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Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant Despinning

Matija Cuk*† and Sarah T. Stewart

A common origin for the Moon and Earth is required by their identical isotopic composition. However, simulations of the current giant impact hypothesis for Moon formation find that most lunar material originated from the impactor, which should have had a different isotopic signature. Previous Moon-formation studies assumed that the angular momentum after the impact was similar to that of the present day; however, Earth-mass planets are expected to have higher spin rates at the end of accretion. Here, we show that typical last giant impacts onto a fast-spinning proto-Earth can produce a Moon-forming disk derived primarily from Earth’s mantle. Furthermore, we find that a faster-spinning early Earth-Moon system can lose angular momentum and reach the present state through an orbital resonance between the Sun and Moon.

The origin of the Moon by a giant impact (1, 2) is the leading theory to explain multiple features of the Earth-Moon system (3), including the current angular momentum, the Moon’s small core compared with those of rocky planets, and the compositional similarity between the Moon and Earth. In the canonical scenario (4), a ~0.1 Earth-mass (M_E) body obliquely strikes the proto-Earth near the escape velocity to generate a circumterrestrial debris disk from which the Moon accretes. Since the formulation of the giant impact hypothesis, ever-improving analytical techniques have revealed that the Moon and Earth are identical in their oxygen, tungsten, chromium, and titanium isotopes (5–8). These isotope systems show considerable variations between planetary bodies and most meteorite groups; thus, the simplest explanation for the isotopic similarity is that the Moon was formed from Earth’s mantle (9). In contrast, giant impact simulations find that the lunar disk is predominantly (>60 weight percent (wt %)) composed of material originating from the impactor (4, 10, 11), which is expected to have a different isotopic signature than Earth.

To reconcile the impact simulations with the observations, post-impact isotopic equilibration by mixing material between the lunar disk and Earth has been suggested as a means to mitigate an initial compositional difference (12, 13). However, based on recent isotopic data from the deep mantle, the whole mantle was not completely mixed at the end of accretion (14, 15). Second, recent simulations find that increasing the impactor mass and velocity combined with a steeper impact angle could reduce the impactor mass fraction in the lunar disk to ~40 wt % at the expense of a small excess in the final angular momentum (16), but the isotopic similarity requires more efficient mixing of impactor and target material (9). Third, one could invoke the special case of an impactor with identical isotopes as Earth, but such a body is unlikely to also satisfy other geochemical constraints such as the relative abundances of moderately siderophile elements [for example, see (17)]. To date, none of the proposed variations on the giant impact model satisfy all of the geochemical observations.

All previous giant impact scenarios were constrained by the present angular momentum of the Earth-Moon system. The Moon accreted from the disk just beyond Earth’s Roche radius (R_{Roche} ~ 2.9 Earth radii (R_E)) (18), the distance at which tidal forces no longer disrupt a satellite. Subsequent tidal interactions between the two bodies (19–21) expanded the lunar orbit to its current 60R_E. During this process, angular momentum was transferred from Earth to the Moon, but the total angular momentum of the system did not change. Tides raised by the Sun have a minor effect on the Earth-Moon system, changing the angular momentum by, at most, ~1% (10). Thus, the present spin of Earth and the orbit of the Moon imply that the post-impact Earth could not have spun faster than once every 4 hours. However, simulations of the accretion of Earth-mass planets produce final spin periods much faster than 4 hours due to multiple giant impacts (22–24). Starting with a fast-spinning proto-Earth, simulations of giant impacts that reduced Earth’s angular momentum to the present value did not produce disks massive enough to form the Moon (11).

Here, we present a different model for the origin of the Earth-Moon system. An erosive giant impact onto a fast-spinning proto-Earth produced a disk that was massive enough to form the Moon and was composed primarily of material from Earth, but the system had more angular momentum than is the case today. Subsequently, the excess angular momentum was lost during tidal evolution of the Moon via a resonance between Earth’s orbital period and the period of precession of the Moon’s perigee.

