IMPLICATIONS OF LUNAR ORIGIN VIA GIANT IMPACT FOR THE MOON'S COMPOSITION AND THE THERMAL STATE OF THE PROTOEARTH. R. M. Canup, Planetary Science Directorate, Southwest Research Institute; 1050 Walnut Street, Suite 300; Boulder, CO 80302; robin@boulder.swri.edu

Introduction: The leading theory for the Moon's origin is that it formed as a result of the impact of a Mars-sized object with the early Earth [1]. Key strengths of the giant impact theory include its ability to account for the Earth-Moon system angular momentum (which implies a terrestrial day of only about 5 hours when the Moon formed close to the Earth), and the Moon's low iron abundance. In addition, dynamical models of the final stages of Earth's accretion suggest that large impacts were common [2].

Prior models of lunar-forming impacts (*e.g.*, [3-5]) assume that both the impactor and the target protoearth were not rotating prior to the Moon-forming event. However, planet formation models suggest that such objects would have had substantial rotation rates during the late stages of terrestrial planet accretion [2]. In a recent work [6], I explore the effects of pre-impact rotation on impact outcomes through > 100 hydrodynamical simulations of potential Moon-forming collisions that consider a range of impactor masses, impact angles and impact speeds. Here the implications of these new and past results for the predicted composition of protolunar material—in particular whether it is derived predominantly from the impactor or the protoearth—and the post-impact thermal state of the protoearth are discussed.

Method: I utilize smooth particle hydrodynamics (SPH, *e.g.* [3-6]) with an improved version [7] of the equation of state ANEOS [8]. The SPH code is a variant of that by Benz (*e.g.* [9]) that employs variable smoothing lengths and a tree code to calculate explicit gravitational interactions. Material strength is ignored, a valid assumption for the planet-scale impacts simulated here. The energy budget is determined by shock dissipation [10], and work done by compressional heating and expansional cooling.

Constraints: A successful lunar-forming impact must account for: *i*) the current Earth-Moon system angular momentum, $L_{EM} \equiv 3.5 \times 10^{41}$ g-cm^2/sec, *ii*) a protolunar disk whose mass and angular momentum are sufficient to produce a Moon containing 1.2% of an Earth mass ($M_\oplus$) outside the Earth's Roche limit, and *iii*) a bulk lunar mass abundance of elemental iron in the few to 10% range (*e.g.*, [4] and references therein). Because the Earth-Moon system angular momentum has decreased over its history due to solar interactions (*e.g.*, [6]), a post-impact system needs to have an angular momentum L_F that is a few to 10% greater than L_{EM}.

Results: Pre-impact rotation, particularly in the target protoearth, can substantially alter collisional outcomes and leads to a more diverse set of final planet-disk systems than seen previously. However, the subset of these impacts that are also lunar-forming candidates—*i.e.* that produce a sufficiently massive and iron-depleted protolunar disk—have similar properties to those determined for collisions of non-rotating objects [4-5]. With or without pre-impact rotation, a lunar-forming impact requires an impact angle near 45°, together with an impact velocity, v_{imp}, that is not more than 10% larger than the Earth's escape velocity, v_{esc} [6]. Sucessful cases produce a protolunar disk containing up to about 2 lunar masses.

Pre-impact spin in the impactor does not have a strong affect on impact outcome. A target protoearth with a pre-impact retrograde rotation (*i.e.* in the opposite rotational sense as the impact itself, Fig. 1 red points) allows for somewhat larger impactors (containing up to 20% of Earth's mass) and provides an improved match with the current Earth-Moon system angular momentum compared to prior results [4-5]. A prograde rotating target (Fig. 1, blue points) results in disks that are not massive enough in nearly all cases that have a collisional angular momentum comparable to L_{EM}. Thus an impact-formed Moon argues against the Earth having had a low obliquity, rapid prograde rotation immediately prior to the lunar-forming event.

