

Citation: Scott, E., J. Yang, and J. Goldstein (April, 2007) When Worlds Really Did Collide. *Planetary Science Research Discoveries*. <http://www.psr.d.hawaii.edu/April07/irons.html> (date accessed).

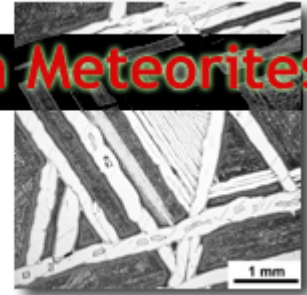


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**Hot Idea**

April 18, 2007

**Iron Meteorites**



## When Worlds Really Did Collide

--- Cosmochemical studies and dynamical models of protoplanetary collisions suggest a new origin for iron meteorites.

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Most [iron meteorites](#) are thought to come from over 50 asteroids 5-100 kilometers in size that were melted, [differentiated](#) into metallic cores and silicate mantles, and broken open by impacts long after they had slowly cooled. However, we find that the cooling rates for one group of iron meteorites (dubbed the IVA group) and other irons require a much more complex history and much larger parent bodies. The IVA metal was probably derived originally from a body at least 600 kilometers in diameter, and possibly much larger, that was dispersed by an impact leaving a molten metal body 300 kilometers in diameter. The molten metal body solidified and cooled slowly with scarcely any enveloping silicate mantle. This history supports several recent theoretical studies that infer that differentiated asteroids and meteorites are debris from protoplanetary collisions, that protoplanets were abundant in the asteroid belt, and that parent bodies of iron-rich meteorites were broken up early.

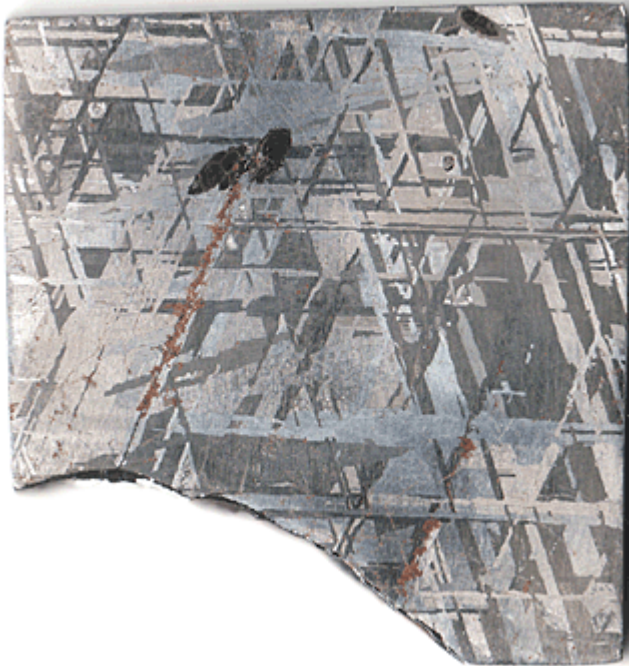
### Reference:

- Yang, J., J. I. Goldstein, and E. R. D. Scott (2007) Iron Meteorite Evidence for Early Formation and Catastrophic Disruption of Protoplanets. *Nature*, v. 446, p. 888-891.

**PSRD presents:** When Worlds Really Did Collide--[Short Slide Summary](#) (with accompanying notes).

## Thermal Histories and Cooling Rates

IVA Iron Meteorite, Gibeon



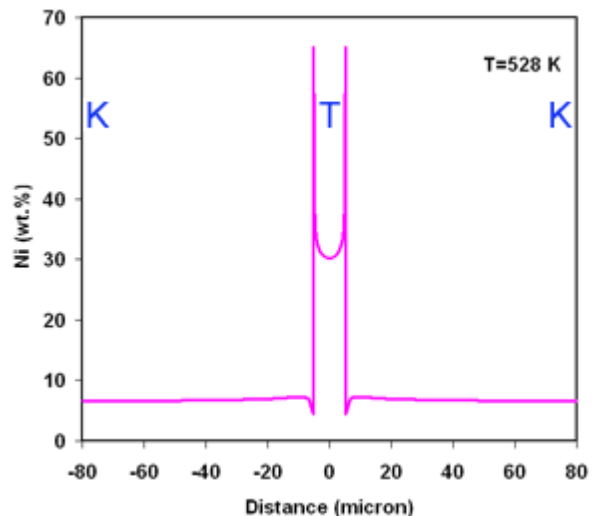
(Photo courtesy of Jeff Gillis-Davis, University of Hawaii.)

