Chemical composition and the origin of the Moon: A geophysical approach

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Chemical composition of the Moon has an important clue on its origin. In this presentation I will discuss two related issues. First after reviewing previous studies, I conclude that isotopic composition of the Moon is very close to that of Earth (e.g., (Zhang et al., 2012)), while major element composition is substantially different (the Moon has a higher FeO content, e.g., (Khan et al., 2007; Kuskov and Kronrod, 1998)). The volatile content (such as water content) in the Moon has been controversial. Early analyses of Apollo samples show evidence of "dry" Moon, but recent analysis of some of the Apollo samples with high-resolution techniques suggested not-so-dry Moon (e.g., (Hauri et al., 2011; Saal et al., 2008)). While these new observations on the water content in the lunar samples are intriguing, interpretation of these data on surface rocks is complicated and the implication of these observations on the water in the bulk of the Moon is unclear. I use geophysical approach to provide complementary constraints on the water content in the lunar mantle. In doing so I use two methods that I developed during the last ~10 years, namely the use of electrical conductivity and anelastic relaxation. Both of them have been inferred for the Moon. Second, a commonly accepted model of the origin of the Moon, i.e., a giant impact model, has a serious difficulty in explaining the chemical composition of the Moon. I suggest that one serious drawback of all previous models is that they did not include an important role of the difference in compressional properties of liquids and solids in collisional heating. I present a new model where the differences and the similarity in the chemical composition between the Moon and Earth are explained as a natural consequence of planetary formation.

The electrical conductivity-depth profile in the Moon was inferred during the Apollo mission (e.g., (Hood et al., 1982)), and anelastic relaxation (Q) was inferred both from lunar seismology (e.g., (Nakamura and Koyama, 1982)) as well as from tidal dissipation (e.g., (Williams et al., 2001)). Remarkably, the electrical conductivity of the deep lunar mantle is as high as that in Earth's asthenosphere, and the tidal Q is as low as ~40.

I interpret these observations based on the laboratory data on these properties. The laboratory studies on electrical conductivity provide robust calibration on the relationship between electrical conductivity and various parameters including water content, temperature, pressure and major element composition. Although less robust, a similar relationship can be developed for anelastic relaxation. The influence of major element chemistry and pressure is not large and can be corrected using other data set such as gravity, seismic wave velocities. After the correction of these factors, one can infer the combinations of water content and temperature that explain the inferred electrical conductivity and anelastic relaxation. If one uses only one of these observations, water content cannot be inferred uniquely (because of a strong trade-off between temperature and water content). However, when one combines these together, a unique solution (with some uncertainties) can be obtained. The results show that the lunar interior are colder than Earth (at the same depth) but the water content in the deep lunar mantle is on the same order of the water content in Earth's asthenosphere (0.01-0.001 wt%) (**Fig. 1**).

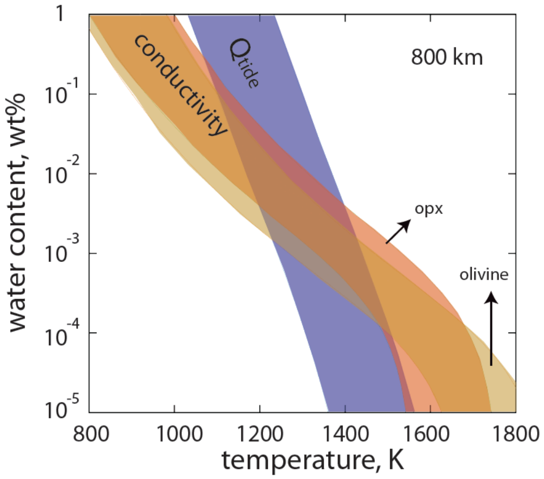

Fig. 1 Temperature-water content that explains geophysically inferred Q and electrical conductivity (corresponding to the depth of 800 km where the resolution of conductivity estimate is the best)

I suggest that this observation can be explained if the Moon was formed from the gas-liquid disk quickly compared to the time scale of cooling of the Moon-forming disk. In such a case, most of water in the disk can be dissolved in the liquids and if accretion occurs faster than cooling then water dissolved in liquids can be preserved in the Moon. Such a relative time-scales of cooling and accretion are consistent with the current model of Moon formation (e.g., (Canup, 2004; Salmon and Canup, 2012)).

One of the major problems in the giant impact model for the origin of the Moon is that when the collision parameters (size of the impactor and the angle of collision) are adjusted to explain the angular momentum of the Earth-Moon system, most of previous models predicted that the materials that are ejected by the collision and became the source materials for the Moon are mostly from the impactor (e.g., (Canup, 2004)). If so, the very similar isotopic compositions of the Moon and Earth cannot be explained. Recently, (Cuk and Stewart, 2012) and (Canup, 2012) developed a modified model of giant impact in which a majority of ejected materials could be from Earth if certain combinations of collision parameters are chosen. I consider that this is not quite satisfactory explanation, because the parameter space that explains the composition of the Moon is so small compared to many possibilities that the choice of such a small parameter space seems *ad hoc* (one should ask why did the God choose such parameters?). Furthermore, these models do not explain the difference in FeO content.

