# Primordial misalignment of the proto-lunar disk and the post-impact spinning Earth

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**Introduction:** A key chapter in our solar system's history involves impacts between planet-sized objects. This giant impact phase of planet and satellite formation is responsible for many of the features we see today. In the canonical scenario for the formation of the Moon, the proto-Earth and a proto-planet (usually called Theia) collide at around the mutual escape velocity with an impact angle of $\sim 45°$ [e.g. 1, 2]. The Moon subsequently accretes from the debris disk that is formed surrounding the Earth following this impact. Some models for how the lunar inclination evolves with time trace it backwards from its present–day inclination to yield an inclination with respect to Earth's equator of $\sim 10°$ when the Moon accreted from the debris disk [3, 4]. However, traditional giant impact models suggest that the resulting debris disk should be near the equatorial plane of the Earth. This has prompted attempts to explain the mutual inclination with mechanisms involving a gravitational resonance between the Moon and accretion-disk material [5], resonances between Earth and Moon [6], or gravitational interactions with Earth-crossing planetesimals that were not yet accreted at the time of the Moon-forming event [7].

We investigate whether different giant impact scenarios can directly produce a misaligned debris disk with respect to the Earth's spin, which could help to explain the origin of the lunar inclination.

**Methods:** For this work we run high–resolution simulations with $10^7$ particles using the smoothed particle hydrodynamics (SPH) code SWIFT [www.swiftsim.com, 8]. SPH is a particle-based method used in a wide range of astrophysical and engineering topics [9, 10], and commonly used in giant impact studies.

For each simulation we fix: the mass of the proto-Earth, $M_{\rm pE} = 0.887\ M_\oplus$; the mass of Theia, $M_{\rm Th} = 0.133\ M_\oplus$; and the total angular momentum, $L = 1.25\ L_{\rm E-M}$, where $L_{\rm E-M}$ is the total angular momentum of the Earth-Moon system today. The orbital angular momentum of Theia is set in the $+\hat{z}$ direction. We start by testing three impact scenarios: one that is similar to the canonical impact and two at lower angles and higher speeds.

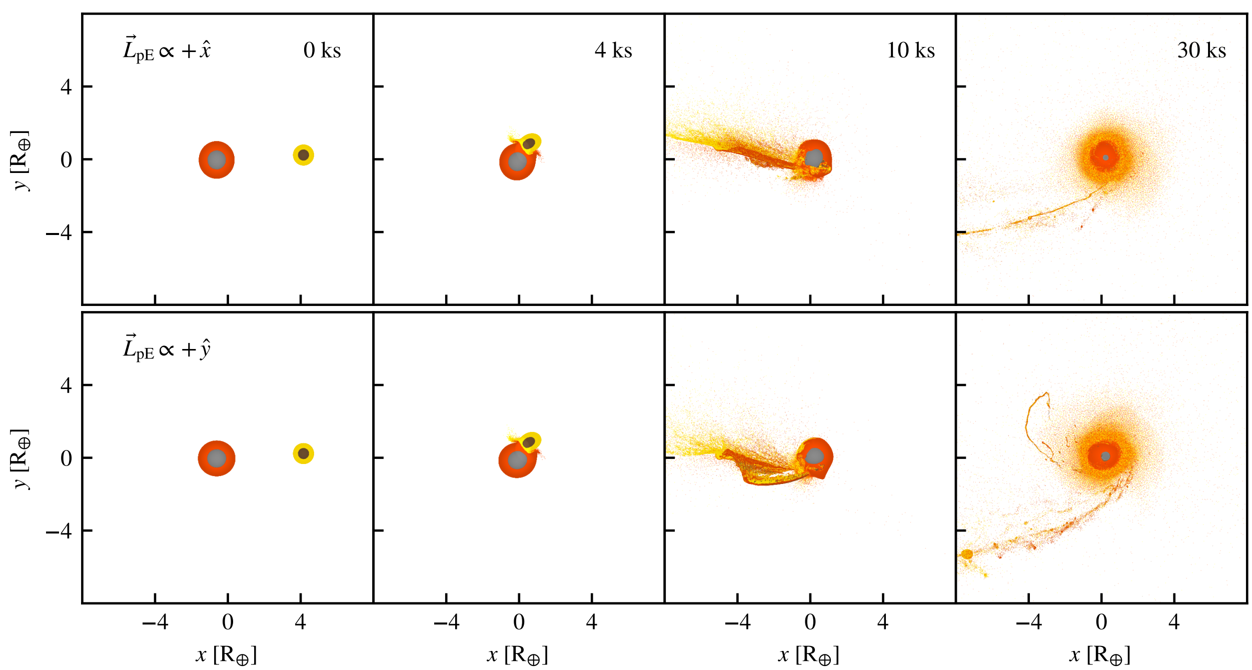


Figure 1: Time evolution of two canonical-like impact simulations where the only difference is the spin direction of the proto-Earth ($\vec{L}_{\rm pE} \propto +\hat{x}$ for the top row, and $\vec{L}_{\rm pE} \propto +\hat{y}$ for the bottom row). The orbital angular momentum is initially in the $+\hat{z}$ direction.

