THERMODYNAMIC PROCESSES DURING THE MOON-FORMING IMPACT. M. Nakajima and D. J. Stevenson, Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E California Blvd., MC 150-21, Pasadena, CA 91125 (mnakajima@caltech.edu).

Introduction: According to the "standard" giant impact hypothesis, the Moon was formed out of a debris disk created by a collision between an impactor and the proto-Earth [1, 2]. Numerical simulations based on this model can successfully reproduce the Moon's mass, its iron depletion, and its angular momentum [e.g., 3]. However, the scenario has difficulty in explaining the identical isotopic ratios between the Earth and Moon, because numerical studies indicate that most of the disks' materials come from the impactor. It has been suggested that there may have been mixing between the disk and the Earth's mantle which could have homogenized the isotopic ratios [4]. This could be an explanation for materials such as oxygen, but it may be difficult to explain the silicon isotopic ratios [5].

Recently, new models have been suggested for the origin of the Moon. Cuk & Stewart propose that an impactor hit a fast-spinning Earth [6], whereas Canup suggests a giant impact between two half Earth-mass objects [9] ("two sub-Earths", hereafter). In these cases, most of the disks' materials are from the Earth's mantle, therefore they can potentially explain the isotopic similarities. After the impact, the angular momentum of the Earth-Moon system is three times as large as its present-day value. It is suggested that an evection resonance can remove the angular momentum [6], but the efficiency of this is not well understood.

One important aspect, which has not been investigated well, is the thermodynamics of the system, although it highly affects the history of the Earth and Moon. For example, the extent of impact-induced mantle melting and mixing is important for linking impact models to geological data. Some mineralogical studies indicate heterogeneity of the mantle [e.g., 8], but its origin, formation, and duration are controversial. Understanding whether a giant impact resets it could constrain the formation time. Also, the disk's temperature and vapor mass fraction are two important factors that determine the time scale of the Moon formation and hence its process [9], but they have not been well determined.

Here, we perform various giant impact simulations including the standard and the recent models and identify the thermodynamics of the Earth-Moon system. We derive thermal structures of the disks and the extent of the melting and mixing in the Earth's mantle.

Methods & Models: The impact is modeled via Smoothed Particle Hydrodynamics (SPH), which is a Lagrangian method for simulating fluid flows. Impact velocities normalized by the escape velocities are 1.0 (standard), 1.8 (fast-spinning Earth), and 1.2 (two sub-Earths). Impactor masses normalized by the total mass are 0.13, 0.05 and 0.45, respectively. ANEOS and SESAME equations of state are used for forsterite (mantle) and iron (core), respectively. SPH outputs entropy, mass, and angular momentum distributions.

The degree of the mantle melting and mixing is investigated via the energy budget. Regions whose entropy increase exceeds that of the entropy of fusion are considered to be molten. The post-impact mantle is stable to convection if $dS/dR > 0$ and unstable if $dS/dR < 0$, where S is entropy and R is the distance from the Earth's center). Whether the mantle gets mixed is estimated by the Richardson number, Ri, which is half the ratio of potential energy and kinetic energy. If this number is smaller than 0.25 [10], the mantle is considered to be unstable and likely to get mixed.

In order to derive the disks' thermal profiles, we take the output of the SPH simulations, apply conservation of entropy, mass and angular momentum, and correct for the additional energy released upon quick relaxation to the hydrostatic circular Keplerian state. This additional procedure is required because the endpoint of the SPH run is not a hydrostatic disk. Given that a liquid layer settles on the midplane and a gas phase exists above it, the thermodynamic properties in the vertical direction, z, are iteratively calculated by satisfying the surface density and entropy values at a given distance from the Earth's spin axis, r.

Results & Discussions: A snapshot of a standard giant impact is shown in Figure 1. It shows that more severely shock heated regions have higher entropy. Figure 2 shows entropy distributions of the mantles as a function of R, normalized by the planet's radius, R_p. The blue broken line, the orange solid line, and the black dash-dotted line correspond to the standard, the fast-spinning Earth, and the two sub-Earths cases, respectively. dS/dR is positive in all cases. It implies that the mantles are stable to convection. The mantles are likely to be molten, because their entropy increments are larger than the entropy of fusion, (465 J/K/kg [11]) everywhere. Rough estimates of Ri are about 0.5, 0.1 and 0.1, respectively. These results imply that the kinetic energy of the standard case is relatively small and may not be high enough to mix the mantle, whereas for the other cases, the impacts are so energetic that the mantles can get mixed. Figure 3 shows the mass distri-

butions of the disks. While the sizes of the disks are similar, the fast spinning-Earth and the two sub-Earths cases are relatively compact. The temperature of the disks at the liquid-vapor interface is shown in Figure 4. The recently suggested models are significantly hotter and more highly vaporized (not shown) than the standard case. These hotter disks may have longer timescales for the Moon formation, because it takes more time to cool them down. This cooling timescale is more important than the disk spreading time. However, this requires further research.

Conclusions: We have run various giant impact simulations with SPH and investigated thermodynamic structures of the Earth's mantles and Moon forming disks. We find out that the mantles are likely to be molten in all cases. The mantles may get mixed in the recently suggested models since the impacts are more energetic. In these cases, the material entering the disk is severely shock heated and highly vaporized. It may take longer time to form the Moon from these disks, but further investigation is required.

