THE INITIAL STATE OF THE MOON FORMING DISK AND THE EARTH'S MANTLE BASED ON SPH SIMULATIONS. M. Nakajima and D. J. Stevenson, California Institute of Technology, 1200 E California Blvd., MC150-21, Pasadena, CA 91125 (mnakajima@caltech.edu)

Introduction: The Moon is thought to be formed by a giant impact between the proto-Earth and an impactor [1]. According to this hypothesis, the impact generates a debris disk around the Earth, from which the Moon is accreted [2]. The disk has a high temperature and is partially vaporized. This scenario can explain the large Earth-Moon angular momentum, the Moon iron depletion, and the similarity of oxygen isotope ratios in the mantles of the Earth and the Moon.

However, the state of the disk and the Earth's mantle right after the giant impact is not well known. This causes several major problems. First, the Moon accretion process is not well understood because it highly depends on the thermal profile of the initial disk. For example, the disk vapor mass fraction affects the disk cooling and the Moon forming time scale, and hence the final Moon mass [3]. Secondly, the mixing process between the Earth's mantle and the disk is not well understood. It has been expected that there is an isotope mixing between the Moon forming disk and the Earth's mantle, given that the proto-Earth and the impactor have difference isotope ratios. The isotope mixing can occur due to rainout, turbulence, and liquid-vapor exchange in the disk-Earth system [4]. This requires a detailed disk model. The initial mechanical mixing of the materials from the two different origins, the proto-Earth and the impactor, within the Earth's mantle is also important. If the impactor-origin materials cover the Earth's surface and experience isotope mixing with the disk [4], the isotope ratios of the whole mantle and those of the Moon may be different if the mantle convection is not efficient over the Moon forming time scale.

In order to understand the Earth and the disk conditions right after the impact, we have performed numerical simulations and derived temperature, density and pressure distributions in the disk as functions of the distance from the Earth's spin axis, r, and the height from the disk midplane, z. The mechanical mixing process in the Earth's mantle is also investigated.

Method & Model: Our numerical method includes multiple steps. First, a giant impact process is calculated with Smoothed Particle Hydrodynamics (SPH), which is a Lagrangian method for fluid simulation. 10^5 particles are used. ANEOS and SESAME equations of state are chosen for forsterite (mantle) and iron (core). The impact velocity is set to the escape velocity and the impact parameter, b, varies between 0.7 and 0.8. The simulations are run for one day.

In order to derive the disk thermal properties, we have taken the output of the SPH simulations, applied conservation of entropy, mass and angular momentum and corrected for the additional energy released upon quick relaxation to the hydrostatic Keplerian state. This additional step is needed because SPH does not determine the state of the resulting hydrostatic disk. It is assumed that a liquid layer settles on the midplane and a gas phase exists above it. Thermodynamic properties in the z-direction are iteratively calculated by satisfying the surface density and entropy values at the given r. We also investigate how the mantle materials originating from the proto-Earth mechanically mix with those originating from the impactor.

Results & Discussions: Figure 1 shows the radially averaged disk entropy distributions at the end of the simulations. The remarkable uniformity of entropy profile arises, because most of the disk particles are initially located near the impact point and experience similar shock heating. Typically, 90% of the disk mass is within 10 Earth radii (R_E). The temperature profile at the liquid-vapor phase boundary is shown in Figure 2. This disk temperature depends weakly on b and ranges from 4500K (inner disk) to 2500K (outer disk). The vapor/liquid mass fraction along the r axis is nearly constant and the overall vapor mass fraction is 0.1-0.2.

Figure 3 shows the time evolution of the angular velocity of the Earth's mantle and the surrounding materials. The values are cylindrically averaged along the r axis. t is the time after the initial impact. At t=8 hours, the Earth experiences a second collision with the impactor. Immediately after the collision, the outer part of Earth's mantle rotates faster than the inner part. However, within 10 hours, the Earth is rotating almost as a rigid body. This relaxation process may happen more quickly than the real physical process due to the artificial viscosity, although angular momentum transfer from outside to inside can actually happen by a Kelvin-Helmholtz instability. Figure 4 shows the entropy profile of the Earth's mantle at t=23 hours. The yellow solid circles represent particles originating from the proto-Earth and the blue open circles represent ones from the impactor. Most of the materials from the impactor are located in the outer part of the Earth's mantle and they are not mechanically well mixed with the materials from the proto-Earth. Since the outer part has a higher entropy, the system is convectively stable. This profile does not change over time. This means that smoothing the rotational shear velocities in the mantle does not mix the mantle materials. However, calculations based on a Richardson number criterion for shear mixing suggest that the mantle materials from the two different origins will mix by a Kelvin-Helmholtz instability. This requires further study.