Origin of protolunar material. Figure 1 shows results from SPH impact simulations [5-6] that all produced iron-depleted disks with < 10% iron by mass. Color indicates pre-impact rotation state (red = retrograde target, black = no pre-impact spin, blue = prograde target), while symbol size scales with impactor mass (small, M_{imp}= 0.11$M_\oplus$; medium, M_{imp}= 0.13$M_\oplus$; large, M_{imp}= 0.15$M_\oplus$; and extra-large, M_{imp}= 0.20$M_\oplus$). The current Earth-Moon system is indicated by the gray line, with q = 0.012, and an initial angular momentum range $1 \leq L_F / L_{EM} \leq 1.1$ shown to allow for up to 10% angular momentum loss over the system's history due to solar interactions. The largest q value shown reflects a disk mass of 2.1 lunar masses produced by the rather extreme case of an impact into a rapidly retrograde rotating target with a 4.1 hr period prior to the lunar-forming collision.

In all cases, impacts that produce sufficiently massive disks to yield the Moon have disks that are derived primarily (60 to 90%) from the impactor's mantle (Fig. 1b). An impactor origin of the majority of protolunar material appears a universal prediction of all successful impact simulations, and one that must ultimately be reconciled with the identical O-isotope compositions of the Earth and Moon [11]. This appears to require either that the impactor and protoearth had identical compositions (unlikely given the compositional variation predicted by accretion models) or that extensive mixing between protolunar and protoearth material after the impact but prior to the Moon's formation allowed compositions to equilibrate [12]. The mixing scenario seems the most promising, but requires the Moon's formation to be delayed by a hundred years or more after the impact. Improved models of protolunar disk evolution and lunar accretion will be needed to assess whether this is plausible.

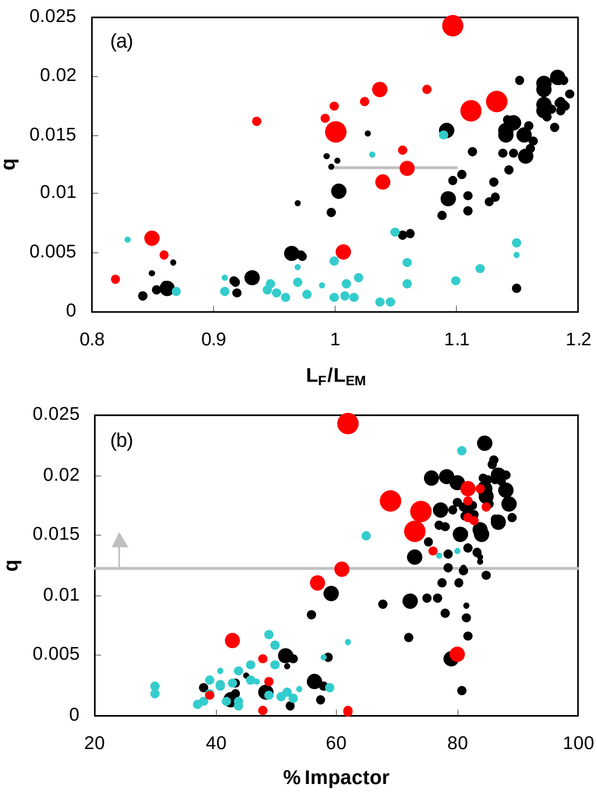

Figure 1. (a) Predicted maximum satellite-to-planet mass ratio, *q*, assuming no mass escapes from the protolunar disk [13] vs. the final angular momentum of the bound planet-disk system, L_F, in units of the Earth-Moon angular momentum, L_{EM}. (b) Predicted maximum satellite-to-planet mass ratio vs. the fraction of the disk mass that originates from the impactor.

