CATEGORY: ASTRONOMY & ASTROPHYSICS - AA01

POSTER
P6200

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GPU TECHNOLOGY CONFERENCE

Angular Momentum Study of Late Lunar Forming Impacts Using NVIDIA GPUs

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Moon Formation Theories

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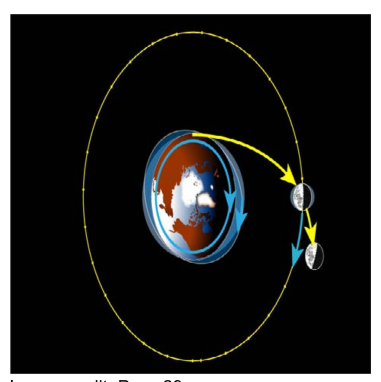
The origin of our Moon is one of the most heavily debated topics in astrophysics today, with new insights making the cover of "Nature" and "Science" on a regular basis. If we do not understand how our own back yard was formed, how can we put faith in our theories about objects millions of light years away?

Our Moon is a satellite that is unique in our solar system in that its relative size to its primary (Earth) is extremely large. The Moon's size rules out it being a captured asteroid such as the two small moons of Mars, Phobos and Deimos. Other hypotheses that arose to explain the formation of our Moon were: the capture theory - that the Moon formed somewhere else in our solar system and was captured by Earth; the co-accretion theory - which states that the Earth and Moon formed along side each other and created a binary system; the fission theory - which states that the Moon was once a part of Earth's crust and mantle that separated to become our Moon.



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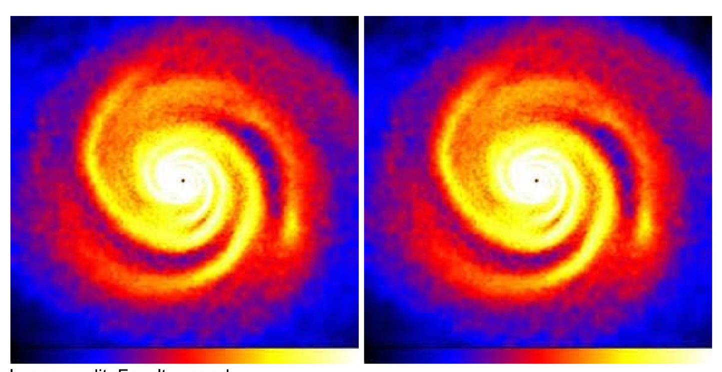

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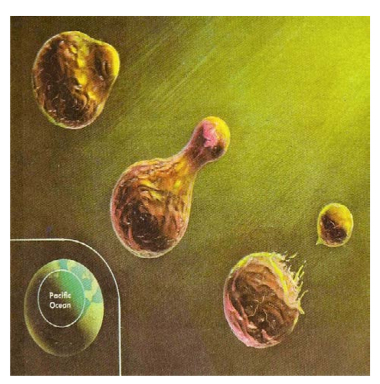

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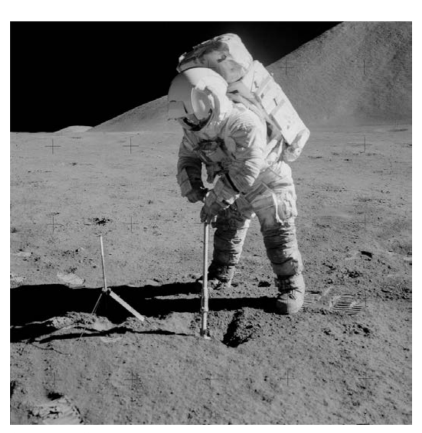
All the rocky planets - Mercury, Venus, Earth and Mars - have large iron cores. The capture theory would then infer that the Moon was a rocky planet. However, the Moon's low density rules out it having a large iron core, making this theory implausible. The co-accretion theory would suggest that the Earth and Moon were created from the same cloud of "star stuff" and would, therefore, have similar densities. Again, the Moon's low density makes this theory implausible.

The fission theory explained the density mismatch because the density of Earth's outer layers and the density of the Moon are similar. The theory had promise until analysis of Moon samples showed that the Moon's composition was much lower in volatiles - elements with low boiling points. This suggests that the Moon, though very similar to the Earth in element type but not ratio, was formed in a hotter environment which boiled away large amounts of the more volatile elements. This led to the creation of the giant impact hypothesis (GIH) by William Hartman in 1975 (1).