I developed an alternative model to explain the similarity in isotopic composition and the difference in the major element composition. One major limitation in all of the previous models of Moon formation is that a common equation of state was used for both impactor and the proto-Earth. I show that when a planet covered with a liquid (magma ocean) collides a completely solid planet, the liquid part of a planet is heated much more than the solid planet. This is due to (1) the higher compressibility of liquid than solid, and to (2) the larger Grüneisen parameter of liquids upon compression. These two differences in the compressional properties between (non-metallic) liquids and solids are caused by the fundamental differences in the mechanism of compression (Jing and Karato, 2011). I have calculated the temperature increase upon a collision of a liquid (planet with a magma ocean on its surface) with a solid (completely solid planet), and found that the temperature increase in liquid is ~20,000K or higher while for solid, it is less than ~5,000 K (for the collision velocity of ~11 km/sec (escape velocity for Earth)). When heated above 20,000K, a majority of materials will be vaporized and expands. This expansion favors these materials to be trapped in the orbit surrounding the proto-Earth to form the

Moon. Therefore, in this model, a majority of the materials to form the Moon was from the magma ocean of the proto-Earth. By melting, the isotopic compositions (of heavy atoms) do not change much. However, the molten materials should be enriched with FeO. Consequently, the prediction of this model is consistent with the known chemical composition of the Moon. The presence of a magma ocean in a large planet such as the proto-Earth, but the absence of a magma ocean in a smaller planet is a natural consequence of formation of planets (e.g., (Sasaki and Nakazawa, 1986)). Therefore, this model explains the composition of the Moon as a natural consequence of planetary formation without invoking any *ad hoc* assumptions.

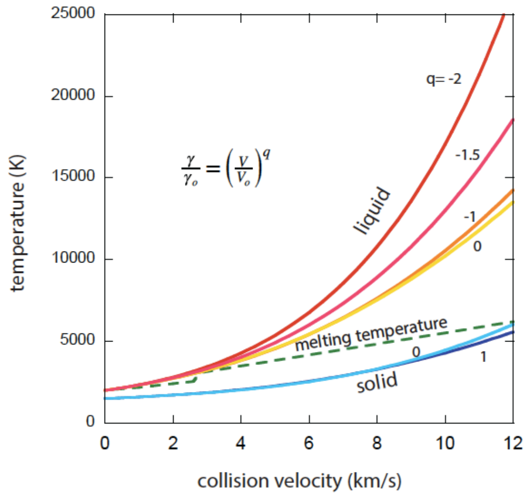

Fig. 2 Temperature increase upon a collision of a liquid planet and a solid planet. The liquid planet is heated much more than the solid planet.

References

Canup, R.M., 2004. Dynamics of lunar formation. Annual Review of Astronomy and Astrophysics 42, 441-475.

Canup, R.M., 2012. Forming a Moon with an Earth-like composition via a giant impact. Science 388, 1052-1055.

Cuk, M., Stewart, S.T., 2012. Making the Moon from a fast-spinning Earth: A giant impact followed by resonant despinning. Science 338, 1047-1052.

Hauri, E.H., Weinreich, T., Saal, A.E., Rutherford, M.C., Van Orman, J.A., 2011. High pre-eruptive water contents preserved in lunar melt inclusions. Science 333, 213-215.

Hood, L.L., Herbert, F., Sonett, C.P., 1982. The deep lunar electrical conductivity profile: Structural and thermal inferences. Journal of Geophysical Research 87, 5311-5326.

Jing, Z., Karato, S., 2011. A new approach to the equation of state of silicate melts: An application of the theory of hard sphere mixtures. Geochimica et Cosmochimica Acta 75, 6780-6802.

Khan, A., Connolly, J.A.D., Maclennan, J., Mosegaard, K., 2007. Joint inversion of seismic and gravity data for lunar composition and thermal state. Geophysical Journal International 168, 243-258.

Kuskov, O.L., Kronrod, V.A., 1998. Constitution of the Moon: 5. Constraints on composition, density, temperature, and radius of a core. Physics of the Earth and Planetary Interiors 107, 285-306.

Nakamura, Y., Koyama, J., 1982. Seismic Q of the lunar upper mantle. Journal of Geophysical Research 87, 4855-4861.

Saal, A.E., Hauri, E.H., Lo Cascio, M., Van Orman, J.A., Rutherford, M.C., Cooper, R.F., 2008. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior. Nature 454, 192-195.

Salmon, J., Canup, R.M., 2012. Lunar accretion froma Roche-interior fluid disk. The Astrophysical Journal 760, 10.1088/0004-1637X/1760/1081/1083.

Sasaki, S., Nakazawa, K., 1986. Metal-silicate fractionation in the growing Earth: energy source for the terrestrial magma ocean. Journal of Geophysical Research 91, 9231-9238.

Williams, J.G., Boggs, D.H., Yoder, C.F., Ratcliff, J.T., Dickey, J.O., 2001. Lunar rotational dissipation in solid body and molten core. Journal of Geophysical Research 106, 27933-27968.

Zhang, J., Dauphas, N., Davis, A.M., Leya, I., Fedkin, A., 2012. The proto-Earth as a significant source of lunar material. Nature Geoscience 5, 251-255.