EARTH AFTER THE MOON FORMING GIANT IMPACT: ACCOUNTING FOR ALL THE ENERGY.

S. J. Lock[1], S. T. Stewart[2], and M. Ćuk[3], [1]Harvard University, Dept. of Earth and Planetary Sci. (slock@fas.harvard.edu); [2]University of California Davis, Dept. of Earth and Planetary Sci.; [3]SETI Institute.

Introduction: The Moon-forming giant impact was a highly energetic event. The post-impact Earth was very hot with tens of percent of the silicate mantle being either supercritical fluid or vapor [1]. In recent high-angular momentum lunar origin models [2-4], post-impact Earth is also rapidly rotating. After the impact, Earth transitioned from this hot, rapidly rotating post-impact state to today's condensed, slowly rotating planet by first cooling and then losing angular momentum (AM) as the Moon tidally receded. This is a key stage of Earth's formation, but many aspects of this period have not been extensively studied.

In particular, the complete energy budget for Earth during the transition has not yet been calculated. Previous work only considered a subset of the energy components. Determining the energy budget is a fundamental step in understanding this period of Earth's evolution. For example, the timescale to cool the post-impact state to a magma ocean is determined by the energy that needs to be radiatively lost. Furthermore, the energy dissipated in Earth during lunar tidal recession dictates Earth's thermal state and the initial conditions for the subsequent evolution of the planet.

A full dynamical calculation of the evolving Earth is currently unfeasible. Here we approach the problem by comparing the total energy of Earth at different stages in its evolution.

Cooling the post-impact body: Previous attempts to calculate the time required to cool the post-impact Earth to a magma ocean (a body with a liquid mantle but no silicate vapor atmosphere) have only considered the latent heat of vaporization of the silicate vapor. However, the size and shape of a body changes significantly upon condensation of the vapor, leading to changes in potential and kinetic energy in addition to the change in internal energy. The post-impact to magma ocean transition is discussed in more detail in [5].

Figure 1 shows the difference in all the relevant energy components between post-impact bodies formed by a suite of smoothed particle hydrodynamics (SPH) simulations and corresponding magma ocean planets calculated using the HERCULES code [1] which utilizes a potential field method. The mantles of magma ocean planets were modelled using the MANEOS forsterite equation of state [6] and assumed to be isentropic with a specific entropy of 4 kJ K^{-1} kg^{-1}. This isentrope intersects the liquid-vapor phase boundary at low pressure (10 bar) and about 4000K. The reduction in the moment of inertia as the post-impact body contracts leads to an increase in rotation rate and hence an increase in rotational kinetic energy. Conversely, the contraction requires the release of gravitational potential energy, which is comparable in magnitude to the change in internal due to condensing the silicate vapor. Thus, the effects of changes in size and shape cannot be ignored in calculating the energy budget of evolving planetary bodies. The energy required to condense and contract the structure is at least seven orders of magnitude greater than the heat produced by radioactive decay over the period of cooling (10^{23} to 10^{24} J).

Based on our calculations, the radiative timescale to cool a post-impact state to a magma ocean planet is on the order of 100s to 1000s years, with the main uncertainty being the radiating surface area.

Tidal recession of the Moon: As the Moon tidally recedes, energy must be dissipated in Earth and the Moon. Current tidal models only consider dissipation due to changes in rotational kinetic energy and the orbital energy of the Moon. The rotational kinetic energy of Earth is calculated assuming tfhat Earth has a constant figure (shape). However, in recent high-AM lunar origin models [2-4], Earth is significantly oblate, in some cases with a ratio of equatorial to polar radii of 2:1 [1]. As Earth loses AM, the figure of Earth evolves towards a sphere.

We determined the energy budget during tidal recession including the effects of changing figure by calculating the difference between initial planets with different AM and a body with the AM of the present-day Earth using the HERCULES code [1] (Figure 2). Note, we have not included orbital energy terms here and just considered the energy budget of the planet in isolation. The total energy change during tidal recession is of the same order of magnitude as that between the post-impact state and the magma ocean for high-AM [2-4] Moon-formation models. In the canonical model [7], the energy change during tidal recession is a factor of a few less than that for cooling. The energy deposited is three orders of magnitude more than radioactive heat over the first 10 Myr of lunar tidal evolution (about 3×10^{28} J). Thus, as expected, the early epoch of tidal recession would have been a substantial thermal event on Earth.

The change in figure results in less tidal energy dissipated in Earth than calculated in previous models [8,9]. Energy is deposited due to changes in both kinetic and gravitational potential energy. Release of potential energy is dissipated by different mechanisms and in different regions of the body than the energy released from changes in kinetic energy. In addition, work is done by compressing the planet as the centrifugal force is reduced and the internal pressure increases [10], reducing the amount of energy that must be dissipated as heat.

Earth is likely mostly solid for much of the tidal recession [11], and the change in pressure would also induce phase changes in the mantle. Exothermic phase transitions in the transition zone and lower mantle release enough heat to raise the temperature of these regions by several tens to hundreds of degrees. The energy released from these phase transitions is an order of magnitude or two more than radioactive heating. Such large temperature rises may lead to partial melting and a concentration of further tidal energy deposition in these regions. Conversely, the endothermic ringwoodite to bridgmanite transition would have led to cooling of the region just below the transition zone by a similar amount.

