MOON-FORMING IMPACTS INVOLVING PRE-IMPACT SPIN. Robin M. Canup (Southwest Research Institute, Department of Space Studies, Boulder, CO; robin@boulder.swri.edu).

Introduction: Prior simulations of giant impacts capable of producing the Earth-Moon system predict that the Moon forms predominately from material originating from the impactor rather than from the protoearth. Yet there are distinct isotopic similarities between the Earth and Moon. To date, simulations of potential lunar-forming collisions have considered impactors and target protoearths that are not rotating prior to impact [1-3]. However, rapid planetary rotation rates are expected throughout late stage terrestrial accretion [*e.g.*, 4], and modeling of Pluto-Charon forming collisions indicates that pre-impact spin can be important, *e.g.* leading to the formation of intact satellites rather than circumplanetary disks [5]. Here I consider the effects of pre-impact spin on the fraction of protolunar material derived from the impactor vs. the target, and on the likelihood of forming a large intact moon via giant impact.

Method: I utilize smooth particle hydrodynamics (SPH, *e.g.* [1-3; 5]) with an improved version [6] of the equation of state ANEOS [7]. The SPH code is a variant of that by Benz (*e.g.* [8]) 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 [9], and work done by compressional heating and expansional cooling [*e.g.*, 3].

Initial conditions: Each collision involves a total mass, M_T (target + impactor), of approximately an Earth-mass, described by between N = 60,000 and 120,000 SPH particles. Targets and impactors are differentiated prior to the collision and contain 30% iron and 70% forsterite by mass, having initial surface temperatures ~ 2000 K (see [3] for details). Two values for γ, the ratio of the impactor mass to M_T, are considered, with $\gamma = 0.05$ and $\gamma = 0.13$. Impact velocity, v_{imp}, is varied from $1 \le v_{imp}/v_{esc} \le 1.2$, where v_{esc} is the mutual escape velocity of the colliding objects, while impact angles are varied from $24° \le \xi \le 53°$, where ξ is the angle between the impact trajectory and the local surface normal, so that $\xi = 90°$ is a grazing impact. The pre-impact spin vectors of either the target or impactor are normal to the plane of the impact, and pre-impact spin is classified as "prograde" if it has the same rotational sense as the impact.

Results: Figs. 1-2 show results of 27 impact simulations after ~ 24 hours of simulated time.

Prograde impactor or retrograde target. Open diamonds show six N = 60,000 particle simulations in which a successful impact from [3] ("Earth 119", Fig. 2) was repeated with either a pre-impact prograde spin in the impactor (with spin period T = 5, 10, or 15 hr), or a pre-impact retrograde spin in the target (with T = 15, 20 or 30 hr). In all six cases, the scaled impact parameter, $b' = \sin \xi$, was fixed at $b' = 0.73$, and $v_{imp}/v_{esc} = 1$. The six simulations yield broadly similar results to those of the comparison simulation without pre-impact spin (which had $M_D/M_L = 1.62$, 85% of the disk originating from the impactor, and 5% of the disk in iron, see [3] and Fig. 1), although the disk masses here are lower in some cases.

The three retrograde target cases yielded massive and iron-depleted protolunar disks. The final system angular momentum, L_F, in each case was in the range $0.94 \le L_F/L_{EM} \le 1.08$ (where L_{EM} is the Earth-Moon system angular momentum), lower than the no-spin case from [3] (with $L_F = 1.18 L_{EM}$) and more consistent with the current Earth-Moon system than successful lunar-forming candidates identified previously [10].

In the simulation involving the slowest prograde impactor spin (T_{imp} = 15 hr), an intact moon resulted which contained 74% of a lunar mass, no iron, and was comprised of 87% impactor material by mass. The moon had an eccentric orbit with $e = 0.45$ and a perigee of 3.2 Earth radii. It has recently been argued that a high early lunar orbital eccentricity is implicated by the current "fossil bulge" in the Moon's figure [11]. However, an intact Moon formed overwhelmingly from impactor-derived material may be difficult to reconcile with the O-isotope compositions of the Earth and Moon that fall on the same fractionation line [12]. The two faster impacator spin cases yielded progressively lower disk masses and did not produce large intact moons.

Prograde target. In twenty-one, N = 120,000 particle simulations, a range of impact speeds, angles, and impactor sizes were considered in conjunction with pre-impact prograde spin periods in the target protoearth ranging from T = 4.3 to 102 hours. In each case, the total pre-impact system angular momentum was between 1.1 and $1.2 L_{EM}$. Similar trends are observed as in cases without pre-impact spin [*e.g.* 3], including that the orbiting mass, and impactor and iron disk mass fractions generally increase for highly oblique impacts.

