Immediate origin of the Moon as a post-impact satellite

J. Kegerreis[1,2]*, S. Ruiz-Bonilla[1], V. Eke[1], R. Massey[1], T. Sandnes[1], L. Teodoro[3,4]. [1]Durham University, UK. [2]NASA Ames Research Centre, USA. [3]BAERI / NASA Ames Research Centre, USA. [4]University of Glasgow, UK. *jacob.kegerreis@durham.ac.uk

Summary: The Moon is traditionally thought to have slowly coalesced from the debris ejected by a giant impact onto the early Earth [1]. However, such models struggle to explain the similar isotopic compositions of Earth and lunar rocks at the same time as the system's angular momentum, and the details of potential impact scenarios are hotly debated [2, 3]. We find that, above a high resolution threshold for simulations, giant impacts can immediately place a satellite with similar mass and iron content to the Moon into orbit far outside the Earth's Roche limit. Even satellites that initially pass within the Roche limit can reliably and predictably survive, by being partially stripped then torqued onto wider, stable orbits. Furthermore, the outer layers of these directly-formed satellites are molten over cooler interiors, and are composed of around 60% proto-Earth material, compared with the ~30% for those grown from canonical debris disks [4, 5]. This could alleviate the tension between the Moon's Earth-like isotopic composition and the different signature expected for the impactor [6, 7]; helps to explain the thin lunar crust that requires an only partially molten early Moon [8]; and offers a simpler, single-stage scenario for the origin of the Moon.

Introduction: In the canonical hypothesis, the early Earth is hit by a Mars-sized impactor, 'Theia'. The collision ejects a debris disk that can explain the Moon's large mass, angular momentum, and tiny iron core; but it creates a Moon derived mostly from impactor material [1, 4]. This is a concern because the Moon has near-identical isotopic composition to the Earth for many elements [e.g. 2, 9], and it seems unlikely that Theia would perfectly match the proto-Earth target's composition [10]. That being said, recent analysis does suggest distinctly different oxygen isotopes with increasing depth in the lunar mantle [11], and hydrogen isotopes also indicate imperfect mixing between the proto-Earth and Theia [12].

Various alternative impact scenarios have been proposed to eject and mix more proto-Earth material into the proto-lunar disk, such as higher angular momentum impacts with rapidly spinning targets [13–16], but removing the correct amount of excess angular momentum could be difficult [3]. A fully molten Moon as produced in these scenarios also conflicts with the thin lunar crust, which requires a shallower magma ocean [8].

Numerical simulations of giant impacts commonly use smoothed particle hydrodynamics (SPH) to model planets using particles that evolve under gravity and pressure. Previous Moon-formation simulations have used typically around 10^5–10^6 particles, but these resolutions can fail to converge on even large-scale outcomes of giant impacts [17, 18]. Here we use a base of 10^7 particles and up to 10^8, using our open-source code SWIFT [19]. At this resolution, a lunar-mass satellite is comprised of around 10^6 particles, which enables us to inspect its composition in detail. Starting from a base scenario similar to a canonical Moon-forming impact, we ran >400 simulations of scenarios with different impact angles, speeds, pre-impact spins, masses, and temperatures.

Results: We find that a key feature of impact scenarios that launch a large satellite directly into a wide orbit is the early separation of the proto-satellite from the main remnant of the impactor. This behaviour emerges reliably with sufficient numerical resolution. The inner remnant then transfers angular momentum to the satellite of ejected proto-Earth mantle and Theia material