Impacts onto a fast-spinning proto-Earth. We define successful Moon-forming impact scenarios by the following observational constraints: (i) the isotopic similarity between the Moon and Earth, (ii) the mass of the Moon (M_M = 0.012M_E), and (iii) the mass of the lunar core. First, the isotopic data limit the difference in the projectile mass fraction between the silicate Earth and the silicate portion of the lunar disk, but the maximum difference depends on the projectile composition. If the impactor had the same isotopic composition as Mars, the difference in projectile mass fraction (Δ_{proj}) is limited to only a few to several weight percent (6, 8, 9). Because the projectile may have been more similar to Earth than Mars, impact scenarios in which Δ_{proj} ≤ 15 wt % are considered successful, although a wider range may be permitted. Second, the mass of the satellite that accretes from the disk must be greater than or equal to one lunar mass (M_M = 0.012M_E). We did not model the accretion of the Moon from the disk. Instead, we used the results from previous simulations of lunar accretion (18, 25), which found that the satellite mass is approximated by

$$M_S \approx 1.9L_{disk}/\sqrt{GM_EM_{Roche}} - 1.1M_{disk} - 1.9M_{esc}$$ (1)

where $L_{disk}$ and $M_{disk}$ are the angular momentum and mass of the disk, and $G$ is the gravitational constant. As in (11), we neglected the mass that escapes during disk evolution, $M_{esc}$. We also estimated the satellite mass by angular momentum conservation ($M_{SAM}$ and found values within ~10% of Eq. 1 (26). Third, the mass of the lunar core was estimated to be only a few weight percent (27, 28). Following (10, 11), we required ≤10 wt % of the disk be composed of material originating from the iron cores of the impactor and target.

We used a smooth particle hydrodynamics (SPH) code (29, 30) to model high-velocity collisions between differentiated planets [2/3 silicate mantle and 1/3 iron core (26)]. We assumed that Earth was nearly fully formed at the time of the Moon-forming impact, or subsequent accretion would increase any compositional difference between the planet and satellite. Hence, we modeled impacts onto a ~1M_E target. At the end of accretion, the average angular momentum of Earth-mass planets is estimated to be ~2.7 times the present value ($L_{EM}$), with possible spin periods up to the instability limit of ~2 hours (24). The minimum stable spin period achieved for the SPH model Earth-mass planets was ~2.3 hours. Our model proto-Earths began with initial spin...
periods from 2.3 to 2.7 hours, corresponding to angular momenta from 1.9 to 3.1 \( \text{L}_{\text{EM}} \). The characteristics of the projectiles were constrained by terrestrial planet-formation simulations, where the typical last giant impactor onto Earth-mass bodies had a mass \( \leq 0.10M_{\oplus} \) and an impact velocity of one to three times the mutual escape velocity \( (V_{\text{esc}}) \) (31). We calculated the properties of a circumterrestrial disk 1 to 2 days after impact (Table 1).

An example of a successful impact scenario is shown in Fig. 1. The post-impact planet has a hot, massive atmosphere that grades into a rotationally supported vapor-dominated disk. The disk is defined by SPH particles that have sufficient angular momentum such that the equivalent circular Keplerian orbital radius is outside the equatorial radius of the planet. The disk is compact with 85% of its mass within the Roche radius. The planet’s post-impact equatorial and polar radii are estimated by a density contour of 1 g cm\(^{-3}\). The post-impact silicate atmosphere, approximated by lower-density material lacking the angular momentum to remain in orbit, has a mass of several weight percent of the planet (Table 1). In this example, the iron core material in the disk is \(<1 \text{ wt \%} \), and the predicted satellite mass is 1.0\( \text{M}_{\oplus} \). The mass fraction of projectile in the disk \( (\delta_{\text{proj}}) \) is only 8 \text{ wt \%}, and the projectile mass fraction in the silicate Earth is 2 \text{ wt \%}. Hence, the compositional difference between the silicate portions of the disk and Earth is only 6 \text{ wt \%} and is within the range allowed by the isotopic data.

A wide range of probable terminal giant impacts onto an Earth-mass planet with a 2.3-hour rotation period produces potential Moon-forming disks that are composed primarily of material derived from Earth (Fig. 2 and Table 1). We find that these giant impacts typically result in partial accretion of the impactor and net erosion from the proto-Earth (a small final mass deficit is neglected in the Moon-formation criteria, as a larger initial planet mass can compensate for the difference). Head-on and slightly retrograde impacts with impact velocities of \( \sim 1.5 \) to \( \sim 2.5V_{\text{esc}} \) generated the most successful Moon-forming disks. In these cases, the impactor mantle is distributed between Earth and disk, and less material escapes compared with prograde impacts, which tend to deposit more impactor mantle in the disk and put more Earth mantle material on escaping trajectories. A wide range of impact angles and velocities produced potential Moon-forming disks with properties very close to the desired traits (Table 1, also bold numbers in Fig. 2). For the impact velocities and projectile masses considered here, oblique impacts at angles of 45° and greater were hit-and-run events (32) that did not create disks massive enough to form the Moon. Head-on impacts with velocities above \( 3V_{\text{esc}} \) begin to substantially decrease the final mass of the planet (32).