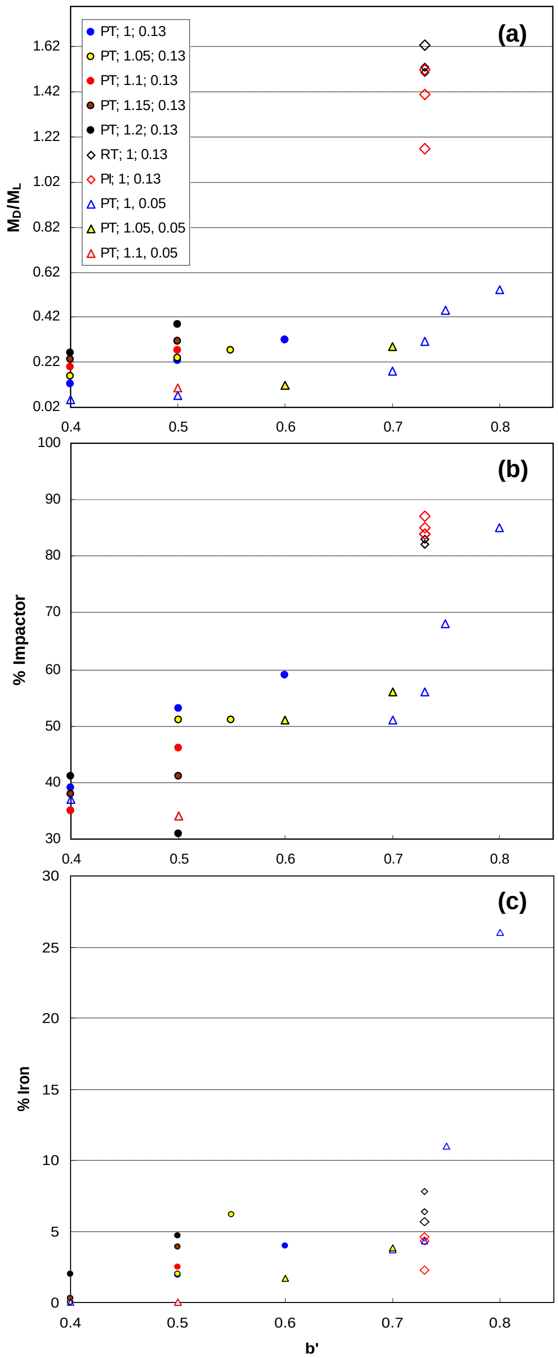

Figure 1: Results of giant impact simulations shown as a function of the scaled impact parameter, b' = sin ξ. The first column in the legend indicates a prograde (P) or retrograde (R) pre-impact spin in the target (T) or impactor (I), the second column is (v_{imp}/v_{esc}), and the third column is γ (see text for definitions). (a) Orbiting disk mass (M_D) in lunar masses (M_L). (b) Percentage of disk mass that originated from the impactor. (c) Fraction of iron in the orbiting disk.

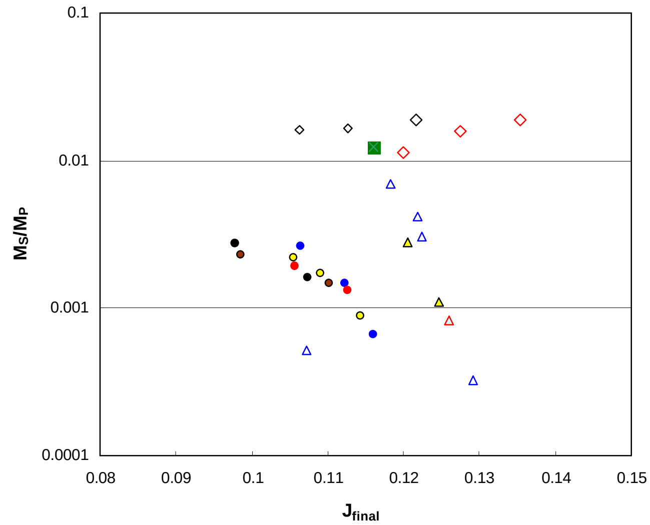

Figure 2: The predicted satellite mass that would accrete from the impact-generated disk, M_S [14], scaled to the final planet's mass, M_P, as a function of the final bound planet-disk angular momentum, scaled to the quantity $[GM_T^3R_T]^{1/2}$, where M_T and R_T are the total final bound mass and the radius of an equivalent spherical object containing that mass. The green square indicates the Earth-Moon system.

Cases involving less grazing collisions and a pre-impact prograde spin in the protoearth can produce disks that are comprised predominately of target material. Such an outcome is advantageous in accounting for compositional similarities between the Earth and Moon [*e.g.* 12-13]. However, at least in the preliminary suite of simulations performed here, the total disk masses in such cases are substantially less than a lunar mass.

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