Meteorites contain a record of the earliest stages in the formation of planetesimals and planets in the solar system. To decipher this record, we need to learn more about the sizes and impact histories of the meteorite parent bodies. Our only clues to their sizes come from the thermal histories of meteorites as the larger a solid body, the longer it took to cool. Most cooling rates for meteorites have been obtained from studies of Fe-Ni metal grains, which on cooling from 1000 to 700 K change their crystal structure. For iron meteorites, which are mostly derived from asteroidal cores, this structural change produces the well-known Widmanstätten pattern of crystallographically oriented kamacite plates in taenite (see photo).

This slice of the Gibeon IVA iron meteorite, 4.6-centimeters wide, displays a Widmanstätten pattern.

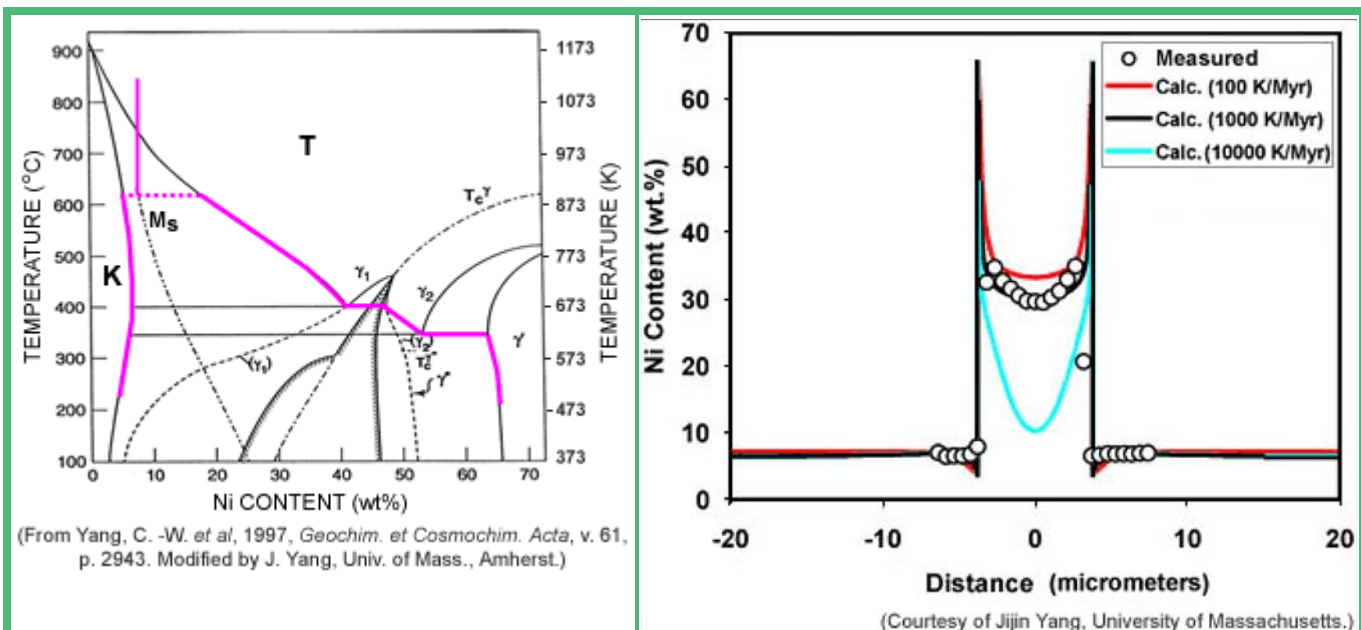
Because the dimensions and compositions of kamacite and taenite depend on the time available for kamacite growth, the cooling rate of an iron meteorite can be determined by analyzing its taenite grains with an electron microprobe and reproducing these data with computer models for kamacite growth together with diffusion rates and equilibrium mineral compositions at 1000-700 K.