Giant impacts onto planets with spin periods of 2.5 and 2.7 hours produced smaller disk masses compared with the 2.3-hour cases. In addition, prograde impacts onto the slower-spinning planets have larger iron core mass fractions in the disk (Table S1). The results imply a more narrow range for potential Moon-formation events for impact scenarios with less angular momentum. Increasing the total angular momentum by adding spin to the impactors generated successful disks from the slower-spinning planets. Because angular momentum is carried away with debris from these erosive giant impacts, the spin period of the planet decreases. Thus, the spin state of Earth is not required to be near fission before or after the Moon-forming impact in our scenario (for example, last entry in Table 1). However, our simulations suggest that the impact-driven formation of a sufficiently massive disk derived primarily from Earth’s mantle is easiest when the total angular momentum of the event (from the spin of each body and the impact geometry) is near the stability limit.

Our candidate Moon-forming events have more than double the kinetic energy of previous scenarios, and the impact velocities were sufficient to substantially vaporize silicates (33). As a result, the silicate atmosphere and vapor-rich disk are more massive and hotter than found in previous work (34). At the resolution of the simulations, the projectile-to-target mass ratio is uniform from the atmosphere to the Roche radius.
The disk contains both volatile and refractory components from the mantles of the colliding bodies, and the observed depletion of volatile elements in the Moon is a result of the separation of volatile and refractory material during lunar accretion from the disk (35, 36). Detailed comparisons between our Moon-formation scenario with the isotopic data require modeling lunar accretion coupled to the chemical evolution of a disk with our calculated initial conditions.

**Tidal evolution and angular momentum loss.**

The successful Moon-forming impacts onto a fast-spinning proto-Earth leave the Earth-Moon system with excess angular momentum (Table 1). To test if our lunar origin scenario can be reconciled with the present angular momentum, we simulated the early tidal evolution of the Earth-Moon system using a custom-made orbital integrator based on a symplectic mapping method commonly used in solar system dynamics (21, 37), which includes mutual precession, both Earth and Moon tides, and solar perturbations (26).

We find that the ejection resonance between the Moon and the Sun (38, 39), which occurs when the period of precession of lunar perigee equals the period of Earth’s orbit, can substantially reduce the angular momentum of the Earth-Moon system. After capture into this resonance, the long axis of lunar orbit librates around 90° from the Earth-Sun line, and the lunar perigee precession period is fixed at 1 year. The ejection resonance is encountered sooner after lunar formation, and the efficiency of capture is a strong function of the lunar semimajor axis at which the resonance happens, which increases with increased flattening of Earth. At larger distances from Earth, solar gravitational perturbations are stronger, and more importantly, lunar tidal recession is slower, enabling more efficient capture. It has been found that capture is possible even for an Earth spinning once every 5 hours (39), as long as tidal evolution is very slow (implying a large tidal quality factor \( Q \) of \( \sim 10^4 \) for Earth; \( Q \) is an inverse measure of the dissipation of tidal energy as heat within a body).

In our simulations (Fig. 3), robust capture into the ejection resonance happened at \( \sim 7R_E \) for a standard tidal quality factor of \( Q = 100 \), 2.5-hour rotation and a simplified flattening model for Earth. After the Moon was captured in the resonance, the lunar orbit continued to evolve outward while keeping a constant precession period, which led to a rapid increase of eccentricity (39). The eccentricity increased until a balance between Earth and lunar tides was reached, but the exact eccentricity at which this happened is model-dependent because the mechanical properties of both Earth and the Moon are uncertain. We used a standard satellite tidal parameter for the Moon in Fig. 3, but other values for \( Q \) give us similar outcomes (Fig. 4).