For each scenario we test 4 proto-Earth spin directions ($\pm\hat{x}$, $\pm\hat{y}$), orthogonal to the orbital angular momentum. The periods used are 7, 6, and 5.3 hours for the three different scenarios respectively. Illustrative snapshots showing the evolution in two canonical-like runs with different target spins are shown in Figure 1.

**Results:** We find that it is possible to create a debris disk that is significantly misaligned with the spin of the post-impact Earth. The angle by which the disk is tilted away from the Earth's equator, $\epsilon$, is higher if the spin angular momentum of the pre-impact Earth is proportional to $\pm\hat{y}$, rather than $\pm\hat{x}$. This is because if Theia collides with mainly low-velocity material near the Earth's pole (as in the $\pm\hat{y}$ case), the change in angular momentum of the Earth would be smaller than the $\pm\hat{x}$ spin case, where Theia would hit a large amount of high velocity material such that the Earth preserves less of its pre-impact rotation. We observe no significant differences in misalignment between $\vec{L}_{\rm pE} \propto -\hat{x}$ and $\vec{L}_{\rm pE} \propto \hat{x}$ simulations, or $\vec{L}_{\rm pE} \propto -\hat{y}$ and $\vec{L}_{\rm pE} \propto \hat{y}$ simulations in the same scenario, as one would expect because of symmetry.

Although there is a distribution of angular momenta in the messy post-impact system, there is a clear offset between the rotation directions of the debris disk material and that in the planet. Both the fast, low-angle and the slower, high-angle impact scenarios produce a highly misaligned disk with $\epsilon = 9$, and $10^\circ$ respectively for the simulations where $\vec{L}_{\rm pE} \propto \pm\hat{y}$. The direction of the angular momentum for every particle in a canonical-like simulation with $\vec{L}_{\rm pE} \propto +\hat{y}$ is shown in Figure 2.

In addition to focusing on the inclination of the post-impact disk, we are also investigating how the disk's total mass, angular momentum and iron content are affected by a proto-Earth spinning in a different direction to the impactor's angular momentum. In terms of the origin of the Moon and its inclination, it remains to be determined whether this misalignment would survive for sufficient time for the Moon to accrete, or if it would be torqued back to align with the Earth's equator.

**Conclusions:** We explore how a post-impact misalignment between the Earth's spin and the debris disk can be formed in giant impacts. We found having a misalignment angle is possible when the proto-Earth has a rapid initial spin, with a period of 7 hours or smaller, that is orthogonal to Theia's orbital angular momentum. Moreover, the misalignment angle is around three times higher when Theia comes from the equatorial plane of the proto-Earth and hits mainly North/South pole material, rather than Theia coming from the North/South pole direction and hitting material near the equator. Future studies of the wider parameter space will establish how the misalignment angle depends on the impact velocity, angle of impact, and the magnitude and direction of the initial spin of the proto-Earth.

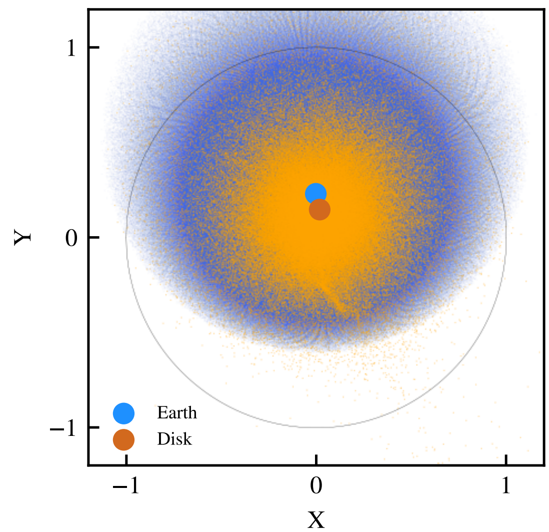


Figure 2: The misalignment between the post-impact disk (orange points) and Earth particles (blue points), shown with a stereographic projection of the directions of the particles' angular momenta. Points inside the unit circle indicate a positive $z$ component of the angular momentum and vice versa. Points sitting on the unit circle indicate a $z$ component of the angular momentum equal to 0. The large dots show the directions of the median angular momenta for each group, in this case showing the 10 degree offset between the disk and equator.

## References

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