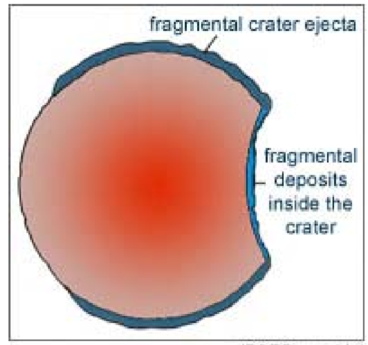
Hot Idea

July 8, 2008



(PSRD graphic)

Heating, Cooling, and Cratering: One Asteroid's Complicated Story

--- Cooling rate data indicate that the H-chondrite parent asteroid was deeply cratered as it cooled slowly.

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In a simple, orderly world, the parent asteroid for the H-chondrites would have heated by short-lived aluminum-26, and then cooled slowly. The deeper regions would have been heated more and cooled slowest, with less heating and faster cooling moving outwards from the center of the asteroid. A large set of mineralogical and age data fit this orderly picture, called the onion-shell model, for several meteorites, as shown by chronological investigations by Mario Trieloff and his colleagues at Heidelberg, Germany, and Paris, France, and by Thornsten Kleine and his colleagues in Switzerland, Germany, England, and the United States. Other meteorites are nonconformist renegades. Some of the most metamorphosed (heated to highest temperatures) cooled too fast, while some of the least metamorphosed (lowest temperatures) cooled too slowly. This conflicting evidence, if borne out by further studies, suggests something more complicated than an onion shell. The H-chondrite asteroid may have suffered one or more large impacts that excavated deep enough that some hot regions were suddenly much closer to a cooling boundary than they had been, and some more rapidly-cooling areas were buried by hot debris thrown out of the crater, slowing their cooling rates.

References:

- Kleine, T., Touboul, M., Van Orman, J. A., Bourdon, B., Maden, C., Mezger, K., and Halliday, A. N. (2008) Hf-W thermochronometry: Closure temperature and constraints on the accretion and cooling history of the H chondrite parent body, *Earth and Planetary Science Letters,* doi:10.1016/j.epsl.2008.03.013.

- Trieloff, M., Jessberger, E. K., Herrwerth, I., Hopp, J., Fiéni, C., Ghélis, M., Bourot-Denise, M., and Pellas, P. (2003) Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronometry, Nature, v. 422, p. 502-506.

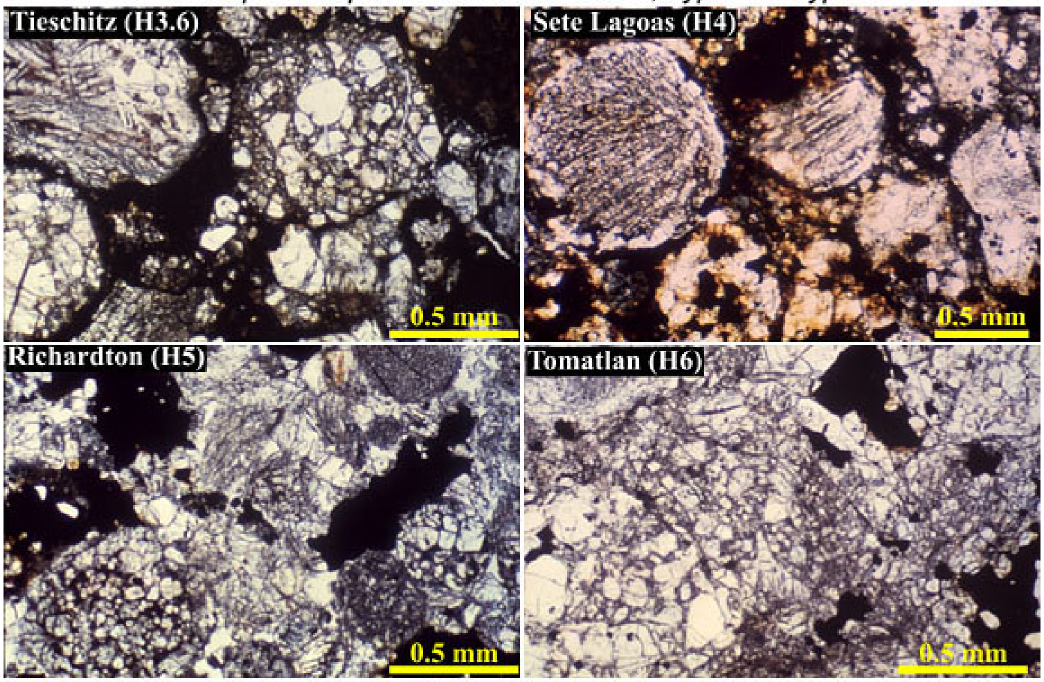
PSRDpresents: Heating, Cooling, and Cratering: One Asteroid's Complicated Story --Short Slide Summary (with accompanying notes).