There was always a substantial period of balance between Earth and Moon tides, where the Moon stayed in the ejection resonance with a roughly constant eccentricity. During this period, Earth tides were transferring angular momentum to the Moon, and Earth’s rotation was slowing down (movies S2 and S3). Satellite tides cannot remove angular momentum from lunar orbit, but the Sun can absorb angular momentum through the ejection resonance. Because the resonance couples lunar perigee and eccentricity with Earth’s orbital period, angular momentum of the lunar orbit can be transferred to the angular momentum of Earth’s orbit around the Sun. Earth tides pass angular momentum to lunar orbit, and the resonance-locked lunar orbit transfers angular momentum to the heliocentric orbit of Earth. Our integrator keeps Earth’s orbit stationary, but in reality, this process makes the Earth-Sun distance slightly larger.

As Earth lost its spin, Earth’s flattening decreased, and the position of the ejection resonance for the equilibrium eccentricity slowly increased to the resonance zone.

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**Table 1. Potential Moon-forming giant impacts onto a fast-spinning proto-Earth.**

<table>
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<tr>
<th>( M_{\text{proj}} )</th>
<th>( V_i )</th>
<th>( b )</th>
<th>( M_{\text{planet}} )</th>
<th>( R_{eq} )</th>
<th>( f )</th>
<th>( T )</th>
<th>( L_z )</th>
<th>( M_{\text{atm}} )</th>
<th>( M_{\text{disk}} )</th>
<th>( M_{\text{sm}} )</th>
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<th>( \phi_{\text{disk}} )</th>
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*Potential Moon-forming simulations with more relaxed criteria of \( 0.8 < M_{\text{proj}}/M_{\text{sm}} < 1.5, \delta_{\text{proj}} < 0.2, \) and \( M_{\text{sm}}/M_{\text{disk}} < 0.1. \)

†Successful Moon-forming simulations with \( M_{\text{sm}} > 1.0M_{\text{sm}}, \delta_{\text{proj}} < 0.15, \) and \( M_{\text{sm}}/M_{\text{disk}} < 0.1. \)

‡Example in Fig. 1.

§Projectile with a 2.9-hour prograde spin; other projectiles have no spin. Targets have 1 to 2 \( \times 10^5 \) SPH particles [additional simulation results and methods in (26)].
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Shifted inward. Eventually, the lunar semimajor axis evolved within $5R_E$, whereas the Moon maintained substantial eccentricity, and Earth’s spin slowed down to ~6 hours. This was typically the point at which the resonance broke in our simulations. The reason for the end of resonance is simple: Tidal acceleration of the Moon at perigee weakened once the rates of Earth’s rotation and the Moon’s orbital motion became comparable. In other words, the Moon at perigee started catching up with the bulge it raised on Earth, reducing the efficiency of Earth tides. Then, lunar tides dominated and (unlike Earth tides) pushed the Moon away from the center of the resonance, leading to larger and larger amplitude of resonant libration. Once librations exceeded the width of the resonance, the lunar orbit exited the resonance in the direction of lower eccentricities. After breaking the resonance, lunar tides damped the eccentricity, whereas Earth tides restarted the outward tidal evolution. As the Moon moved away from synchronous orbit, its eccentricity stabilized, and the standard tidal evolution continued.

For a range of initial spin periods and tidal evolution paths (Fig. 4), the final angular momentum is close to the observed value. Touma and Wisdom (39) started the evolution of the Earth-Moon system with its current momentum and found that capture in the evection resonance is possible, but in their case, the resonance was broken soon after capture with no long high-eccentricity phase and no large angular momentum loss. The observed state is actually close to the lowest angular momentum reachable by resonance, and this result only weakly depends on the model of tides used when close to synchronous rotation. An analytic calculation (26) shows how the parameters of the system naturally lead to evection resonance breaking when the Moon has a semimajor axis of ~$5R_E$ and Earth has a spin period of ~6 hours (assuming that the resonance persists close to the synchronous orbit). Therefore, Earth could have had a range of fast spin periods before capture into evection, and the present angular momentum of the system does not carry information about Earth’s primordial spin.

Our model predictions of capture into the evection resonance and exiting near the present angular momentum depend on a number of parameters, some of which are poorly constrained. A wide range of tidal evolution rates could have delivered the system to its present state, as long as the ratio of tidal dissipation rates within Earth and the Moon is within ~50% of the value optimal for their balance (26). This balance of tides requires similar dissipation factors $Q$ for the two bodies (assuming modern-day response to deformation) or Earth being about an order of magnitude more dissipative than the Moon (assuming fluid bodies).

