

Hot Idea

— posted November 27, 2006

Hit-and-Run as Planets Formed

--- Collisions between large protoplanets as the planets formed may have ripped some of them to shreds, producing molten asteroid-sized bodies, driving off water and other volatiles, and scrambling partially molten protoplanets.



(from Asphaug *et al.*, 2006, *Nature*, v. 439, p. 155-160.)

Written by [G. Jeffrey Taylor](#)

Hawai'i Institute of Geophysics and Planetology

Planet formation involved collisions between Moon-sized or larger protoplanets to make even bigger ones. However, planet growth is not the only result of the collisions. Erik Asphaug, Craig Agnor, and Quentin Williams (University of California, Santa Cruz) point out that many protoplanet interactions were what they call "hit-and-run" collisions, causing substantial effects on the bodies, particularly on the smaller one. The effects might have included widespread melting, disruption, and formation of an assortment of metal-rich objects that might be found among asteroids and meteorites. Their ideas give cosmochemists a whole new way of looking at asteroid formation and planetary differentiation.

Reference:

- Asphaug, E., C. B. Agnor, and Q. Williams (2006) Hit-and-run planetary collisions. *Nature*, v. 439, p. 155-160.

Giant Impacts as Planets Formed

Planet formation was rough, messy, and complicated. Dust grains did not settle gently onto slowly-growing rocky bodies. Instead, bodies a few hundred kilometers across grew fast and then accreted into larger objects that ranged in size from 1000 km across to the size of Mars. These protoplanets smashed into each other over a period of about 50 million years to form the terrestrial planets and one such collision, a slightly off-centered one, resulted in formation of Earth's Moon. Computer simulations of the process of planet formation generally assume that most of the collisions result in accretion. That is, the smaller protoplanet becomes part of the larger one, and the now larger object has taken another step towards planethood.



James Garry, Fastlight Used with permission.

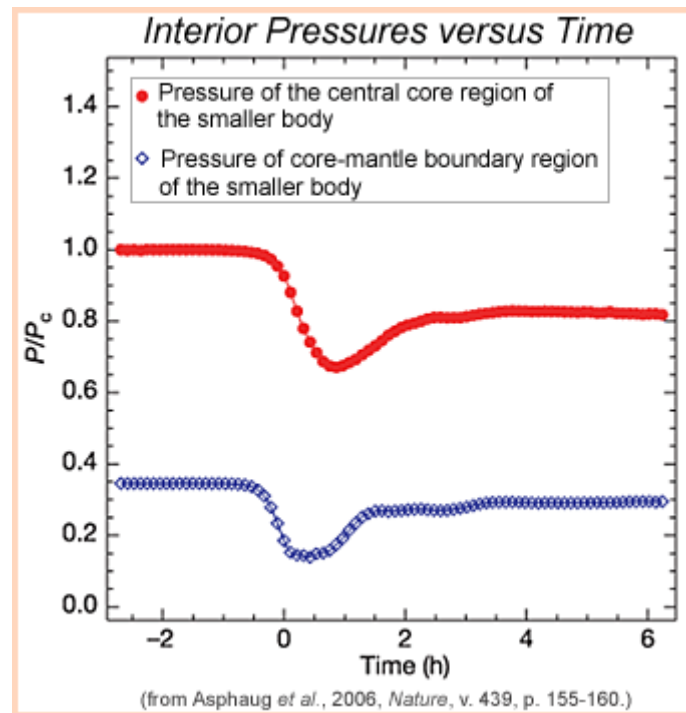
The current view of formation of the terrestrial planets involves collisions between growing protoplanets. In this painting by James Garry an object larger than the Moon is hit by a smaller one, resulting in growth of the larger protoplanet.

Erik Asphaug and his colleagues point out that not all protoplanetary encounters result in accretion. In many cases the smaller object barely hits the bigger one, but ends up greatly affected by the close encounter. It may even be ripped apart. Part of the reason for this destruction is that the gravity field of the larger protoplanet extends well beyond the surface of the object. There is a zone of interaction from the center out to about 2.5 times the radius of the target that is strong enough to exert tidal forces on solid or molten objects, even if the smaller protoplanet does not make physical contact with the larger one. The outer limit of this zone is called the [Roche](#) limit, named after Edouard Albert Roche, a French mathematician. (The Roche limit is the smallest distance at which a planetary object that has no internal strength can orbit another body without being torn apart by the larger body's gravitational force.)

