A MULTIPLE IMPACT HYPOTHESIS FOR MOON FORMATION.

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Introduction: The Moon is the most studied planetary body outside Earth, but its origin remains enigmatic. The common theory for the Moon's formation is that a Mars-sized planetisimal impacted the late-stage accreting Earth [1, 2]. A giant impact can indeed explain some of the characteristics of the system, including the high angular momentum and the Moon's relatively low iron abundance. The classic simulations invoke an off axis-impact resulting in a disk composed mainly of the impactor. The observed extreme isotopic similarity between the Moon and Earth is explained by achieving equilibrium between a hot protoplanetary silicate atmosphere and the protolunar disk [3], or by impact dynamics alone in specific geometries [4, 5]. The isotopic mixing in the disk is efficient for oxygen but insufficient for more refractory elements such as Titanium [3, 6]. Moreover, N-body simulations of late-stages of planet formation predict that an Earth-Moon system has a $\sim 8\%$ probability of forming, mainly because it is rare to form in-line with the ecliptic [7]. The most succsesful theories suffer from the difficiency that the range of initial conditions required during and following the impact process is narrow [4, 5].

In this work, we investigate the multi-impact hypothesis, in which the proto-Earth is exposed to consecutive collisions by medium to large size bodies. Satellites smaller than the present Moon are formed from a sequence of impact-generated disks and advance outward controlled by tidal interactions, faster at first and slower as the body retreats away from the proto-Earth. The slowing migration could cause the satellites to enter their mutual Hill radii and eventually coalesce to form the final Moon, or alternatively to scatter into the proto-Earth or out of the system. In this fashion, the Moon forms as a direct consequence of multiple impacts in contrast to a precisely tuned single impact. The project is motivated by emerging dynamical and geochemical perspectives on Earth's Moon formation, but we seek to uncover general traits for formation of other moons as well.

Method: We probe a large phase space by simulating impact scenarios with ranging values of the impactor's velocity, mass, angle of impact and initial rotation of the target (Table 1). In this manner, we obtain boundaries in phase space separating classes of outcomes and search for conditions where it is possible to produce moons with smaller impacts than previously considered. We examine smaller and faster impactors which can lead to disks that originate mostly from Earth and not the impactor. We use a Smoothed Particle Hydrodynamics (SPH) code to simulate impacts in the gravity dominated regime with a tabulated equation of state [8]. Simulation use $N \sim 10^5$ particles. The colliding bodies contain 30% iron and 70% mantle (represented as pure forsterite), similar to current Earth, and are generated with isentropic thermal profiles with a surface temperature of 2000 K comparable to a 'warm start' in previous studies [2]. Preliminary results of Citron et al. [9] show that a pre-existing satellite does not affect the general disk mass evolution as long as the satellite is not close to the Roche limit where the new moon forms, therefore we can perform our simulations with only two bodies.

Parameter	Values				
γ	0.010	0.024	0.053	0.091	-
$V_{\mathrm{imp}}/V_{\mathrm{esc}}$	1.0	1.1	1.4	2.0	4.0
β [°]	0	30	45	60	-
$\omega/\omega_{\mathrm{breakup}}$	0	0.5	-	-	-

Table 1: Values selected of the various initial conditions for the simulations performed, with γ, the mass ratio between the impactor and total mass, V_{imp}, the impact velocity, V_{esc}, the escape velocity, β the impact angle, ω initial rotation velocity of the proto-Earth, and $\omega_{\mathrm{breakup}}$ the rotation rate at centrifugal break-up.

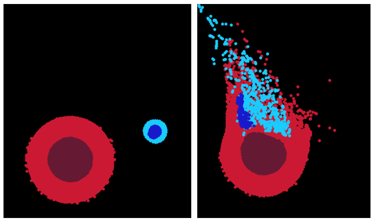

Figure 1: Snapshots of an impact with $\gamma = 0.025$, $V_{\mathrm{imp}} = 4V_{\mathrm{esc}}$, $b = 30°$ with an initial planetary rotation, before impact (left) and 10 min after (right). The red (blue) points represent particles originating from the planet (impactor). Darker (brighter) colors represent the core (mantle). The plot is cross section in the equatorial plane of the target and its radius is $\sim$7100 km.

After each simulation we follow an interactive procedure [4, 10] to classify all particles into one of three categories: planet particles whose angular momentum is insufficient to escape the gravitational pull of the planet; disk particles whose orbital pericenter is outside the planetary radius, and escaped particles, which are gravitationally unbound. We define that simulations which yield an iron fraction and impactor fraction smaller than 10% are disks that fulfill the compositional constraints. This constraint should be regarded with flexibility, because it is the sum of multiple disks that contribute to the final moon's composition, so each disk can vary to some extent while maintaing the average.