Cooling rates of iron meteorites can be calculated using a computer model that simulates the formation of the Widmanstätten pattern of oriented kamacite plates.



(J. Yang & J. I. Goldstein, Univ. of Mass, and E. Scott, Univ. of Hawaii)

The animation, above, shows how the Ni concentration varies with distance in an iron meteorite containing 8.4 wt% Ni and 0.08 wt% P as it cools at 500 K/Myr. Decreasing temperatures are shown in the upper right corner. In this model, kamacite (K) nucleates at 883 K at -80 and +80 micrometers in the taenite (T). The purple, vertical lines mark the boundaries between the taenite (in the center) and the kamacite. Kamacite grows inwards causing taenite to develop a characteristic M-shaped profile.

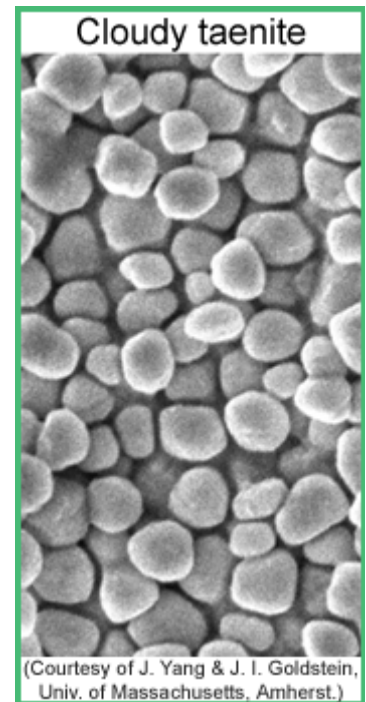
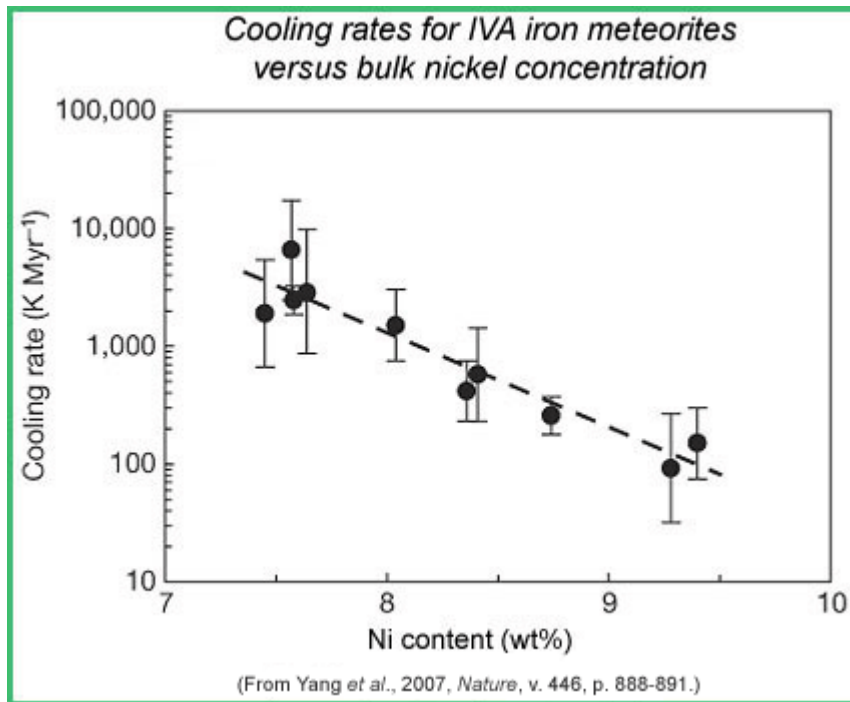