Heating and Metamorphism

Chondrites come in assorted flavors. We'll concentrate on H chondrites, so named because they contain more metallic iron-nickel and more total iron (metallic plus iron oxide in the rocky portions) than other common chondrites, thus H=high iron. Since H chondrites were named cosmochemists have found chondrites with even more iron, but too late--H was already taken.

The H chondrites, like most other groups of chondrites, have a distinctive range of textures, as shown by the set of photomicrographs below. This sequence was identified by John Wood and Randy Van Schmus more than 40 years ago. They interpreted it a sequence of progressively more metamorphosed rocks. (Metamorphism is the process in which rocks recrystallize as a result of changes in temperature, pressure, and chemical environment. Chondrite metamorphism is caused by heating.) They classified ordinary chondrites into type 3, where chondrules are readily visible and contain glassy areas in them, to type 6, where chondrules are not so easy to see because their boundaries have grown together, small crystals have become larger, and minerals have crystallized in the glassy areas. Mineral compositions become uniform throughout during the progression from type 3 to type 6, and there are some changes in crystal structures from type 3 to 4.

Metamorphic Sequence for H Chondrites, Type 3 to Type 6



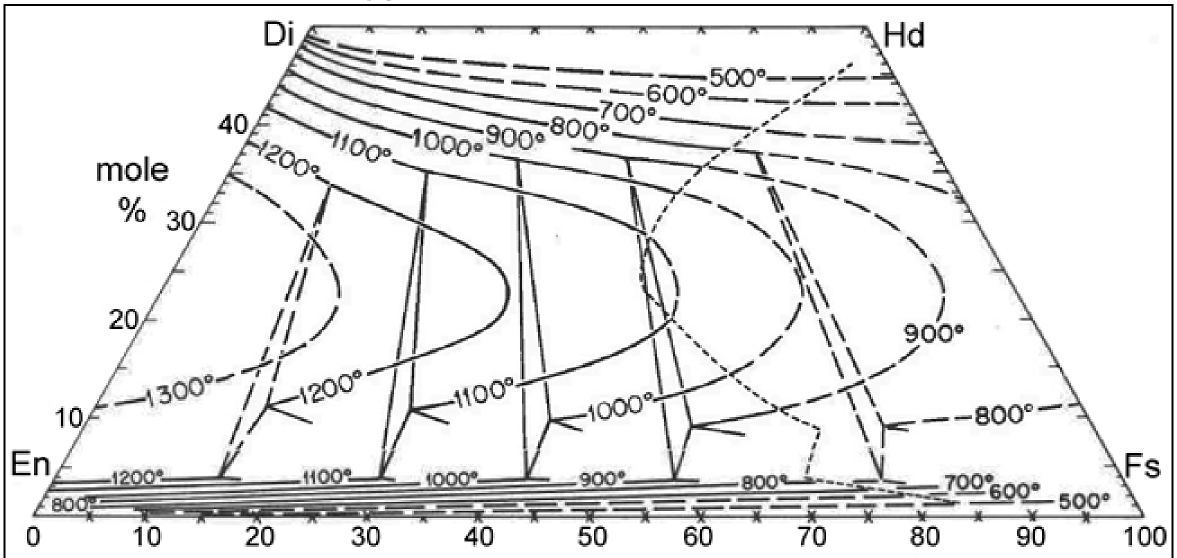
(Courtesy of Gary Huss.)