Post-impact thermal state of the protoearth. A Moon-forming impact delivers an energy to the Earth $E_{imp}/M_{\oplus} \sim 4\times10^{10}$ erg/g $(M_{imp}/0.1)(v_{imp}/v_{esc})^2$, which is much greater than the latent heat of fusion for rock, $l \sim$ few $\times\, 10^9$ erg/g. Figure 2 shows the initial and post-impact temperatures within the target protoearth from a sample simulation ([6], run 82) in which a $0.13M_{\oplus}$ impactor collides with a retrograde-rotating, $0.89M_{\oplus}$ target with an impact angle of 45° and $v_{imp} = 1.05v_{esc}$. The initial protoearth temperatures were generated by applying an adiabat with a 2000K surface temperature to the uncompressed protoearth, which was then settled with SPH to achieve a compressed hydrostatic state (as in the "warm start" cases in [5]). Even when the target's interior is initially subsolidus, most of the protoearth is heated to a mixed solid-melt state by the impact, with material in the outer $\sim10^3$ km melted completely.

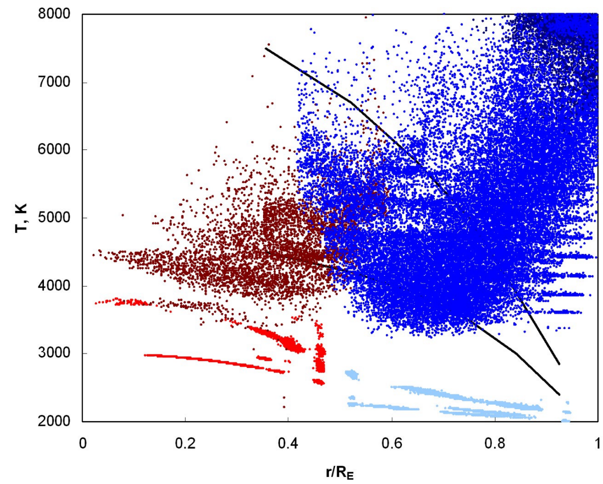

Figure 2: Temperature in the protoearth as a function of depth (where *r* is the distance from the planet's center and R_E = 6378 km) for an impact simulation from [6]. Iron and silicate particles in the initial, pre-impact protoearth are shown as red and light blue points. Dark red and blue points show the original protoearth material at the simulation's final time step (31 hr), while dark blue points (upper right) are silicate particles originating from the impactor that are accreted by the protoearth. The great majority of the impactor's iron core is accreted by the protoearth, and this material has extremely high predicted post-impact temperatures (> 15,000K) which are above the scale of this plot. Shown in black are example solidus and liquidus curves for a three component ($MgSiO_3$, MgO, and FeO) lower mantle magma ocean model [14].

References: [1] Cameron, A.G.W, Ward, W.R. (1976) *LPSC*; [2] Agnor, C.B., Canup, R.M., Levison, H.F. (1999) *Icarus* 142, 219-237; [3] Cameron, A.G.W. (2000) *Origin of the Earth and Moon*, Eds. Canup, R.M. & K. Righter, 133-144; [4] Canup, R.M. & Asphaug, E. (2001) *Nature* 412, 708-712; [5] Canup, R.M. (2004) *Icarus* 168, 433-456; [6] Canup, R.M. (2008) *Icarus*, in press; [7] Melosh, H.J. (2008) *MAPS*, submitted; [8] Thompson, S.L. & Lauson, H.S. (1972) *Sandia Tech. Rep. SC-RR-710714*; [9] Benz, W., Cameron, A.G.W. & Melosh, H.J. (1989) *Icarus* 81, 113-13; [10] Balsara, D. (1995) *J. Comput. Phys.* 121, 357-372; [11] Weichert, U., *et al.* (2001) *Science* 294, 345-348; [12] Pahlevan, K., Stevenson, D.J. *Earth Plan. Sci. Let.* 262, 438-449; [13] Ida, S., Canup, R.M. & Stewart, G.R. (1997) *Nature* 389, 353-357; [14] Solomatov, V.S., Stevenson D.J. (1993) *J. Geophys. Res.* 98, 5391-5406.

Acknowledgements: Support from NASA's Origins of Solar Systems program is gratefully acknowledged.