**LEFT:** The purple lines on the temperature-composition diagram, above, show how the Ni concentrations of kamacite (K) and taenite (T) change at their contact as the temperature decreases. The M-shaped profile in taenite develops because atoms diffuse much slower in taenite than kamacite and the diffusion rate decreases with falling temperature. The kamacite nucleates in this low-phosphorus iron meteorite at 610 °C (883 K) when martensite forms. Martensite is a different form of taenite. As martensite begins to form it rearranges the crystal structure, thereby producing locations called nucleation sites on which kamacite crystallizes. The martensite formation curve is labeled  $M_s$  in the diagram. **RIGHT:** The diagram, above, shows the comparison of the measured Ni concentration across a taenite grain that is 8 micrometers wide with calculated Ni concentration profiles for three different cooling rates. The data match the calculated profile for 1000 K/Myr.

The cooling rates for irons that have been obtained from their Widmanstätten patterns using computer models range from 1 to 5000 K/Myr and are compatible with slow cooling in asteroids that were 5-200 km in diameter. The major problem with this is that we have irons whose chemical compositions show clearly that they formed in the same body. However, their cooling rates differ considerably, which is incompatible with cooling in a metallic core that was insulated by a silicate mantle. Since thermal conduction is about 30 times faster in metal than in silicate, the thermal gradient in an insulated core would be negligible compared to that in the mantle so that all samples should have indistinguishable cooling rates. This problem is largest for the IVA irons, the fourth largest group, which have cooling rates that differ by factors of 10-100 and are inversely correlated with bulk Ni concentration. For 40 years, meteoriticists have wrestled with this problem. Some workers have attempted to find more complex histories for IVA irons involving impacts prior to cooling, but these have not provided a convincing explanation for the correlation between cooling rate and bulk Ni. Others like John Wasson (UCLA) have concluded that this correlation must be an artifact arising from errors in the thermodynamic data or diffusion rates or from incorrect assumptions about the kamacite nucleation mechanism.

## Understanding How IVA Iron Meteorites Cooled

To obtain the most accurate cooling rates for IVA irons, we made a number of improvements in the techniques and evaluated all possible sources of errors, including all those suggested by Wasson. We used the latest diffusion coefficients and phase equilibria data and included recent advances in understanding how kamacite plates nucleated. We found that ten IVA irons had cooling rates that ranged from 100 to 6000 K/Myr. These were inversely correlated with bulk nickel and had uncertainties that were 10-20 times smaller than the total IVA range (see diagram below). We also derived relative cooling rates at 600 K from a transmission electron microscope study of sub-micrometer intergrowths at the edge of taenite, called cloudy taenite for its appearance in reflected light after etching in acid (see image below).