Conclusions: Condensing Earth and reducing the Earth's AM after the Moon-forming giant impact require massive changes in energy. The spatial pattern of kinetic and potential energy dissipation and localized heating and cooling from phase transitions during tidal recession would have had a strong effect on convection and heat transport in the mantle. Understanding these processes is vital to constrain the thermal state of the mantle at the start of the Hadean.

References: [1] Lock, S. J. & S. T. Stewart (2017) *JGR: Planets* **150**, 950 [2] Ćuk, M. & S.T. Stewart (2012) *Science* **338**, 1047 [3] Canup R. *Science* **338**, 1052 [4] Lock, S.J., et al. (revised) *JGR*: Planets [5] Stewart, S. T., et al. (2018) *LPSC* [6] Melosh, H. J. (2007) *MPS* **42** 2079 [7] Canup, R.M. (2004) *Icarus* **168**, 433 [8] Tian, Z-L, et al. (2017) *Icarus* **281**, 90 [9] Ćuk, M., et al. (2016) *Nature* **539**, 402 [10] Lock, S. J., et al. (2017) *AGU Fall Meeting* P53F-07 [11] Zahnle, J., et al. (2015) *EPSL* **427**, 74

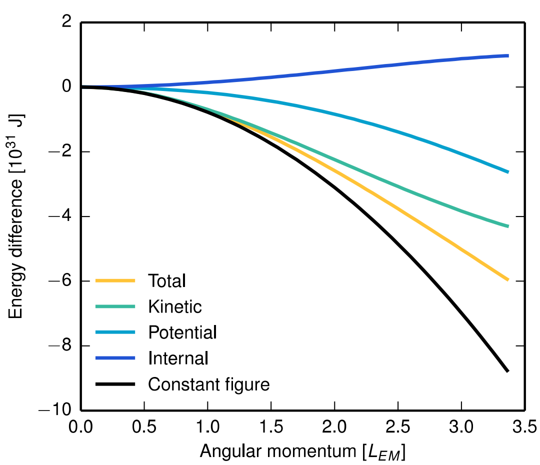

Figure 2: The change in energy between an Earth-mass planet of a given AM and a non-rotating planet with a thermal profile described by the same isentrope. The black line is the change in kinetic energy using the common assumption of constant figure. The colored lines show the energy components for a full calculation including changes in shape.

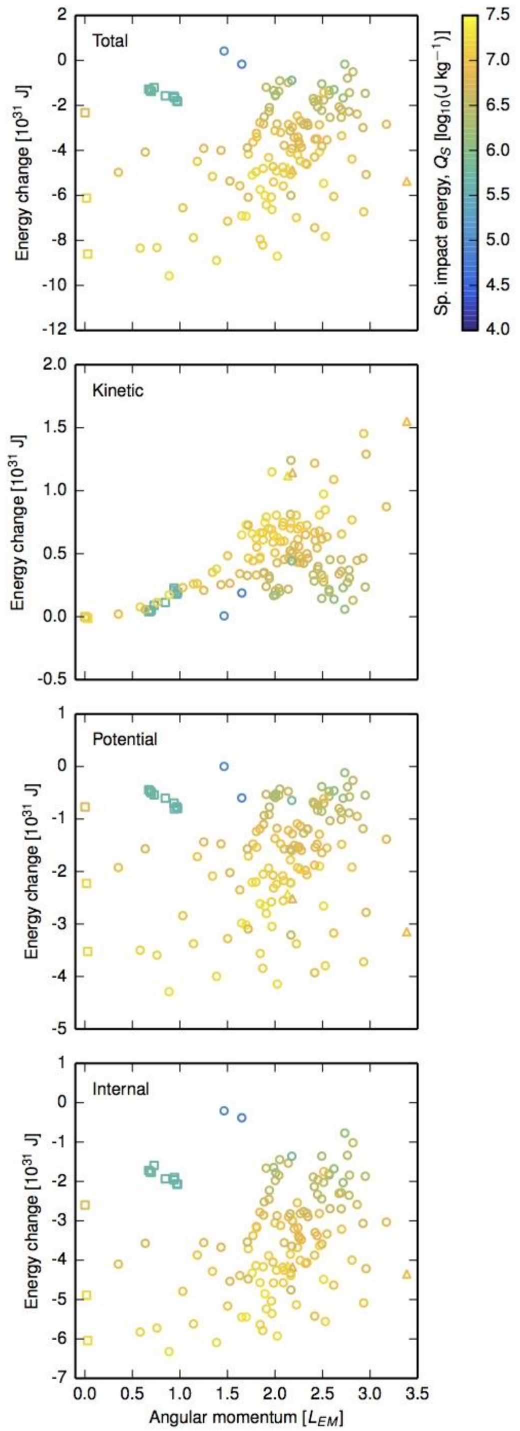

Figure 1: The change in energy required to cool from a post-impact state to a magma ocean planet of the same mass, AM and composition for bodies that are below (squares), coincident with (triangles) or above the corotation limit (circles) from [1]. Panels show different energy components. Higher impact energies (color bar) produce post-impact bodies with more vapor and hence lead to larger energy changes during cooling.