Photomicrographs showing the metamorphic sequence among H chondrites from type 3 (upper left) to type 6 (lower right). Chondrules (round objects clearly visible in the photograph of type 3 chondrite Tieschitz) become progressively less visible with metamorphic grade (as in type 6 chondrite Tomatlan). Glass in the chondrules transforms to mineral crystals, and minerals become chemically homogeneous in the sequence from type 3 to type 6. Different temperatures of metamorphism and different cooling rates almost certainly caused the changes.

Mineral Thermometers

We have spent countless cosmochemist-hours trying to determine the details of the metamorphic sequence. The highest temperatures reached by each chondrite, and each petrographic type, is important for understanding the metamorphic processes and for determining the source of heat. Peak temperatures can be determined from the chemical and isotopic compositions of minerals in the rocks. For example, the calcium concentration in two forms of pyroxene, low-calcium and high-calcium, is related to the highest temperature they were last in chemical balance. As the temperature decreases, the calcium concentration in low-calcium pyroxene decreases and the concentration in high-calcium pyroxene increases. The compositional variations with temperature for pyroxenes and other mineral pairs have been calibrated experimentally, so we can measure the compositions of minerals in a rock (usually minerals grains in contact with one another) and determine the highest temperature at which they were in chemical balance (also called "equilibrium").

Two-pyroxene Geothermometer at 1 atm



(From Lindsley, D. H., 1983, Pyroxene Thermometry, *American Mineralogist*, v. 68, p. 477-493.)

Don Lindsley's (Stony Brook University) pyroxene thermometer is shown here, from his paper in 1983. The diagram is a truncated three-component plot that depicts pyroxene composition as mixtures of calcium (top), magnesium (left) and iron (right) end members. Di and Hd are calcium-rich pyroxenes, En and Fs are low-calcium pyroxenes. The temperature-composition contours are based on experiments at 1 atmosphere pressure. Note that as temperature decreases, calcium decreases in low-calcium pyroxene and increases in high-calcium pyroxene.

The trick is that the highest temperature a pair of minerals records is related to the cooling rate. To maintain the chemical balance, elements must move within crystals and between crystals. They do not move fast. The motion involves jumping from one site in a crystal to another. The rate of element site-leaping decreases sharply as temperature decreases. In addition, element hopping rates are different in each mineral, so some mineral pairs reflect higher temperatures than do others because the element exchange rate does not keep up as the temperature decreases. As a result, different minerals have different "closure temperatures," the temperature at which diffusion is so slow that composition does not change. The closure temperature is dependent on cooling rate (less time for elements to diffuse, so a higher temperature is recorded) and on mineral grain size (smaller grains maintain equilibrium better than larger grains because atoms have a shorter distance to travel during metamorphism). A final complication is that if heating is not sufficient (that is, the peak temperature is too low), minerals will not equilibrate, and a temperature cannot be calculated. This can be a problem for lightly-metamorphosed type 3 and 4 chondrites.

This sounds impossibly complicated. The good news is that using different minerals and pairs of minerals allows us to scope out the cooling history over a large range in temperature. Doing so quantitatively to determine the cooling rate requires knowing the speed of element migration in each mineral, called the diffusion rate. Cosmochemists and geochemists have done experiments to determine diffusion rates of quite a few minerals, allowing us to paint a quantitative picture of chondrite cooling rates. It's all really quite amazing. We can determine the highest temperature to which a chondrite was heated and the rate at which it cooled after reaching the peak temperature--the art and science of extracting important numbers about asteroids from pieces of them.

