earth's atmosphere. This model requires the detailed thermodynamical models of the system, but it is not well known yet. Here, we investigated thermal structures of the disk and the Earth's mantle after the impact based on SPH simulations, by looking at the entropy of the system. We found out the following results: (1) The disk has a remarkably uniform entropy. (2) The disk's vapor fraction is 20% by mass. (3) The mantle is likely to be molten and stable to convection. The result (3) can be a potentially problem for the isotope mixing model.

Background

The Moon forming process



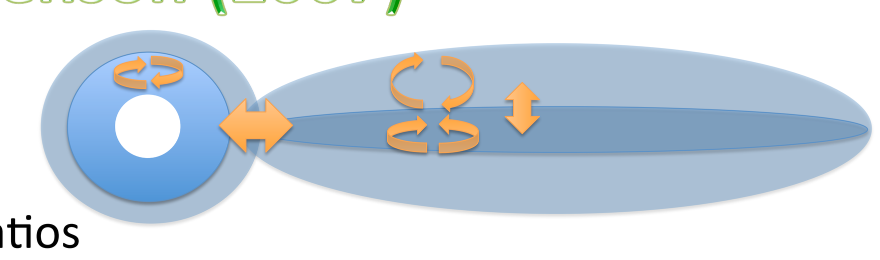
Problem: Most of the disk consist of the impactor-origin materials

→ The similarities of the isotope ratios cannot be explained!

Pahlevan & Stevenson (2007)

Convection

Exchange



→ Uniform isotope ratios

BUT, the process requires detailed thermodynamic models.

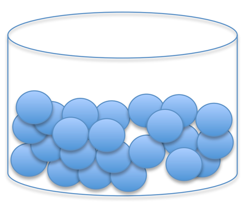
ex.
- Vapor mass fraction in the disk
- Convection in the mantle

Motivation

We need to identify the initial thermal state of
(1) the Earth's mantle
(2) the disk
In order to investigate the isotope mixing model

Method

Smoothed Particle Hydrodynamics (SPH)



- A Lagrangian method for fluid dynamics simulations
- Each particle has a same mass

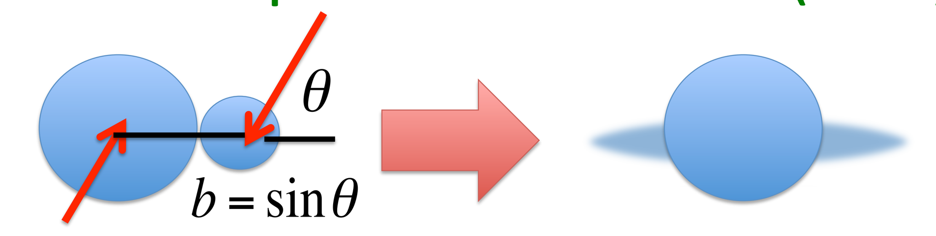
$$\frac{dv_i}{dt} = -\frac{\nabla p}{\rho} - \sum_j \frac{Gm_j}{|r_i - r_j|^3}(r_i - r_j) \qquad \frac{du_i}{dt} = \frac{p}{\rho^2}d\rho$$

Momentum Eq   Energy Eq

Entropy is independent of resolution
(∵adiabatic expansion/compression)