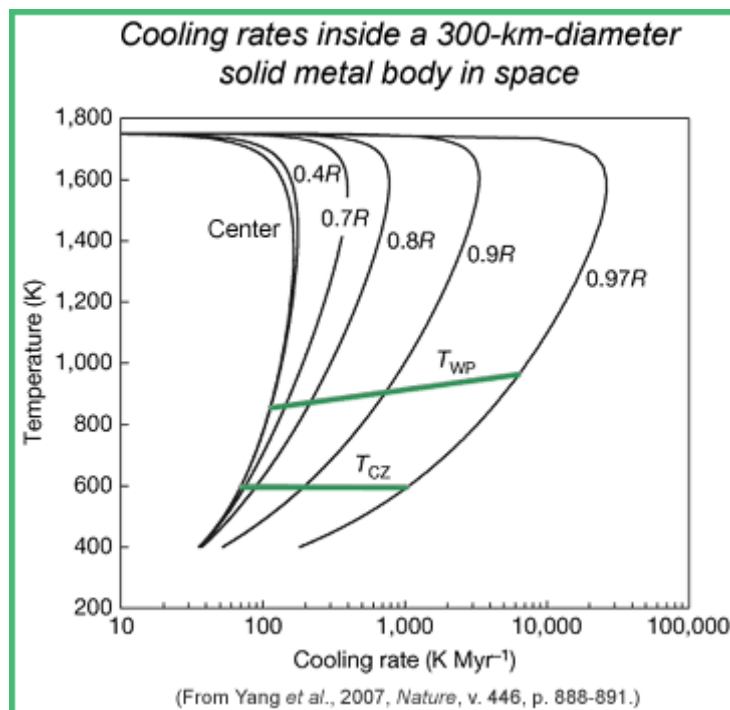


Cooling rates for IVA irons derived from modeling the growth of the Widmanstätten pattern vary by a factor of ~60 and are inversely correlated with the bulk Ni content of the iron meteorite.

This scanning electron microscope image shows a cloudy taenite intergrowth in a stony-iron meteorite after etching in acid. The rounded particles are 0.5 micrometers across and their size depends on the cooling rate.

Cooling rates of seven IVA irons at 600 K, inferred from the cloudy taenite microstructure, differ by a factor of ~15, and are negatively correlated with bulk Ni, like the cooling rates inferred from the Widmanstätten patterns. Thus two different techniques show diverse cooling rates in the IVA irons.

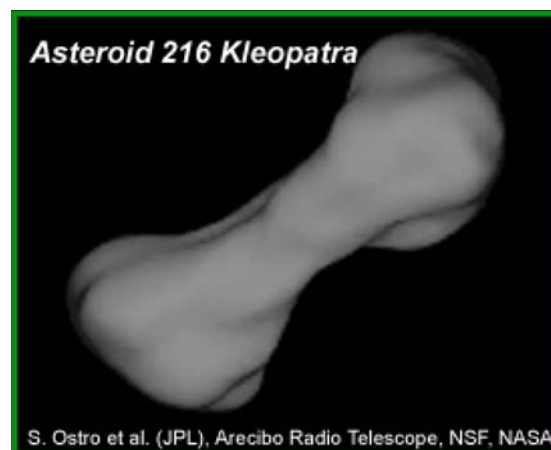
Since two different techniques show that the IVA irons cooled at very diverse rates, they could not have cooled in a mantle-covered metallic core. Instead, we propose that mantle and core material were separated in a major impact so that the IVA metallic body cooled in space with virtually no silicate shell. In this case, the IVA cooling rates can be explained if the irons crystallized inwards and cooled in a metallic body 300 kilometers in diameter that was surrounded by less than 1 kilometer of silicate mantle material (see diagram below).



Each curve in this diagram shows how the cooling rate changes with falling temperature at a specific location inside the metallic body. Our IVA cooling rates, indicated by the two straight lines, suggest that the IVA irons were located between 0.4R and 0.97R, where R is the radius of the body (150 kilometers). In other words, the meteorites come from depths 97% of the way to the surface (0.97R) from the center to only 40% (0.4R).

The IVA irons with the lowest Ni concentrations would have formed on the outside of the 300-kilometer metallic body and cooled fastest, consistent with the cooling rate data. This body would have been  $\sim 10^4$  times more massive than earlier estimates for the IVA core—larger than the metallic asteroid, Kleopatra, which is 217 kilometers long (see image), and larger than the inferred core of the largest melted asteroid, Vesta, which is 530 kilometers across. (See [images of Vesta](#) from NASA's Hubble Space Telescope, in a new window.) The 300-kilometer metallic body was either the solid core of a 600-kilometer body that was surgically separated from its mantle by an impact, or more likely it was a part of a much larger molten core that was disrupted on impact.