The UC Santa Cruz researchers used computer models of planetary interactions to examine what happens during close encounters that do not lead to accretion. In the calculations, both the impactor and the larger target protoplanet are [differentiated](#) into metallic core and silicate (rocky) mantle, with the core making up 30 weight percent of the volume.

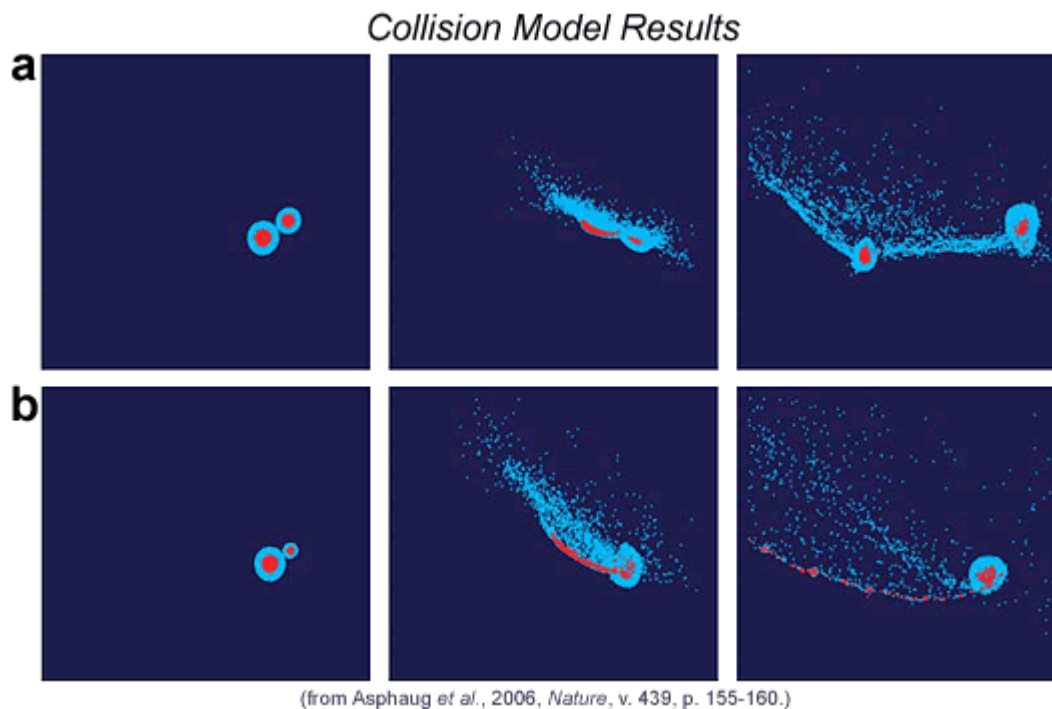
Sudden Pressure Decrease

Large protoplanets would have been compressed because gravity pulls everything towards the center of the body. There is considerable energy tied up in this compression. For a Mars-sized protoplanet, Asphaug and coworkers calculate that decompression of the planet's mantle releases about the same amount of energy per gram as does TNT. This energy is available for heating the entire body, including considerable melting of the rocky mantle. This happens because the melting temperature of rock increases with increasing pressure. If the pressure drops without cooling, melting ensues. The hit-or-miss team calculates that the pressure inside the smaller protoplanet could decrease 30 to 50% for about an hour during a non-impact close approach (see graph below), resulting in a permanent decrease of 20% because of mass loss and increase in the protoplanet's rate of rotation. The pressure drop could cause widespread melting or, if the body is already partly molten, widespread increase in the percentage of the interior that is molten.



This graph depicts how a non-impacting close approach of a Moon-sized protoplanet with a body the size of Mars would result in a dramatic, though short-lived (about an hour) decrease in the pressure inside the smaller body. This could lead to widespread heating and melting of the interior.