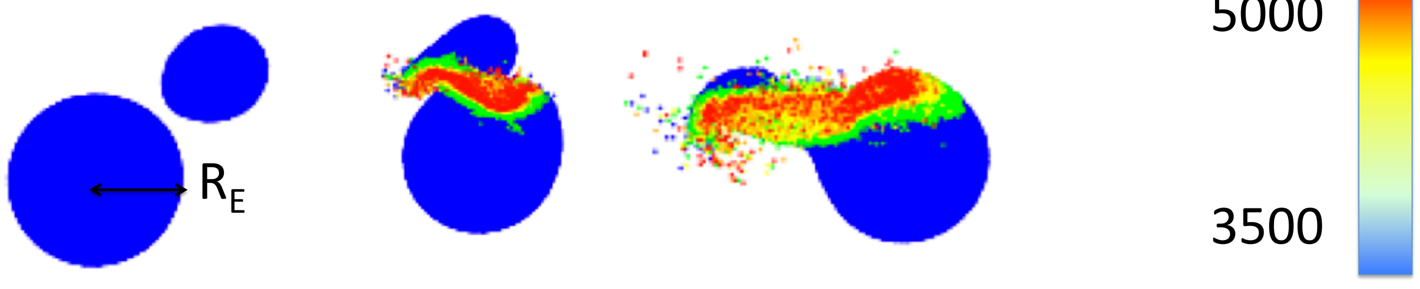
Procedures

1. Giant impact simulations (SPH)



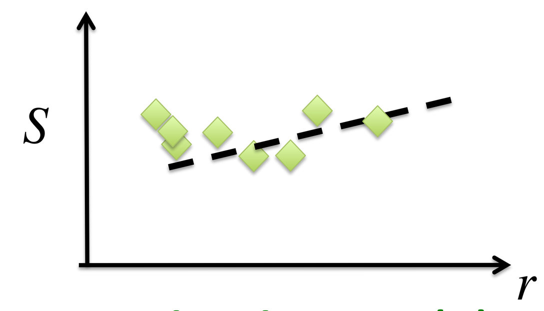
EOS: ANEOS (forsterite mantle) SESAME (iron core)

Resolution: N=10^5 Impactor/Target mass ratio: 0.13



2. Calculate $S(r)$ from SPH

Mantle



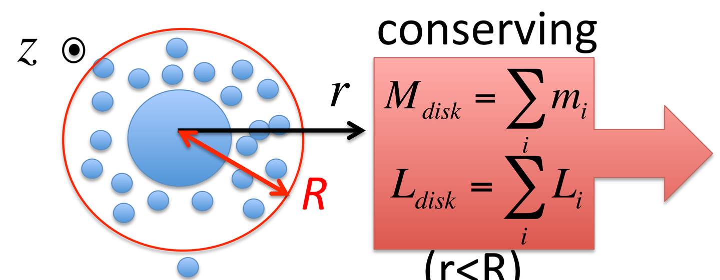
Convection

dS/dr > 0 : → Stable

dS/dr < 0 : → Unstable

3. Calculate $S(r)$ and $\Sigma(r)$ from SPH

Disk

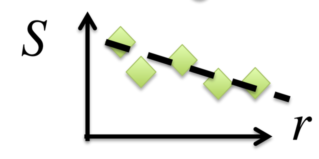


conserving

$M_{disk} = \sum_i m_i$

$L_{disk} = \sum_i L_i$

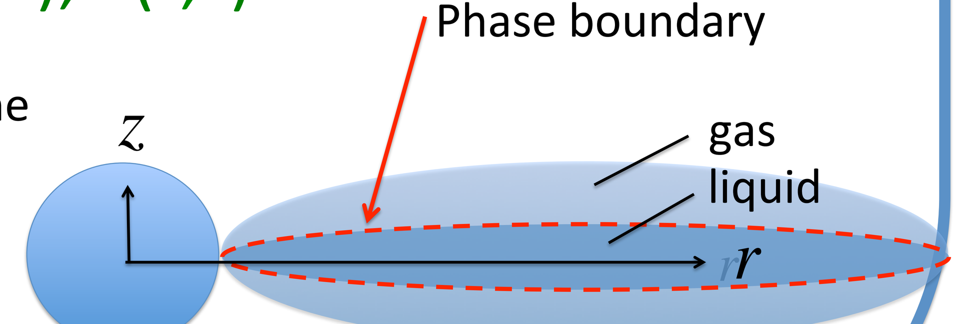
(r<R) → Surface density $\Sigma(r)$



(averaged in z direction) → Entropy $S(r)$

4. Calculate $p(r,z)$, $\rho(r,z)$, $T(r,z)$

Assumptions
- Liquid is settled on the mid-plane
- $\Sigma_{liquid}(r) >> \Sigma_{gas}(r)$
- $p = p_{saturation}, \rho = \rho_{saturation}$