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http://www.hq.nasa.gov/office/pao/History/alsj/a15/AS15-92-12424.jpg
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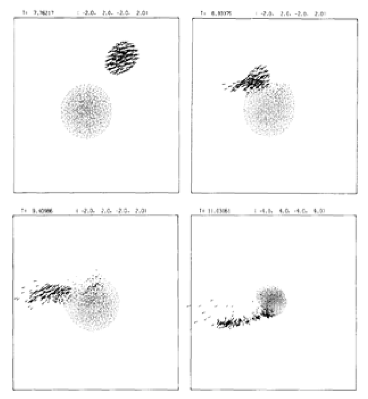
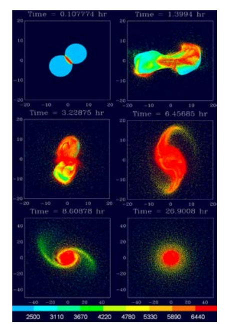
The GIH proposes that a rocky planet, roughly the size of Mars, struck Earth. Their iron cores coalesced, and a large amount of the super heated crust and mantle material was ejected into orbit around the resultant Earth. Later, this disk of debris coalesced into our Moon. Computer simulations showed that the GIH was indeed plausible (2).

History of Giant Impact Simulations



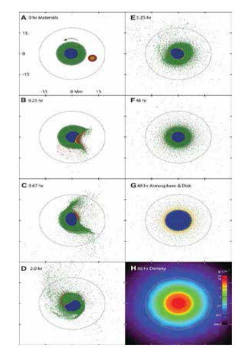
Benz, W., Slattery, W. L., Cameron, A. G. W. Icarus 1986, *66*, 515.

Early simulations produced a disk of debris around Earth that was composed predominantly from the Mars sized impactor. However, closer analysis of the Moon samples showed that the Earth and Moon have almost identical isotopic signatures. This similarity suggests that they could not be formed from material from different proto-planets, but had to evolve from the same parent material. This spurred researchers to create simulations that produced a disk of debris around Earth that was composed of equal parts from both impacting proto-planets (3,4).



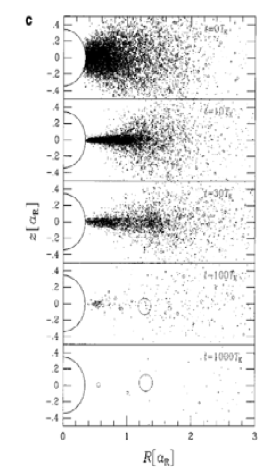
R. M. Canup, Science 2012, *338*, 1052

Science Cover
23 November 2012



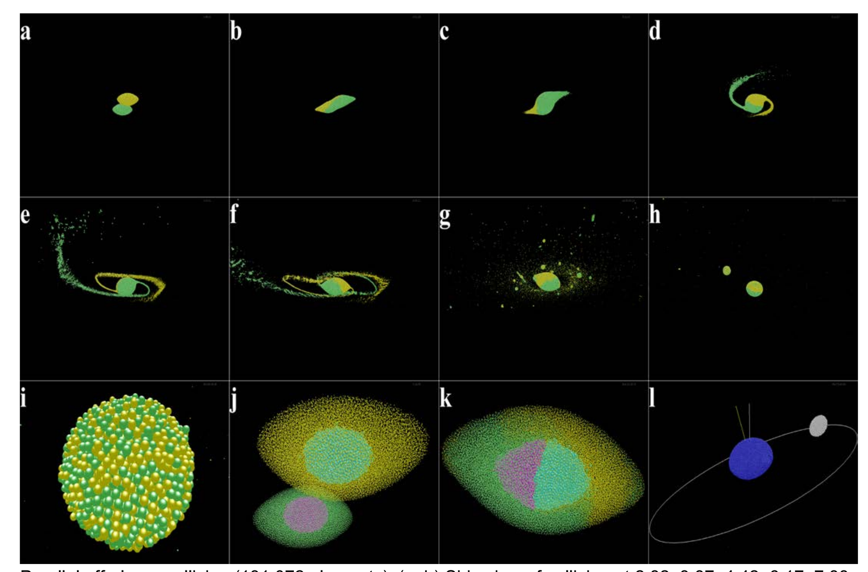
M Ćuk, and S T Stewart, Science 2012, 338, 1047

Standard giant impact simulations focus only on producing a disk of debris orbiting Earth, but do not have this disk coalesce into the Moon. They then have to refer to an earlier work, done at the University of Tokyo, which starts with a disk of debris around Earth and shows how this disk can coalesce into our Moon (5).