Discussion. Our tidal evolution simulations are consistent with the two prevailing models for generating the Moon’s high inclination and, similarly, require a low post-impact obliquity for Earth (<10°, (26)). Interaction with the evection resonance does not excite lunar inclination, and any primordial lunar inclination would decrease somewhat during evolution through the resonance. As the Moon does not interact with the evection resonance until 7$R_E$ or more, our model is compatible with the disk-interaction hypothesis for the origin of lunar inclination (40). Because the evection resonance in our model breaks at about the same configuration as in Touma and Wisdom (39), our model is also consistent with subsequent generation of lunar inclination through temporary inward migration and capture into a mixed resonance (39).

A high spin rate during the giant impact phase of planet formation would affect all major

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**Fig. 2.** Summary of the range of outcomes for expected terminal giant impacts onto the proto-Earth: $M_{\text{proj}} \lesssim 0.1M_E$ and 1 to 3$V_{\text{esc}}$ ($V_{\text{esc}} \sim 10$ km s$^{-1}$). The target was a 0.99$M_E$ body with a 2.3-hour spin. Projectiles had no spin and masses of 0.026, 0.05, or 0.10$M_E$. The radius of each filled colored circle is proportional to the satellite mass; the black circle indicates $M_S = 1.0M_E$. Color indicates the difference in projectile composition between the silicate disk and silicate Earth. Within a colored circle, a gray dot denotes too much iron core mass fraction in the disk. The number above each symbol gives the final mass of the planet; bold numbers indicate cases that satisfy the relaxed Moon-formation criteria in Table 1. Collisions in the middle region of the figure, head-on and slightly retrograde impacts from 10 to 30 km s$^{-1}$, are the best fit to the observational constraints for Moon-forming impacts.
Fig. 3. Tidal evolution of the Moon through the ejection resonance, starting with an Earth spin period of 2.5 hours. The Moon is captured into the resonance at ~9 thousand years (kyr) [at a semi-major axis of 6.8RE in (A)] and stays in the resonance until ~68 thousand years, when the Moon almost reaches an orbit that is geosynchronous at periapsis (gray line). During this time, the long axis of lunar orbit is locked to 90° from the Earth-Sun line. At first, the Moon keeps evolving outward (A) in the resonance while the eccentricity (B) increases, until the eccentricity stabilizes and a slower inward migration ensues, ending at ~5RE. During the resonance lock, Earth’s rotation slows down dramatically (C), with the spin period increasing from just over 2.5 hours to almost 6 hours. During resonance capture, resonant argument ϖ = 2ϖSun − 2ϖMoon (ϖSun, the Sun’s mean longitude; ϖMoon, longitude of periapsis) librates around 180° (26) (D). Also see movie S2.

processes on the growing Earth, including mantle convection patterns and overturn rates. Within 100 million years of solar system formation, major chemical reservoirs were established in Earth’s lower mantle that were not destroyed by a Moon-forming impact (14, 15). The isotopic constraints require the Moon’s formation to occur at the end of Earth’s accretion, but the exact timing remains uncertain (41). Although the SPH technique generally underestimates the mixing of materials, our simulations show that the relatively cooler and denser material from the lower mantle in the hemisphere opposite the impact is not well mixed with material from the impacted hemisphere and upper mantle during gravitational reequilibration (fig. S1). The post-impact planet is stably stratified with the entropy of the upper mantle higher than the entropy of the lower mantle, which would inhibit deep convective mixing. Hence, our Moon-formation scenario need not destroy preexisting chemical differentiation within the proto-Earth.

Our model for the origin of the Moon blends aspects of the original impact hypothesis, in which material was ejected from Earth by a large impact (I), and the fission hypothesis first proposed by Darwin (19), in which Earth lost material via spin instability. We show that an erosive giant impact onto a fast-spinning proto-Earth followed by despinning during passage through the ejection resonance can reproduce the isotopic homogeneity and present angular momentum of the Earth-Moon system. References and Notes

26. Supplementary materials are available on Science Online.
34. It is difficult to accurately calculate the mass of the atmosphere and the vapor fraction of the disk, as current numerical methods lack equations of state for multiple silicate phases in the mantle and multiphase flow of partially vaporized material (28). Although early work on the accretion of the Moon focused on a gas-poor disk (18, 25), recent studies indicate that the Moon may also accrete from a more vapor-rich atmosphere-disk structure (35, 36).