References: [1] Hartmann W. K. and Davis D. R. (1975) *Icarus*, 24, 504-515. [2] Cameron A. G. W. and Ward W. R. (1976) *Lunar Sci.*, 7, 120-122. [3] Benz W. et al. (1986) *Icarus*, 66, 515-535. [4] Pahlevan K. and Stevenson D. J. (2007) *EPSL*, 262, 438-449. [5] Armytage R. B. et al. (2012) *Geochim. Cosmochim. Acta*. 77, 504-514. [6] Cuk M. and Stewart S. T. (2012) *Science*, 1047-1052. [7] Canup R. M. (2012) *Science*, 338, 1052-1055. [8] Touboul M. et al. (2012) *Science*, 335, 1065-1069. [9] Thompson C. and Stevenson D. J. (1988) *ApJ*, 333, 452-481. [10] Miles J. W. (1961) *J. Fluid Mech.,* 10, 496-508. [11] Richet P. et al. (1993) *GRL*, 20, 1675-1678.
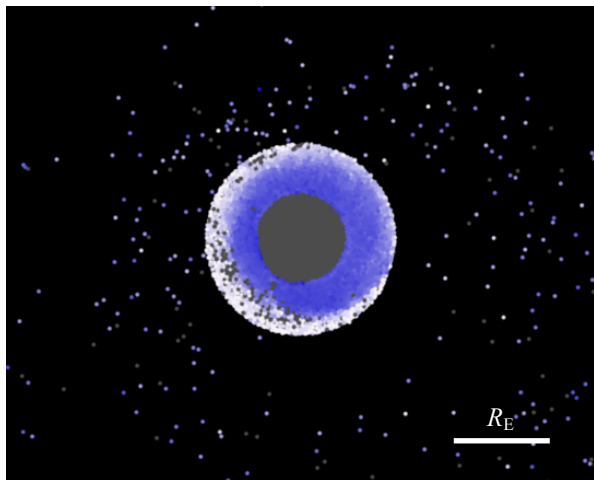

Figure 1. A snapshot of a final state of a standard giant impact simulation. Entropy of forsterite is shown in blue (low) and white (high). The grey scale indicates iron.
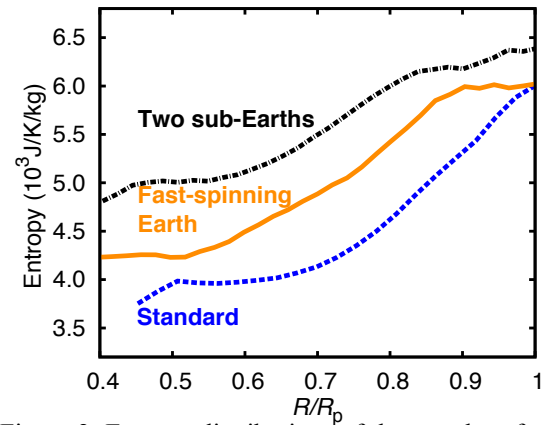

Figure 2. Entropy distributions of the mantles after the impacts. The mantles initially have a uniform entropy $(3.2 \times 10^3$ J/K/kg).
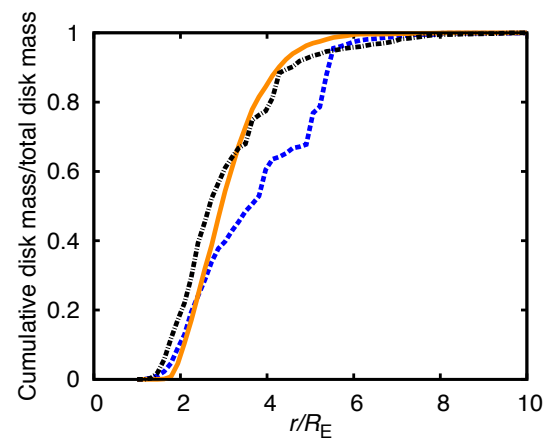

Figure 3. Mass distributions of the disks. The typical size of the disk is 6-8R_E. About 60% of the disks' mass exists within the Roche radii ($\sim 3R_E$) for the fast-spinning Earth and two sub-Earths cases, whereas 40% of the mass is located within it for the standard case.
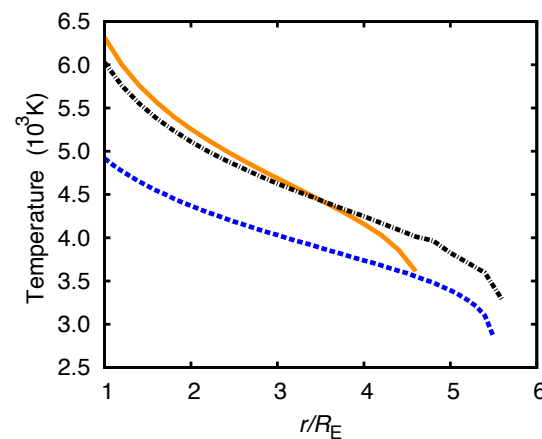

Figure 4. The disks' temperature at the phase boundary. Recently suggested models are more severely heated and they are 500-1000 K hotter than the standard case.