High-precision age determinations are also useful at determining the cooling rates of meteorites. If we know the accretion time, the rock's age, and the closure temperature of the appropriate minerals, we can figure out the temperature interval and divide it by the time, giving us a cooling rate. We can also use just the age of the mineral and the closure temperature to test the onion shell concept, as shown below.

Here's a run down of the major techniques used in deciphering the heating and cooling histories of chondrites:

Two pyroxenes: Use of high-calcium and low-calcium pyroxene is a classic geothermometer used widely in studies of terrestrial and extraterrestrial rocks. It involves using the calcium concentration in each mineral, although the calcium concentration in either one is also useful. The lower the equilibrium temperature, the higher the calcium in high-calcium pyroxene and the lower it is in low-calcium pyroxene. The two-pyroxene thermometer applies to the temperatures above 800 Celsius. This was the focus of attention of a paper about petrographic type 6 chondrites by Valarie Slater-Reynolds and Hap McSween (University of Tennessee).

Olivine-spinel: Olivine (iron-magnesian silicate) and spinel (iron-magnesian-chromium oxide) exchange iron and magnesium. The ratio of iron to magnesium is not the same in the two minerals and it correlates with temperature. To test the onion shell model, Ronit Kessel (Hebrew University of Jerusalem) and her coworkers John Beckett and Ed Stolper (Caltech) applied the olivine-spinel thermometer to a suite of H, L, and LL ordinary chondrites of all metamorphic types.

Metallic iron-nickel minerals: Kamacite (low nickel) and taenite (high nickel) give some information about peak temperature, but most importantly, they allow us to determine the cooling rate at around 500 Celsius, the temperature at which taenite becomes chemically zoned. Zoned taenite has lower nickel in the center of grains and much higher at the rims. For details about this system, see **PSRD** article: When Worlds Really Did Collide.

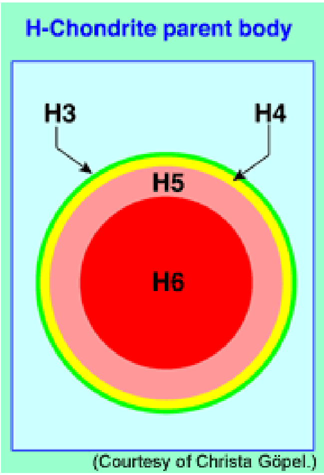
Plutonium-244 fission track ages: Plutonium-244 is a now extinct isotope that was present when the solar system formed. It concentrates in phosphate minerals in chondrites. It decays by spontaneous fission with a half life of 81 million years to lighter nuclei, e.g. xenon isotopes. The preservation of fission tracks in the phosphate minerals is dependent on how fast a rock cooled and can be used to derive an age. Its closure temperature is lowest of all the geothermometers, about 160 C. Fission track ages were used more than two decades ago by the late Paul Pellas (Mineralogical Museum, Paris) to test the onion shell model and published in 2003 by Trieloff and colleagues.

Potassium-argon ages: Potassium-40 decays to argon-40, giving us a powerful chronometer. Thousands of ages have been determined by this method. It is now usually done by irradiating a sample with neutrons to produce argon-39 from potassium-39. The sample is then heated sequentially and the amounts of argon-39 (which measures the potassium concentration) and argon-40 (which says how much potassium had decayed, hence gives us the age) are measured by mass spectrometry. Ideally, each temperature interval gives the same age. The method has a closure age of about 275 Celsius. Mario Trieloff and his colleagues report high-precision argon-argon ages for H chondrites.

Lead-lead ages: Lead-lead dating uses the fact that lead-207-lead-206 are produced at different rates from their parent isotopes, uranium-235 and uranium-238, respectively. By also measuring lead-204, which is not produced by radioactive decay, cosmochemists can make a diagram called an isochron. The samples, if all have the same age, lie on a line whose slope defines the age. It takes a bit of math and knowledge of the decay rates of uranium isotopes. Lead-lead ages have been determined for phosphate minerals, which have a closure temperature for lead of about 475 Celsius, and for chondrules and other major silicate components, which have a closure temperature of about 725-775 Celsius. Several research groups have determined lead-lead ages for the metamorphic sequence in H chondrites, e.g. Christa Göpel and colleagues (1994).