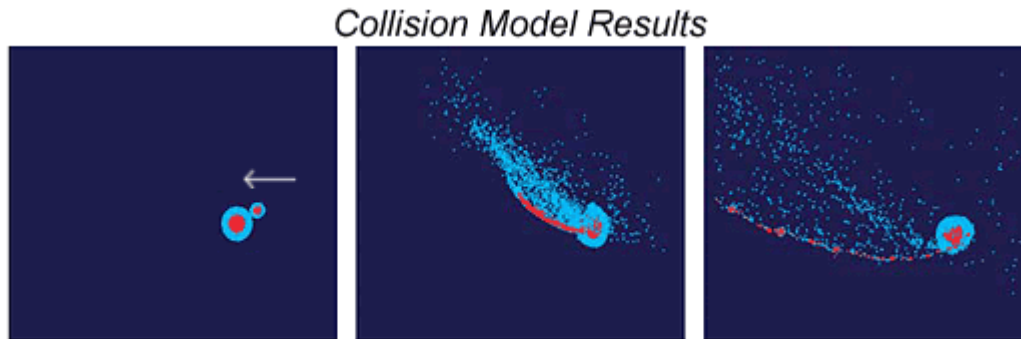
Kleopatra, image on right, is probably made largely of metallic iron-nickel and might have been formed in an impact like that described by Asphaug and coauthors.



## Irons from Glancing Collisions

Until very recently, it was assumed that metallic meteorites and asteroids formed as a result of impacts that smashed differentiated asteroids into fragments over billions of years. However, asteroidal impacts cannot

simply strip mantles from cores--a projectile capable of removing the mantle from a 600-kilometer asteroid would blow the core to smithereens. Fortunately, another mechanism of impact disruption has been discovered recently by Erik Asphaug and colleagues at the University of California, Santa Cruz. They proposed that metal-rich asteroids and meteorites are formed in "hit and run" collisions between protoplanets (see [PSRD article: Hit-and-Run as Planets Formed](#).) They showed how a glancing collision between a Moon-sized and a Mars-sized protoplanet could have disemboweled the smaller body, converting its core into a string of metal-rich bodies. If protoplanets were once abundant in the asteroid belt, as many dynamicists conclude, the IVA irons could have been derived from part of a molten protoplanetary core.



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

This illustration shows, from left to right, what happens when a smaller protoplanet has a "hit and run" collision with a protoplanet with the mass of Mars. The arrow shows direction of the smaller body. Red indicates the metallic cores and blue indicates the rocky mantles of the bodies. The impacting protoplanet is destroyed and a chain of metal-rich protoplanets results, possibly leading to formation of metal-rich asteroids.

Evidence for early large impacts in the asteroid belt has steadily accumulated from cosmochemical studies of meteorites over the past 20 years. Three kinds of igneously formed meteorites, ureilites, mesosiderites, and the Shallowater aubrite, have thermal histories requiring early disruption of their parent bodies. In addition, two other features of IVA irons might be explained by a protoplanetary impact: abundant silicates in two IVA irons, and the enormous depletion of moderately volatile elements like gallium (Ga) and germanium (Ge) (Ge/Ni values are 0.01-0.001 of chondritic values). The depletion of volatile elements in the Moon is attributed to the giant impact that was responsible for its formation, favoring a protoplanetary impact origin for low-Ge irons like the IVA irons.

Three other groups of irons, IIAB, IIIAB and IVB, show cooling rates that vary by a factor of 6-12, from which we infer that they too come from bodies that experienced eviscerating impacts that formed metallic bodies with little or no silicate mantle. Early disruption of differentiated bodies before they had cooled is also required to understand the relative rarity of olivine-rich asteroids and meteorites, as well as the high proportion of irons (~0.7) among the samples of separate meteorite parent bodies (see [PSRD article: Iron Meteorites and the Not-So-Distant Cousins of Earth](#).)