Kokubo, et al., Icarus 2000, *148*, 419

This two part simulation was unnatural and made simulations seem contrived. Also, this made it hard, if not impossible, to study many aspects of the resultant Earth-Moon system, such as axial tilt, angular frequency and angular momentum. This motivated Eiland to create a new discrete element model that was the first to produce an Earth-Moon system in a single simulation and showed how the Earth's axial tilt could be incorporated into the GIH (6). In short, Eiland showed how one could smoothly dial in the composition of the Moon and the axial tilt of the Earth by adjusting the initial spin planes and collision angles of the impactors.



Parallel off-planar collision (131,072 elements). (a–h) Side view of collision at 2.82, 3.87, 4.42, 6.17, 7.88, 9.07, 24.00 and 720.00 hours, respectively, into the simulation. Both impactors would be spinning clockwise if viewed from the positive y direction. (i) Close up of the resultant Moon. (j) View of impactor cores at impact. (k) View of the resultant Earth's core. (l) Trace of resultant Moon's orbit and tilt off ecliptic. The white ray is normal to the ecliptic plane, and the yellow ray is normal to Earth's equatorial plane.

J. C. Eiland, et al., Journal of Astrophysics and Astronomy 2014, *35-4*, 613

Purpose of the Study and Methodology

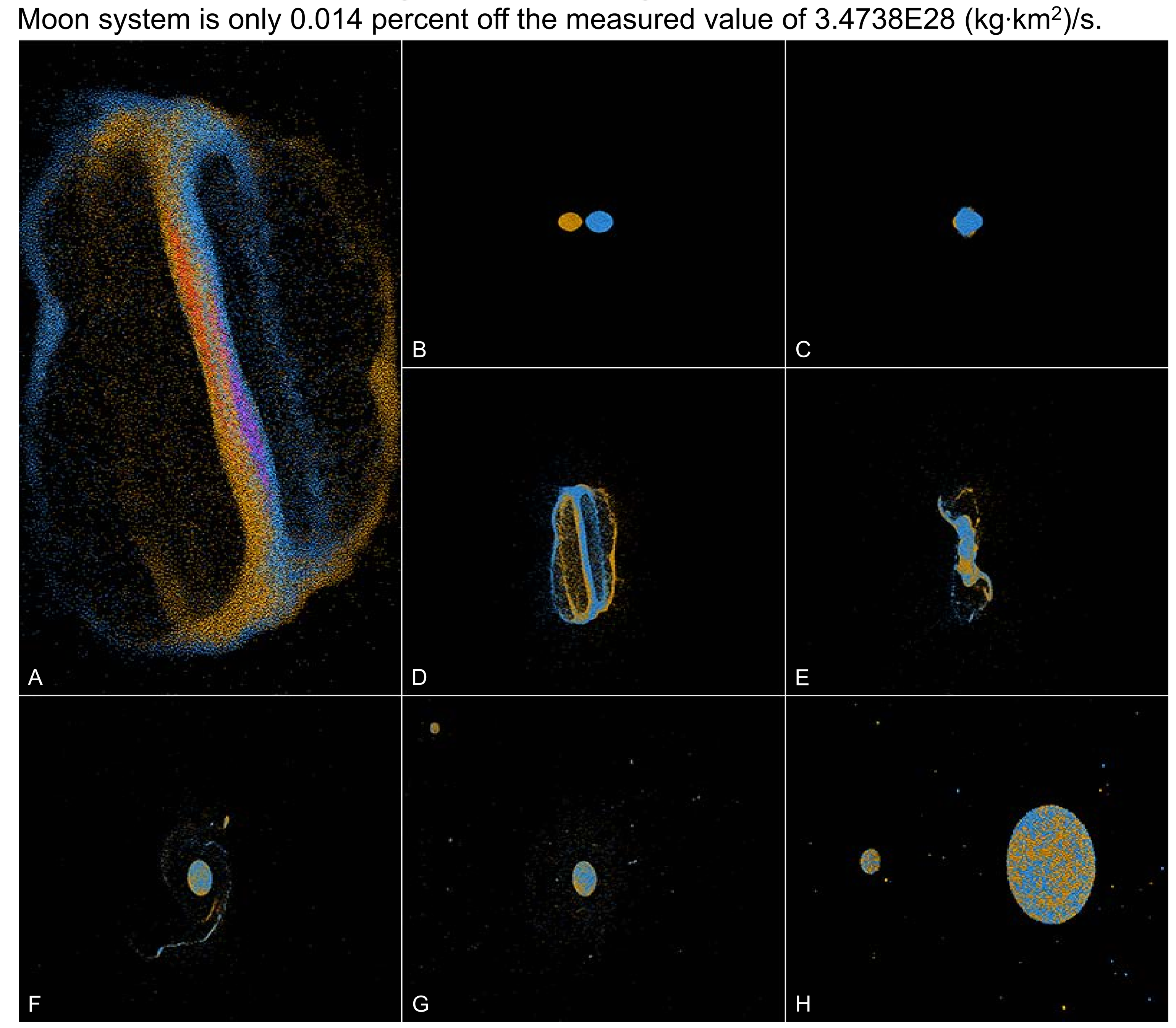
Nature Cover
5 December 2013

To date, all simulations have excess angular momentum. This has been justified by stating that evection resonance with the sun could remove this excess angular momentum. The September 2013 Royal Society meeting in London (the first devoted to the formation of the Moon in 15 years) rejected this explanation for removal of excess angular momentum, leaving the giant impact hypothesis in question (7). It is the angular momentum discrepancy that we are addressing in our work.

Because Eiland's model produces an actual Earth-Moon system, not just an appropriate disk of debris around Earth which could form our Moon, it is ideal for attacking the angular momentum problem. In addition, Eiland's model is fast and easily modified. This speeds the process of searching through the vast initial parameter space to find regions of this space that will produce Earth-Moon systems with the proper angular momentum, while preserving all the desired aspects of previous simulations.
Eiland used slightly off planar and off centered collisions with both impactors spinning out of the collision to produce the proper composition of the Moon and axial tilt of the Earth. Our group did an extensive study of this technique and we found it readily produced Earth-Moon systems in a smooth and predicable manner. However, the resultant systems always had excessive angular momentum, without which, moons would not form. Hence, we were forced to modify Eiland's approach and have both impactors spin into the collision. This produces violent collisions that are somewhat chaotic and unpredictable, but do produce Earth-Moon systems with the proper composition, axial tilt, and angular momentum.