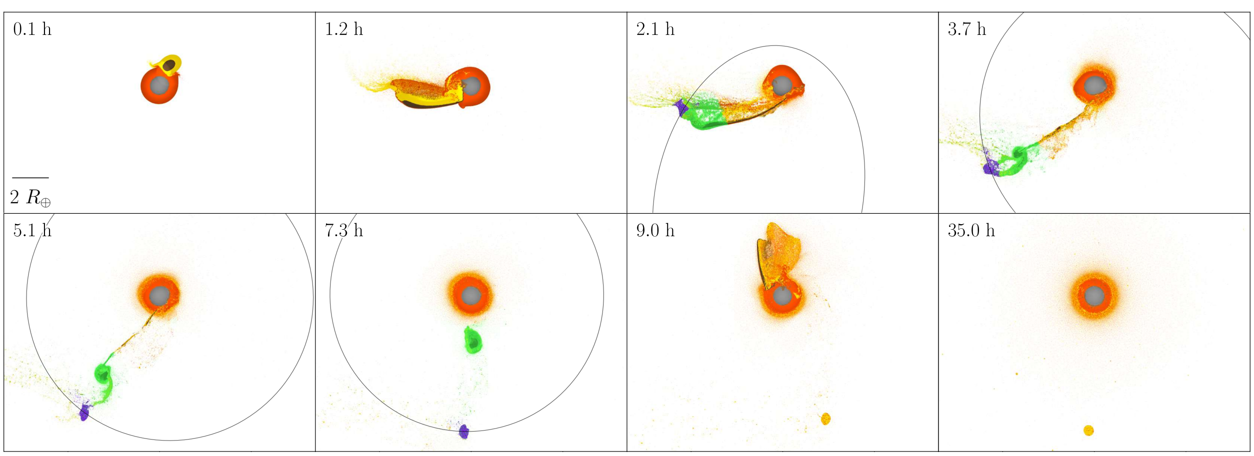

Figure 1: Snapshot cross-sections from an impact simulation where a satellite is placed directly onto a wide orbit. In the middle panels, the particles that will form the satellite and inner remnant are highlighted in purple and green. Grey and orange show the proto-Earth's core and mantle material respectively, and brown and yellow show the same for Theia. The black lines show the satellite's estimated orbit. An animation is available at icc.dur.ac.uk/giant_impacts/moon_wide_orbit_slice.mp4, and with the same data rendered in 3D at icc.dur.ac.uk/giant_impacts/moon_wide_orbit_houdini.mp4.

and slingshots it into orbit, as illustrated in Fig. 1, before falling back to re-impact the target.

The initial satellite separation is consistent for simulations with $>10^{6.5}$ SPH particles, up to and including our highest resolution of 10^8. Lower resolutions instead produce a single larger remnant that stays intact until it grazes or re-impacts the proto-Earth to produce a spray of debris. In the particular scenario of Fig. 1, the satellite actually overtakes the inner remnant briefly around 5 h (fifth panel), and the now-reversed torque slightly shrinks and circularises the final orbit. This resulting satellite has a mass of $0.69\ M_{☾}$ and a nearly circular orbit with a periapsis of $7.1\ R_\oplus$, far outside the Roche limit of $\sim 2.9\ R_\oplus$.

For non-spinning planets, the range of satellite-producing impact angles is relatively small, but for spinning planets – especially a prograde-spinning proto-Earth, wider ranges become feasible. Overall, we find similar behaviour across ranges of different angles, speeds, spins, temperatures, and masses. The region of parameter space for the immediate formation of stable satellites is not huge, but appears to be numerically robust and not fine-tuned to any particular values or low-likelihood scenarios.

In some scenarios, the satellite is not launched out quite as far, and its initial periapsis falls within the Roche limit. However, not only can these satellites survive partial tidal disruption on their initial orbit, but the stripped material can torque the surviving body onto a stable final orbit. Across the wide diversity of pre-periapsis satellites, the periapsis distance is raised by the tidal stripping in every case of significant mass loss, often to well beyond the Roche limit. We find that the fraction of mass that survives is fit well by a simple analytical prediction: $m_{\rm f}/m_{\rm i} \approx r_{\rm p}^3 \sqrt{2\pi\rho/(3GM^2)}/t_{\rm Roche}$, where $r_{\rm p}$ is the periapsis, ρ is the satellite's density, M is the planet mass, and $t_{\rm Roche}$ is the time spent within the Roche limit.

In the regions of parameter space that produce otherwise Moon-like bodies, the satellites show a strong gradient in provenance with radius, with a deep interior of mostly Theia material under outer layers that can reach over 60% proto-Earth material. The outer 30% by radius ($\sim\frac{2}{3}$ the mass) then averages to around 50% proto-Earth. This corresponds to a depth of about 500 km, relatable to the 300–1000 km depths that are considered for the lunar magma ocean [8], within which an initial gradient may be expected to mix.

The outer material is molten, typically heated to at least 4000 K by the impact, but the deeper interior is only a few hundred Kelvin above its initial near-solidus state. Depending on the initial temperatures of the planets, the satellite interiors are thus largely solid or sub-liquidus melt. The deep interiors of all our simulated satellites contain some iron from the impactor's core. For satellites with masses similar to the Moon, the typical iron content ranges from around 0.1 to 3%, comparable with the $\sim$1% mass of the lunar core [20].

Conclusions: A satellite produced immediately after a giant impact can match the Moon's mass, iron content, and angular momentum. To determine whether this can satisfy all the constraints for the Moon, significant work and bespoke future studies are required to extrapolate the outputs of these simulations to the present day – as also remains an ongoing challenge for standard debris-accretion models as well [1].

With that in mind, this scenario may help to resolve the isotopic conundrum. Depending on the extent of long-term mixing in the satellite and Earth [21], we find $\delta f_{\rm t} \approx -35$ to -10% [15], which indicates a sufficiently similar isotopic makeup for the Earth and Moon to satisfy a range of Theia compositions [6, 22]. The cooler interiors of these immediate satellites may limit radial mixing and are also more consistent with the Moon's thin crust, unlike the fully molten Moon expected from other models [8]. A cohesive interior might also help to explain the lunar fossil figure, depending on the extent of tidal heating [23]. In addition, the compositional gradient aligns with measurements of less Earth-like isotopes in the deep lunar mantle [11]. Finally, a satellite on a wide, inclined orbit produced by misaligned pre-impact spins might preserve its inclination to help to explain the tilted lunar orbit [24].

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