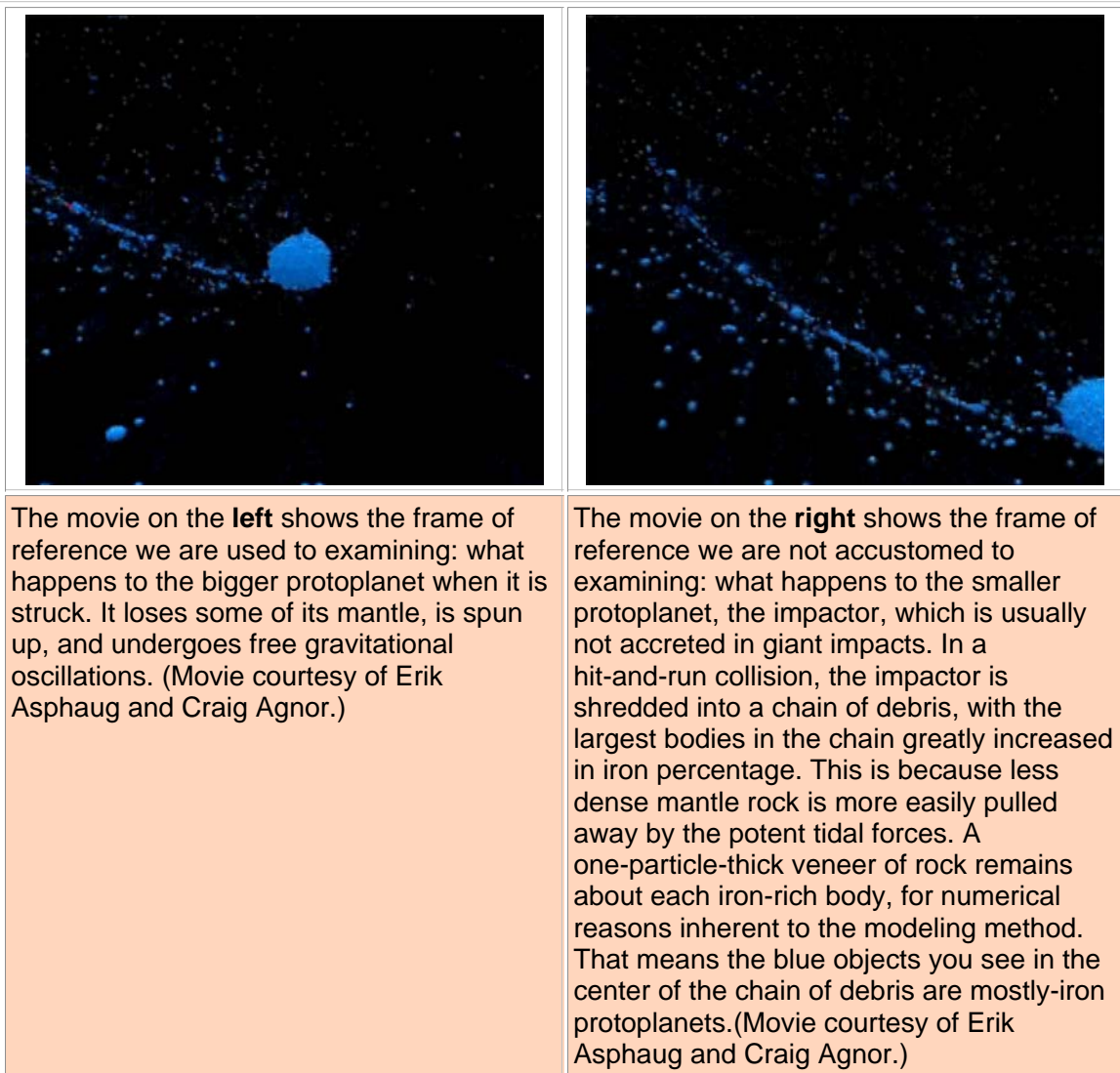
If the bodies experience a grazing collision, shearing and mechanical stresses are considerable, and add to the effects of pressure release. Collisions like this could lead to partial, or complete, disruption of the smaller protoplanet, spewing its rocky and metallic guts into a strung out collection of protoplanets.