Simulation

Below is an example of an off-planar, off-centered collision, with both impactors spinning into the collision. The collision was violent, but produced excellent results: the resultant Moon is 77.43 times smaller than the resultant Earth (which is close to the measured value of 81.30), it has a low iron content and is made of substantial silicate material from both impactors; the resultant Earth has an axial tilt that is only 1.32 degrees off the measured value of 23.44 degrees; and the angular momentum of the resultant Earth-Moon system is only 0.014 percent off the measured value of 3.4738E28 (kg·km^2)/s.



Initial run parameters for the above simulation are as follows:
Positions: (44500, 300, 2100) and (-44500, -300, -2100) kilometers, Velocities: (-8.5, 0, 0) and (8.5, 0, 0) kilometers per second, Spin vector (0, 0.48, 0) and (0, 0.48, 0) revolutions per hour, for blue and brown impactors respectively. Both impactors had an initial mass of 60% of the Earth's mass and an iron to silicate ratio of 0.2/0.8. Picture A is the apex of the collision represented using point masses to show the cores of the impactors. The cores are red and purple. Pictures B-G were taken early in the collision. Picture H was taken 2106 hours into the collision, at which time the run statistics were calculated.

If you would like to see a simulation video, follow the QR-CODE or visit our YouTube channel (Tarleton Particle Modeling Group) at https://www.youtube.com/channel/UCbkVkINAwMrAz6r0ku7f8IA
If you would like to see a virtual reality simulation, ask us how!

Conclusion

We will never know how our Moon was formed. Simulations are only a crude attempt to approximate the universe around us. Although flawed, they are the best tools we have. Benz, Cameron and Kokubo demonstrated that a giant impact could produce a Moon with low iron content. Cuk and Canup showed how to remove the isotope concerns from the GIH. Eiland produced a comprehensive model and incorporated the Earth's axial tilt into the GIH. Here we show how to remove the excess angular momentum concerns from the GIH. The GIH may have its shortcomings, but to date, it is by far the best explanation of how our Moon was created.

Acknowledgements

All of the work done here was produced on workstations equipped with dual NVIDIA GPUs. Thousands upon thousands of simulations were run to find a range of initial conditions that would produce an Earth-Moon system with the desired physical properties. This would have been far outside the financial scope of our group were it not for CUDA and the affordable compute power of NVIDIA GPUs.

References

1) Hartmann and Davis, *Icarus* 1975, **24**, 504.
2) Benz, Slattery, and Cameron, *Icarus* 1986, ***66***, 515.
3) Canup, R. M., *Science* 2012, **338**, 1052.
4) Cuk and Stewart, *Science* 2012, **338**, 1047.
5) Kokubo, et al., *Icarus* 2000, ***148***, 419.
6) Eiland et al., *Journal of Astrophysics & Astronomy* 2014, **35**, 610.
7) Stewart, *Nature* 2013, **504**, 90.