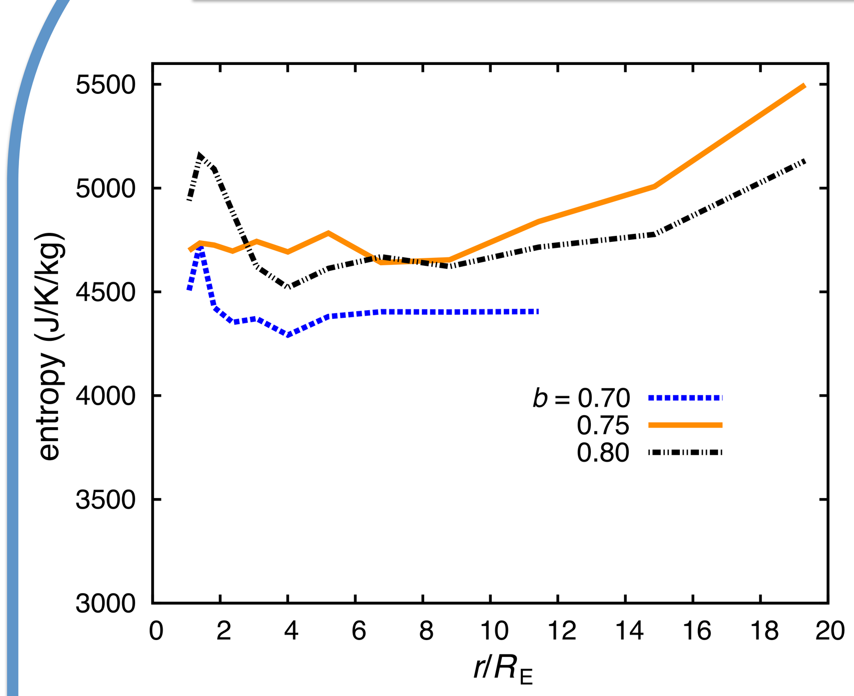
Basic equations
- Hydrostatic equation

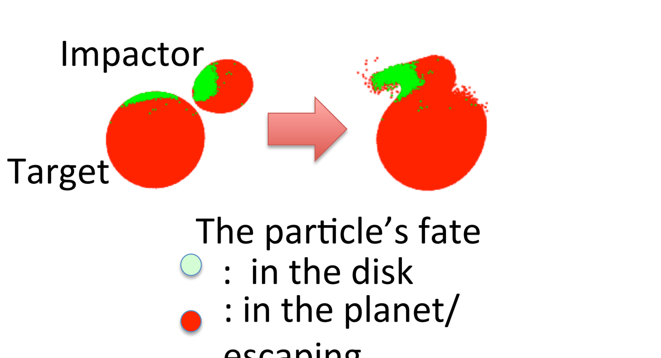
$$\frac{1}{\rho}\frac{dp}{dz} = -\frac{GM_p}{r^3}z - 2\pi G\Sigma_l$$