Two examples of a non-accretion collision between a protoplanet with the mass of Mars and a smaller protoplanet. In **a** (top sequence), the impactor has a mass equal to half that of the target; in **b** (bottom sequence), the impactor has a mass of only one-tenth that of the target. Red indicates the metallic cores and blue indicates the rocky mantles of the bodies. When the impacting protoplanet is close to the mass of the target protoplanet (top sequence), it experiences loss of rocky mantle, but the residue stays intact. Its ratio of metal to silicate has increased, however. The rocky debris could accrete to form an object with a smaller than normal amount of metallic iron. When the impacting protoplanet is small (bottom sequence), it is destroyed and a chain of metal-rich

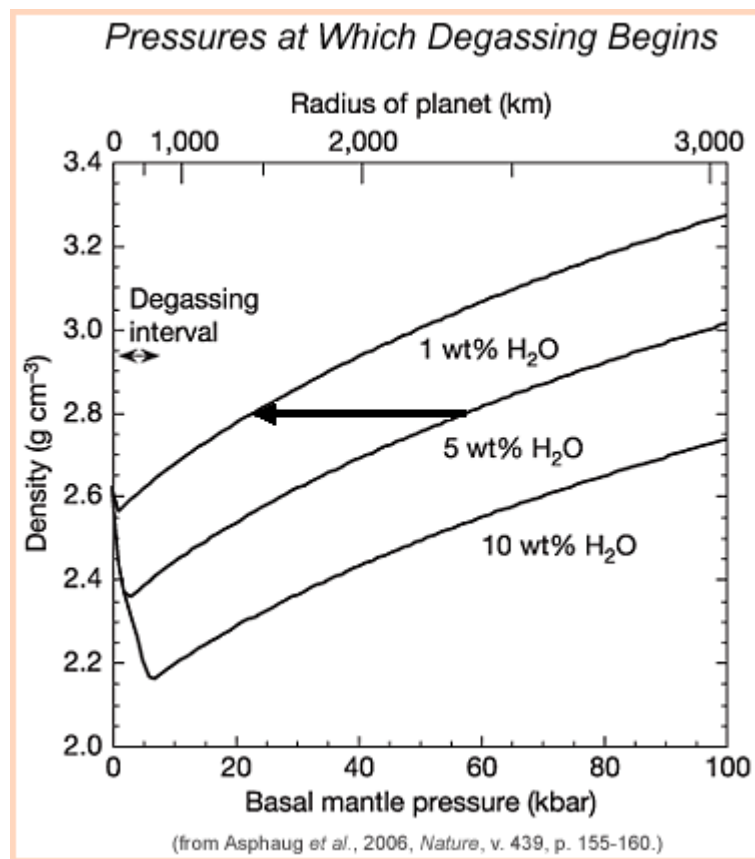
protoplanets results, possibly leading to formation of metal-rich asteroids.

The two movies, below, show collisions between a Mars-mass protoplanet and a Moon-mass protoplanet (1:10 mass ratio collision), where the encounter occurs at twice the mutual impact velocity, at an impact angle of 45 degrees. Neither protoplanet is rotating initially.



Fizzing Protoplanets

Water can be dissolved in silicates, including in magma. How much dissolves, however, depends on pressure: the higher the pressure, the more H₂O can be dissolved. If protoplanets had H₂O inside them (reasonable, but not a guarantee), the pressure release associated with a close encounter or a grazing impact could cause the H₂O to bubble out as vapor. The huge volume change associated with the gas loss could cause widespread, dramatic eruptions and even loss of silicate from smaller objects. The escaping H₂O gas might also react with the rocky materials or metallic iron, to change the chemical composition and oxidation state of some regions. Asphaug and his colleagues have not yet studied the chemical effects, but their results show that there is interesting work to be done.



This graph shows the rock density versus the pressure at the base of the mantle of a Moon-sized impactor. The curves represent the amount of H₂O that can be dissolved in the rock. Note that for any concentration, the amount that can be dissolved increases with pressure. The higher the H₂O content, the lower the density. If a Moon-sized protoplanet were disrupted so that the pressure decreased suddenly, the pressure would move to the left. This is illustrated, by the black arrow, for the case of 5% H₂O at a pressure of 60 kilobars (60,000 times the pressure at Earth's surface). If the pressure drops to about 20 kilobars, the solubility of H₂O drops to only 1%. The rest escapes rapidly as gas, causing the planet to fizz like a shaken carbonated drink.