## Iron Meteorites Come From the Oldest Bodies

Iron meteorites provide insights into the earliest stages of accretion in the solar system as they come from bodies that formed and differentiated before the parent bodies of the chondrites had formed. We know this from Hf-W isotopic data: the parent isotope,  $^{182}\text{Hf}$ , which decays with a half-life of 9 Myr, prefers silicate to metallic iron whereas the reverse is true for the daughter isotope  $^{182}\text{W}$ . Since the proportion of  $^{182}\text{W}$  relative to other tungsten isotopes is indistinguishable in most irons from the initial isotopic ratio in calcium-aluminum-rich inclusions ([CAIs](#)), which were the first objects to form in the solar system, molten metal in their parent bodies must have separated from silicate almost immediately after CAIs formed. Allowing for errors in the measurements, we can infer that molten metal cores formed in most parent bodies within 1.5 Myr of CAI

formation. Radiometric ages for chondrules, however, show that chondrites come from bodies that accreted 1-4 Myr after CAIs formed. Formation of molten metal cores before chondrites accreted is entirely consistent with the work of Phonsie Hevey and Ian Sanders (Trinity College, Dublin, Ireland) and Henning Haack (Geological Museum, Copenhagen) who modeled how planetesimals would have melted due to heat from the decay of the short-lived isotope  $^{26}\text{Al}$ , which has a half-life of 0.72 Myr. Bodies >20 km across that accreted within 1.5 Myr of CAI formation would have melted. So the IVA results show that protoplanets 1000 km or more across formed within 1.5 Myr of solar system formation, as dynamicists suspected, and that debris from these bodies survived as asteroids.

The remarkable consistency between cosmochemical studies of iron meteorites and dynamical modeling of protoplanet formation has validated the methods used by meteoriticists for over 40 years to improve our understanding of the cooling rates of metal-bearing meteorites. Because of the continued efforts of numerous cosmochemists and dynamicists, it is now time to rewrite the textbooks to reflect our new appreciation for the sizes of meteorite parent bodies, the mass of the primordial asteroid population, and its early impact history.

## Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRD presents:** When Worlds Really Did Collide--[Short Slide Summary](#) (with accompanying notes).
- Asphaug, E., C. B. Agnor, and Q. Williams (2006) Hit-and-Run Planetary Collisions. *Nature*, v. 439, p. 155-160. [NASA ADS entry](#)
- Bizzarro, M., J. A. Baker, H. Haack, and K. L. Lundgaard (2005) Rapid Timescales for Accretion and Melting of Differentiated Planetesimals Inferred from  $^{26}\text{Al}$ - $^{26}\text{Mg}$  Chronometry. *The Astrophysical Journal*, v. 632, p. L41-L44. [NASA ADS entry](#)
- 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>
- Chabot, N. L. and H. Haack (2006) Evolution of Asteroidal Cores. In *Meteorites and the Early Solar System II*, D. S. Lauretta and H. Y. McSween Jr. (eds.), University of Arizona Press, Tucson, 943 pp., p.747-771.
- Hevey, P. J. and I. S. Sanders (2006) A Model for Planetesimal Meltdown by  $^{26}\text{Al}$ , and its Implications for Meteorite Parent Bodies. *Meteoritics and Planetary Science*, v. 41, p. 95-106. [NASA ADS entry](#)
- Kleine, T., K. Mezger, H. Palme, E. Scherer, C. Munker (2005) Early Core Formation in Asteroids and Late Accretion of Chondrite Parent Bodies: Evidence from  $^{182}\text{Hf}$ - $^{182}\text{W}$  in CAIs, Metal-rich Chondrites, and Iron Meteorites. *Geochimica et Cosmochimica Acta*, v. 69, p. 5805-5818. [NASA ADS entry](#)
- Taylor, G. J. (November, 2006) Hit-and-Run as Planets Formed. *Planetary Science Research Discoveries*. <http://www.psr.d.hawaii.edu/Nov06/hit-and-run.html>
- Yang, C. -W., D. B. Williams, and J. I. Goldstein (1997) Low-temperature Phase Decomposition in Metal from Iron, Stony-iron, and Stony Meteorites. *Geochimica et Cosmochimica Acta*, v. 61, p.2943-2956. [NASA ADS entry](#)
- Yang, J., J. I. Goldstein, and E. R. D. Scott (2007) Iron Meteorite Evidence for Early Formation and Catastrophic Disruption of Protoplanets. *Nature*, v. 446, p. 888-891.



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