Conclusions: We have performed SPH simulations to understand the disk and the mantle state right after a giant impact. SPH outputs give the disk size, mass, angular momentum and entropy distributions. The typical disk sizes are 10 R_E. The entropy is nearly constant along the *r* axis. Based on the SPH outputs and the assumption that the disk is in a hydrostatic equilibrium, the disk pressure, the density and the temperature distributions are derived. Typical vapor mass fractions of the disk are 0.1-0.2. For the Earth's mantle, most of the materials from the impactor are distributed on the Earth's surface and are not mechanically well mixed with the materials from the proto-Earth. The entropy is higher outside, which means the system is convectively stable. The Earth reaches rigid body rotation very quickly, although the artificial viscosity may be facilitating the process. However, it does not support the mixing process. It is possible that the artificial viscosity inhibits the physically correct process of angular momentum mixing, which is a Kelvin-Helmholtz instability. Further study is required here. Other limitations may be due to the use of forsterite, which will tend to underestimate the vapor fraction, and the imperfections of ANEOS and SPH.

References:

[1] Hartman W. K., and Davis D. R. (1975) *Icarus*, 24, 504-515. [2] Stevenson D. J. (1987) *AREPS*, 15, 271-315. [3] Machida, R., and Abe Y. (2004) *ApJ*, 617, 633-644. [4] Pahlevan K., and Stevenson D. J. (2007) *EPSL*, 262, 438-449.

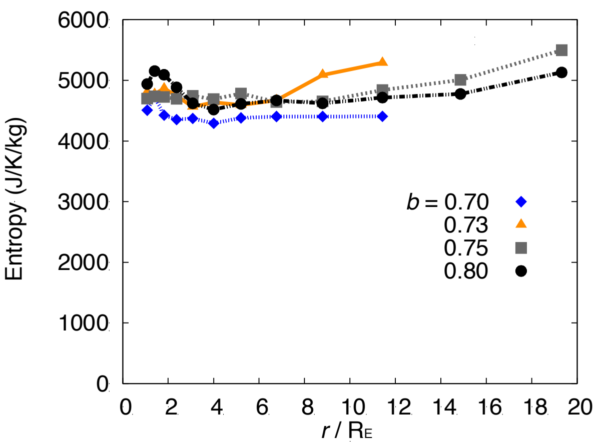

Figure 1. The distance from the Earth spin axis, *r*, vs. averaged disk entropy with various *b* values. R_E is the current Earth radius. Although the disks extend up to 20 R_E, most of the disk mass exists within 10 R_E.

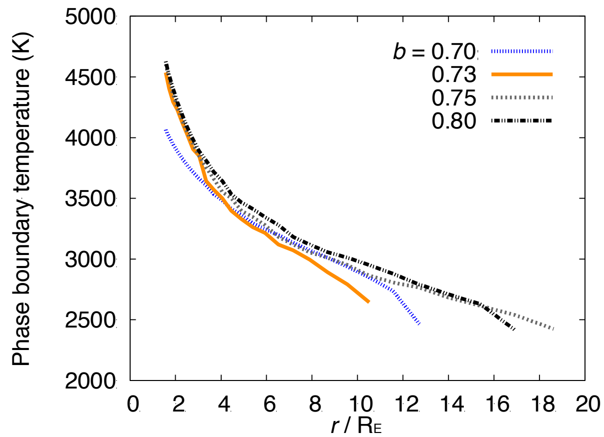

Figure 2. The disk's radial temperature profile at the liquid-vapor phase boundary.

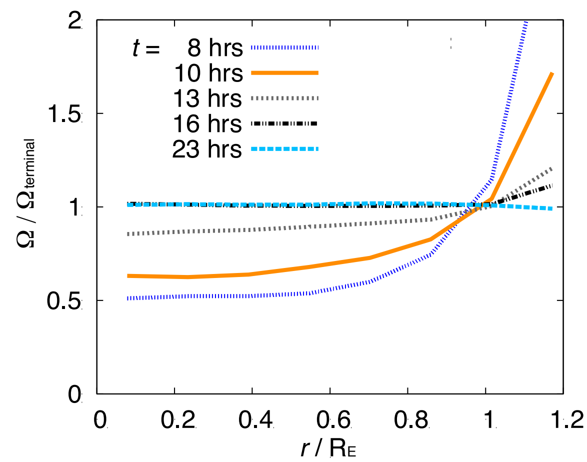

Figure 3. Cylindrically averaged angular velocity normalized by the average value at *t*=23 hours ($\Omega_{terminal}$). The boundary between the Earth mantle and surrounding disk is at r/R_E~ 1.1. *b*=0.75.

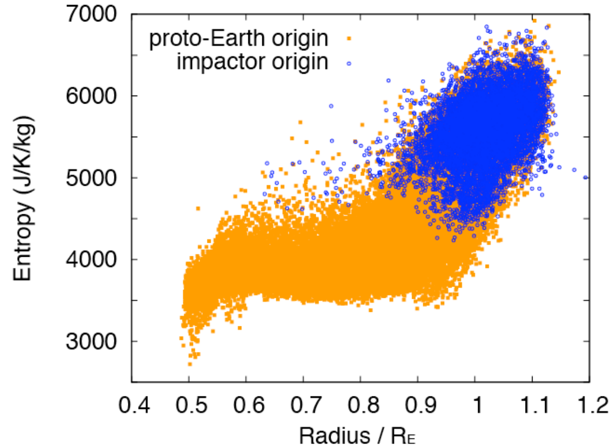

Figure 4. The distance from the center of the Earth vs. the Earth's mantle entropy profile at *t*=23 hours. The yellow solid circles originate from the proto-Earth and the blue open circles originate from the impactor.