Ripping Asunder

If the smaller projectile were solid, it can still be disrupted by the shear forces on it as it passes near the larger protoplanet. A 500 kilometer body would crack into fragments about 200 meters across. A solid object double that size would break into smaller fragments, only 70 meters across, because the disassembly releases more gravitational energy. However, because many (perhaps most) protoplanets would have been heated by the decay of short-lived radioactive [isotopes](#) such as aluminum-26 (²⁶Al) or by impacts, the usual case is interaction between partially molten objects. In that case, disruption occurs more readily.

The bottom line is that close encounters and grazing impacts during planet formation lead to planet growth, but it is accompanied by creation of a lot of protoplanet debris.

Answering Asteroid Mysteries

The idea of hit-and-run collisions provides an answer for some meteorite and asteroid mysteries. A classic idea of asteroid history is that they formed cool, heated up by the decay of ²⁶Al, and differentiated into a core and mantle, with subsequent melting of the mantle to create a crust. Curiously, we have lots of samples of chemically distinct iron meteorites and a few basaltic crusts (such as asteroid 4 Vesta), but few of the mantle.

We do not see much of it among the meteorites or from spectral observations of asteroids. Planetary scientists have wondered for a long time where the missing mantle is hidden. The most common explanation is that the mantle rock is weaker than the iron cores, which are basically steel, so that impact disruption over the eons has destroyed it. Nobody really likes that idea because some objects have basaltic crusts. Why, skeptics ask, would impacts strip away so many mantles completely, while leaving some asteroids with their basaltic crusts intact?

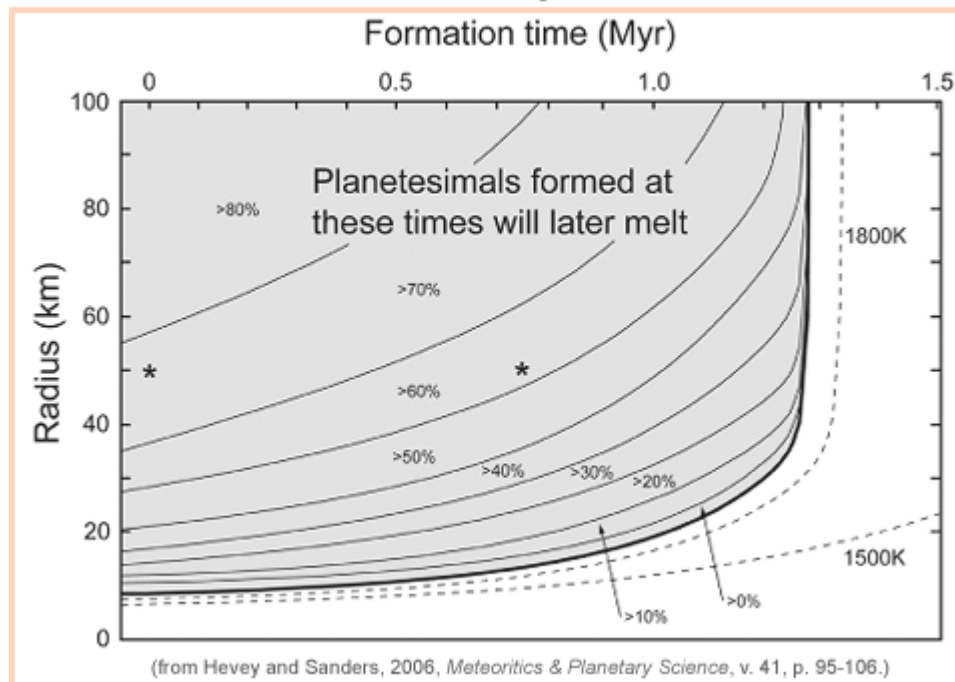
Now we have an alternative explanation. If the mantle rock is not molten, a close encounter with another protoplanet could cause it to break into thousands of little pieces tens to a couple of hundred meters across. These small objects would not survive the collision-dominated early Solar System. Or, if partially molten and water-rich, larger protoplanets could have fizzed out lots of water and droplets of molten asteroid. If the water reacted with the silicates from which it was evolving, the resulting product might not even be recognizable as a chunk of a protoplanet mantle. Mixing of iron and silicate during this process would also create a large volume of stony-iron objects, not just rocky ones. This view is complementary to one proposed by Bill Bottke (Southwest Research Institute, Boulder) and colleagues in which some iron meteorites are fragments of the long lost precursor material that formed the Earth and other terrestrial planets. (See [PSRD article Iron Meteorites and the Not-So-Distant Cousins of Earth](#).)