Planet gravity
disk self-gravity

Results

Disk: Entropy distribution



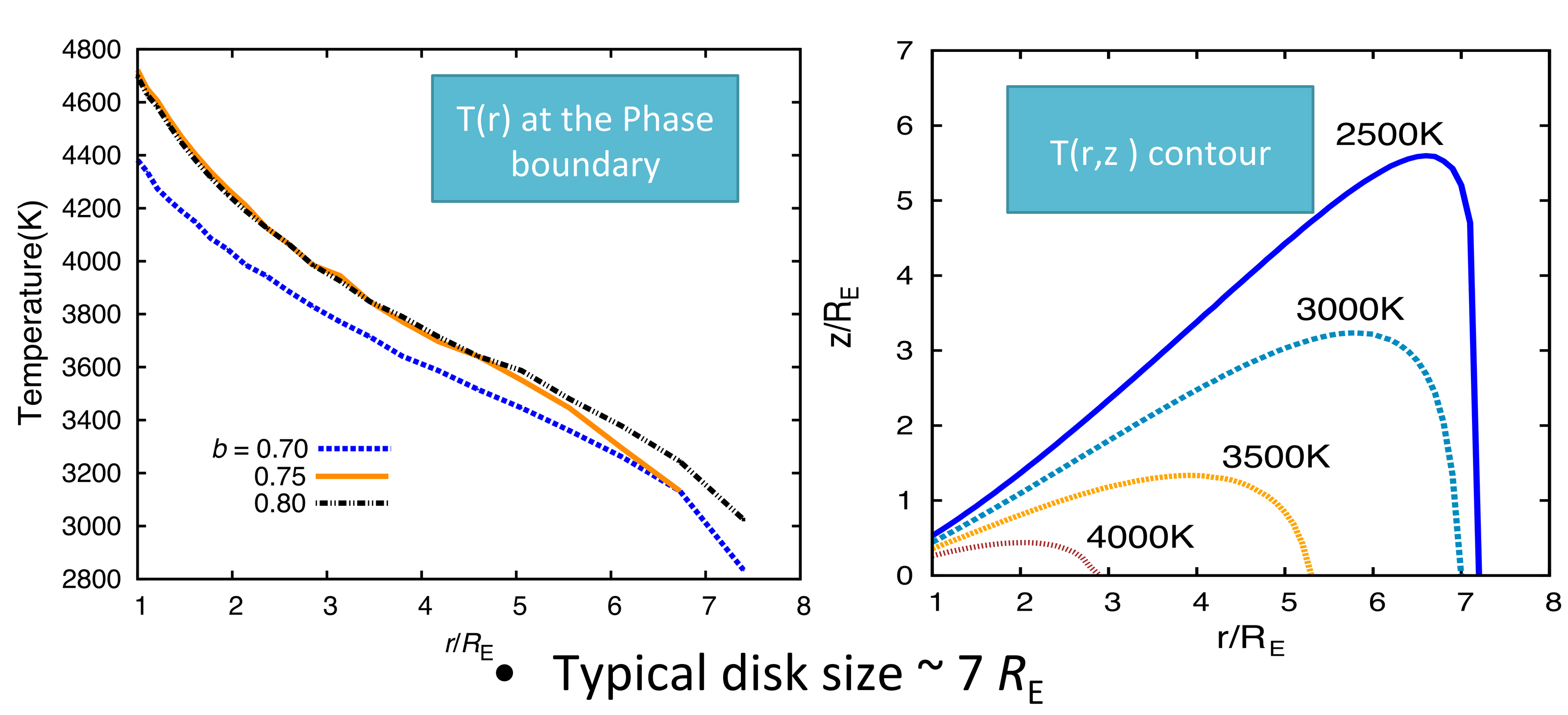


The disk particles experienced similar shock heating

- Uniform entropy in the disk

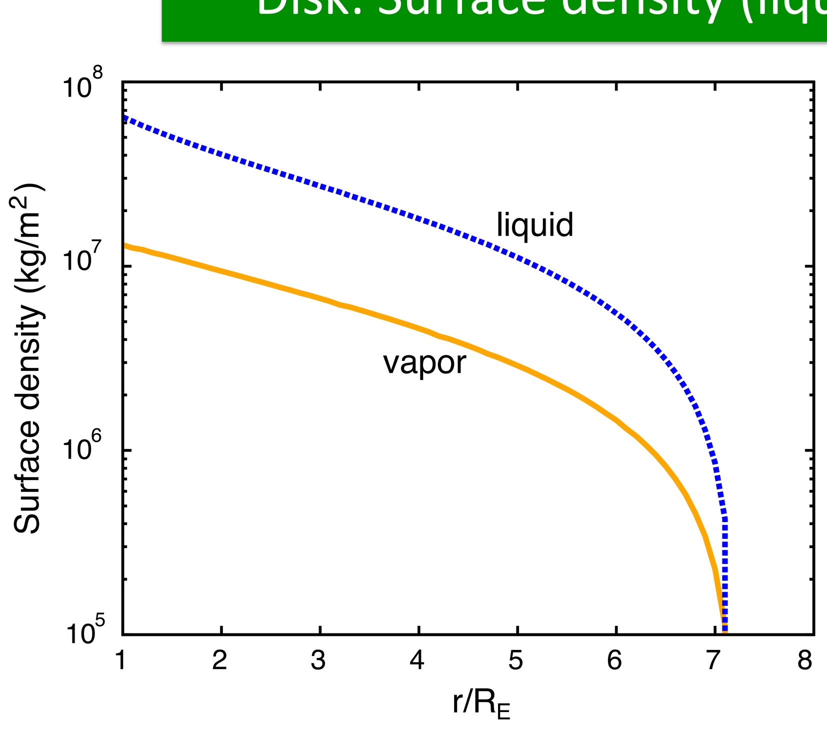
Uniform entropy disk

Disk: Temperature at b=0.75



- Typical disk size ~ 7 R_E
- Temperature range 2800- 4800K

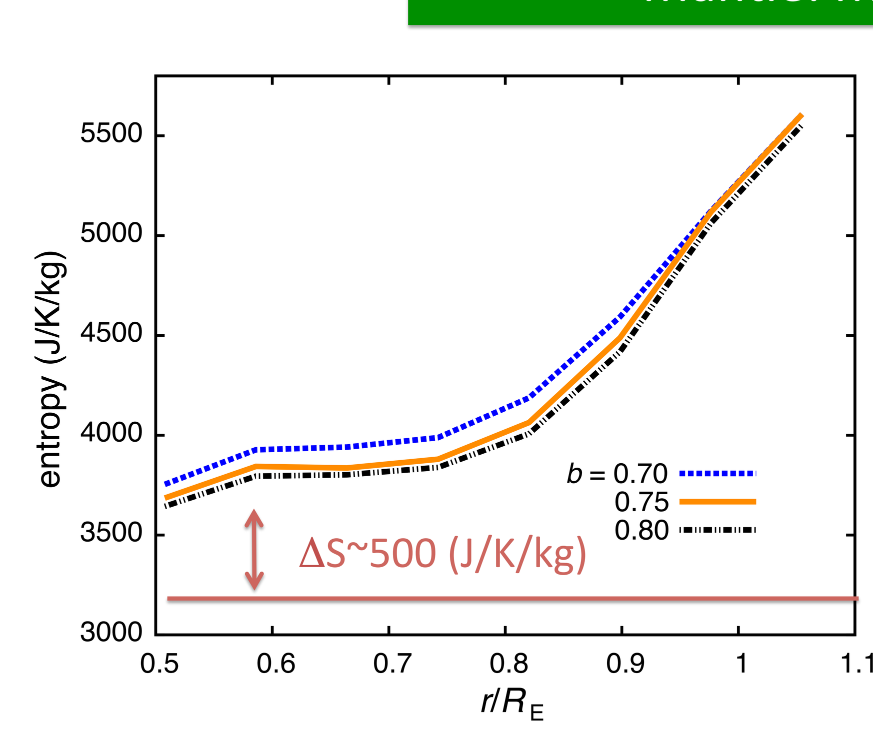
Disk: Surface density (liquid/vapor)



- Overall vapor mass fraction ~ 0.1-0.2
- $\Sigma_{liquid}(r) >> \Sigma_{gas}(r)$ is valid.
- These feature does not depend on b value.

Vapor mass fraction ~ 0.2

Mantle: Molten + Stable



- $dS/dr > 0$ → Stable to convection
- $\Delta S > \Delta S_{melting}$ → Molten mantle?

Potentially a big challenge for Pahlevan & Stevenson's model

- $S(r)$ is almost uniform in the disk.
- Overall vapor mass fraction is 0.1~0.2.
- The Earth's mantle is molten and stable to convection after the impact.