Impact Results: Results for these simulations (**Figure 2**) show that, excluding the head-on impacts (represented by low impact angular momentum), there is a positive correlation between disk mass and impact angular momentum until $L_{\mathrm{imp}} \sim 1.7 L_{\mathrm{EM}}$, beyond which the disk mass decreases with additional angular momentum. Moreover, the mass of the disk is higher at higher rotation rates (light blue circles) because the particles of the planet are more weakly bound and can eject from the surface more easily.

After impact, the planet can lose or gain mass, depending on the balance of impactor merger and net erosion of material. Most of the cases examined produce partial merger, but 8 high energy cases produce net erosion of the planet. Two extreme cases ($\gamma = 0.091$; $V_{\mathrm{imp}}/V_{\mathrm{esc}} = 4$; $\beta = 0°$ both with and without planetary rotation) stripped nearly half the planet's mass, and produced very massive disks with low angular momentum. These findings are in good agreement with [11], which found that planetary erosion is more common at lower impact angles than at high angles due to the larger interacting mass and interacting energy. For these energetic cases, particles from the planet's core contaminate the disk, causing the iron fraction to increase.

Discussion: We consider a range of initial conditions and explore the behavior at different regions of phase space. The 160 simulations performed exhibit several trends. Disk mass first increases with increasing impactor angular momentum, until excess angular momentum leads to escaping mass (Fig. 2, dashed line). Similarly initial rotation contributes to more massive disks, as mass is more weakly bound to the planet. The majority of the disks are iron depleted, as most of the iron comes from the relatively small impactor. Two energetic impacts (head-on impacts with high velocity and high mass) produced massive erosion to the planet and succeeded to harvest iron from the target's core (dashed oval). Importantly, head-on impacts are the best candidates for building disks compatible with the known constrains. The initial rotation of the planet proved to have an important effect, because it introduces angular momentum necessary for moonlet formation to systems with a shallow impact angle (cyan points).

Additional simulations in progress will investigate the intermediate values of rotation. With their lower system angular momentum ($\omega/\omega_{\mathrm{breakup}} < 0.5$), the resulting systems are expected to have $< 1 L_{\mathrm{EM}}$, yet the disks produced may suffice to form a moonlet.

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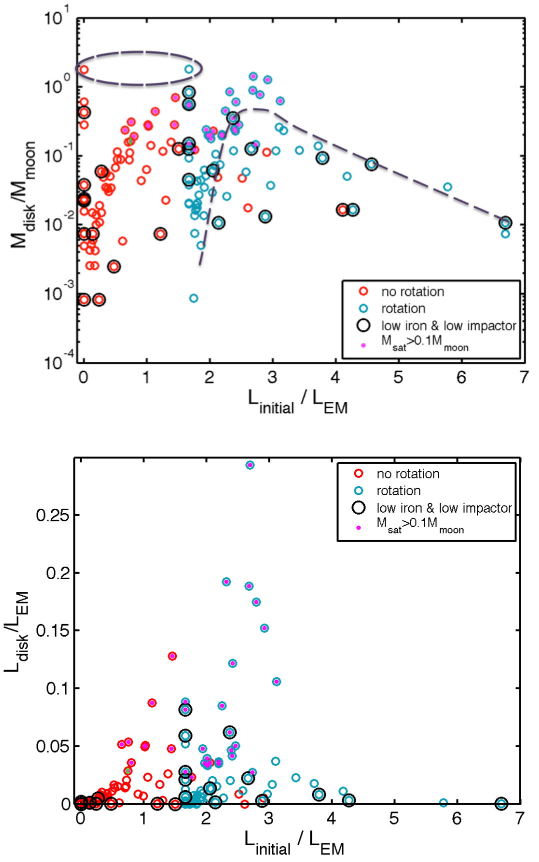

Figure 2: Mass of the disk (top) and angular momentum of the disk (bottom) versus the total system angular momentum. Shown are simulations without initial rotation (red) and at 0.5 breakup rotation rate (cyan). Also indicated are simlulations with a disk with low iron and low fraction of impactor mass (<10%, black), and simulations with disks which produce moonlets larger than $0.1 M_{\mathrm{moon}}$ (pink). A sensitivity test indicates the errors are comparable to the marker sizes (small green bar).

References: [1] Hartmann, W. K. & Davis (1975), *Icarus*, 24, 504-515. [2] Canup, R. M. (2004), *Icarus*, 168, 433-456. [3] Pahlevam, K. & Stevetson, D. J. (2007), *EPSL*, 262, 438-449. [4] Canup, R. M. (2012), *Science*, 338, 1052-5. [5] Cuk, M. & Stewart, S. T. (2012), *Science*, 338, 1047-52. [6] Zhang, J., *et al.* (2012), *Nature Geoscience*, 5, 251-255. [7] Elser, S., *et al.* (2011), *Icarus*, 214,357-365. [8] Marcus, R.A., *et al.* (2009), *ApJ*, 700, L118-L122. [9] Citron, R., *et al. (2014) LPSC,* . [10] Canup, R. (2001), *Icarus*, 150, 288-296. [11] Leihardt, Z. M. & Stewart, S. T. (2012), *ApJ*, 745, 79.