Meteorite studies show that there are at least 100 chemically distinct types of iron meteorites. That's a lot of protoplanet core material to reveal by impacts chipping away at small, differentiated asteroids. The problem is at least partly solved if many of those iron cores formed by a hit-and-run collision, as depicted above.

More Than One Way to Cook an Asteroid

Asphaug and his coworkers give us a whole new way of looking at how asteroids might have formed and melted, but other ideas are certainly in the running. In particular, asteroid heating by the decay of short-lived ^{26}Al and other isotopes (e.g., ^{60}Fe) also explains the widespread melting of asteroids. There might be problems with getting rid of rocky mantles, but it makes a simpler explanation for the history of asteroid 4 Vesta, ancestral home of the eucrite, howardite, and diogenite meteorites. As shown by Phonsie Hevey and Ian Sanders (Trinity College, Dublin, Ireland), even asteroids as small as 20 kilometers in radius would have melted enough to differentiate into core and mantle, if they formed with the ^{26}Al to ^{27}Al ratio measured in calcium-aluminum rich inclusions ([CAIs](#)) in primitive (unmelted) meteorites. Short-lived isotopes also provide a good explanation for the heating and thermal metamorphism (without melting) of chondritic meteorites.

Asteroid Melting Calculations



Calculations of asteroid heating indicate that even small asteroids will melt inside if they form while ^{26}Al is still present. The longer it takes for an asteroid to form, the less ^{26}Al and heating from it, hence a body must be larger to heat to its melting temperature. Curves in the shaded region indicate how much of the body is heated above the melting temperature (assumed to be $1450\text{ }^{\circ}\text{C}$). Dashed contours outside the melting zone indicate the maximum temperature reached.

The next step is to reconcile these two likely mechanisms of asteroid heating. Erik Asphaug, his colleagues, and other experts in modeling planet formation are working on more elaborate models and investigating collisions between protoplanets with a wide range in size. Meteoriticists are searching for evidence to prove or disprove the theoretical models. We are at the beginning of a fascinating intellectual adventure.

Effects on Final Planets

Hit-and-run collisions between protoplanets might drastically disrupt the course of crystallization of their magma oceans. Consider, for example, the Martian magma ocean. Linda Elkins-Tanton and her colleagues at Brown University have constructed geochemically and geophysically reasonable models of the crystallization of the Martian magma ocean, including its overturn triggered by an unstable density gradient resulting from initial crystallization (see [PSRD article A Primordial and Complicated Ocean of Magma on Mars](#)). A hit-and-run collision during magma ocean crystallization would scramble the pile of crystals deposited at its base up to that time, perhaps resulting in a temporarily stable configuration of the cumulates. Continued crystallization would produce a density gradient atop that rearranged pile. Subsequent overturn would be substantially more complicated than the simpler models predict, perhaps leading to a mantle even more heterogeneous than predicted and a complicated primary crust.

The theoretical studies of Erik Asphaug and his colleagues present challenges to cosmochemists, the scientists who are testing the ideas through chemical and isotopic analyses of meteorites and samples returned from the Moon, and eventually, asteroids and Mars.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Asphaug, E., C. B. Agnor, and Q. Williams (2006) Hit-and-run planetary collisions. *Nature*, v. 439, p. 155-160.
- Bottke, W. F. and L. M. V. Martel (2006) Iron meteorites as the not-so-distant cousins of Earth. *Planetary Science Research Discoveries*. <http://www.psr.d.hawaii.edu/July06/asteroidGatecrashers.html>.
- Hevey, P. J. and I. S. Sanders (2006) A model for protoplanet meltdown by ^{26}Al and its implications for meteorite parent bodies. *Meteoritics and Planetary Science*, v. 41, p. 95-106.
- Taylor, G. J. (2006) A primordial and complicated ocean of magma on Mars. *Planetary Science Research Discoveries*. http://www.psr.d.hawaii.edu/Mar06/mars_magmaOcean.html.