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Supplementary Materials
www.sciencemag.org/cgi/content/full/science.1225542/DC1
Supplementary Text
Figs. S1 to S7
Table S1
References (42–52)
Movies S1 to S3
Computer Codes
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REPORTS

Forming a Moon with an Earth-like Composition via a Giant Impact

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In the giant impact theory, the Moon formed from debris ejected into an Earth-orbiting disk by the collision of a large planet with the early Earth. Prior impact simulations predict that such that of the disk material originates from the colliding planet. However, Earth and the Moon have essentially identical oxygen isotope compositions. This has been a challenge for the impact theory, because the impactor’s composition would have likely differed from that of Earth. We simulated impacts involving larger impactors than previously considered. We show that these can produce a disk with the same composition as the planet’s mantle, consistent with Earth-Moon compositional similarities. Such impacts require subsequent removal of angular momentum from the Earth-Moon system through a resonance with the Sun as recently proposed.

The oblique, low-velocity impact of a roughly Mars-mass planet with Earth can produce an iron-depleted disk with sufficient mass and angular momentum to later produce our iron-poor Moon while also leaving the Earth-Moon system with roughly its current angular momentum (1–3). A common result of simulations of such impacts is that the disk forms primarily from material originating from the impactor’s mantle. The silicate Earth and the Moon share compositional similarities, including in the isotopes of oxygen (4), chromium (5), and titanium (6). These would be consistent with prior simulations if the composition of the impactor’s mantle was comparable with that of Earth’s mantle. It had been suggested that this similarity would be expected for a low-velocity impactor with an orbit similar to that of Earth (4, 7, 8). However, recent work (9) finds that this is improbable given the degree of radial mixing expected during the final stages of terrestrial planet formation (10). Explaining the Earth-Moon compositional similarities would then require post-impact mixing between the vaporized components of Earth and the disk before the Moon forms (9), which is a potentially restrictive requirement (11).

A recent development is the work of Ćuk and Stewart (12, 13), who find that the angular momentum of the Earth-Moon system could have been decreased by about a factor of 2 after the Moon-forming impact because of the ejection resonance with the Sun. This would allow for a broader range of Moon-forming impacts than previously considered, including those involving larger impactors.

Prior works (1–3, 14) focus primarily on impactors that contain substantially less mass than that of the target, with impactor masses $\text{M}_{\text{imp}} \sim 0.1$ to 0.2$\text{M}_\oplus$, where $\text{M}_\oplus = 39.8560$ is the total colliding mass and $\text{M}_\oplus$ is Earth’s mass. If the target and impactor have different isotopic compositions, creating a final disk and planet with similar compositions then requires that the disk be formed overwhelmingly from material derived from the target’s mantle. However, gravitational torques that produce massive disks tend to place substantial quantities of impactor material into orbit (2, 3).

We considered a larger impactor that is comparable in mass with that of the target itself. A final disk and planet with the same composition are then produced if the impactor contributes equally to both, which for large impactors is possible even if the disk contains substantial impactor-derived material because the impactor also adds substantial mass to the planet. For example, in the limiting case of an impactor whose mass equals that of the target and in the absence of any pre-impact rotation, the collision is completely symmetric, and the final planet and any disk that is produced will be composed of equal parts impactor and target-derived material and can thus have the same silicate compositions even if the original impactor and target did not.

We describe the impactor and target as differentiated objects with iron cores and overlying silicate mantles (15). We simulated impacts using smooth particle hydrodynamics (SPH) (Fig. 1) as in (1–3, 15, 16), representing the impactor and target with 300,000 SPH particles. Each particle was assigned a composition (either iron for core particles or dunite for mantle particles) and a corresponding equation of state (17, 18), and its evolution was tracked with time as it evolved owing to gravity, pressure forces, and shock dissipation.

We simulated a given impact for approximately 1 day of simulated time. We used an iterative procedure (1–3, 15) to determine whether each particle at the end of the simulation is in the planet, in bound orbit around the planet (in the disk), or escaping. Given the calculated disk mass $\text{M}_D$ and angular momentum $\text{L}_D$, we estimated the mass of the moon that would later form from the disk, $\text{M}_\text{Moon}$, using a conservation of mass and angular momentum argument (19, 20).

Assuming that the disk would later accumulate