Hafnium-tungsten ages: Hafnium-182 is another one of those short-lived isotopes that are useful for understanding events that took place in the early solar system. It decays to tungsten-182 with a half life of only 9 million years. The hafnium concentrates in silicates, more in high-calcium pyroxene than in olivine and low-calcium pyroxene. Although most of the tungsten is concentrated in the metallic iron, new tungsten-182 is produced by the decay of hafnium-182 in the high-calcium pyroxenes. Metamorphic heating facilitates the movement of tungsten from the silicates into metallic iron, and the slower the cooling rate, this transfer will have occurred later and the apparent age will be younger. The system has a closure temperature of between 800 and 900 Celsius. Thornsten Kleine and his colleagues applied this technique to a suite of type 4-6 H chondrites.

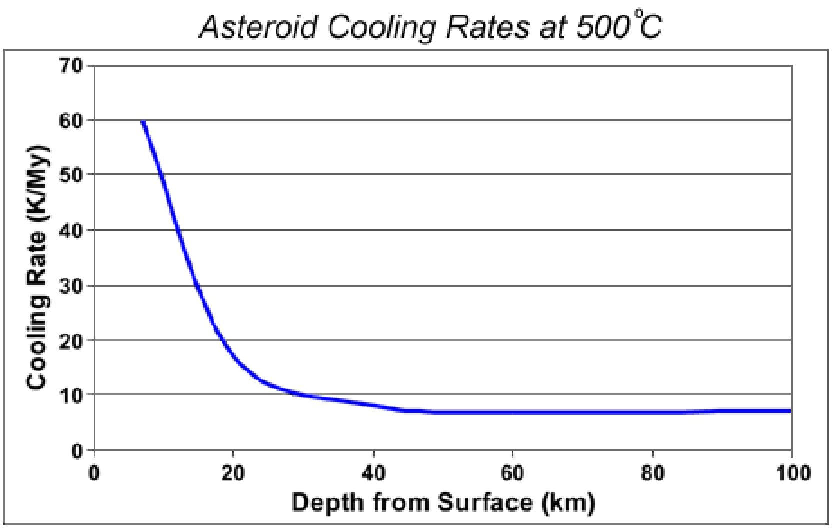
Cooling in an Onion



It has been the common assumption that this festival of thermal metamorphism took place inside a single asteroid. Chondrules, metallic minerals, and fine-grained materials usually called "matrix" accreted from the gas-dust cloud surrounding the Sun. Heat from the decay of aluminum-26 heated the asteroid internally. How hot it got was determined by when it accreted--aluminum-26 has a half life of 750,000 years, so waiting that long means that there was only half the amount of heat available. It was necessary to delay a while, though, because if there was too much aluminum-26 the asteroid would have melted. Because rock is a poor conductor of heat, internal heating results in a generally uniform temperature in the interior, with peak temperature uniform over much of the radius. Closer to the surface the cooling is faster.

Onion shell model of the parent asteroid of ordinary chondrites of type H.

Thorsten Kleine and his colleagues modeled the heating and cooling of the H-chondrite asteroid, assuming that decay of aluminum-26 was the source of heat. (Similar calculations have been done by others, including Ernst Zinner and Christa Göpel, as reported in the **PSRD** article: Using Aluminum-26 as a Clock for Early Solar System Events, and by Mario Trieloff and his colleagues.) Kleine's calculations show that peak temperatures in the interior are reached about 5 million years after the asteroid formed, assuming a radius of 100 kilometers and accretion 2.7 million years after the first solids formed in the Solar System (the delay is required to prevent the body from melting). The interior remains at the peak temperature of about 890 Celsius for a few million years, depending on depth (see graph below). The outer regions do not get as hot as those deeper, and cool faster, predicting that we ought to have an onion shell structure.

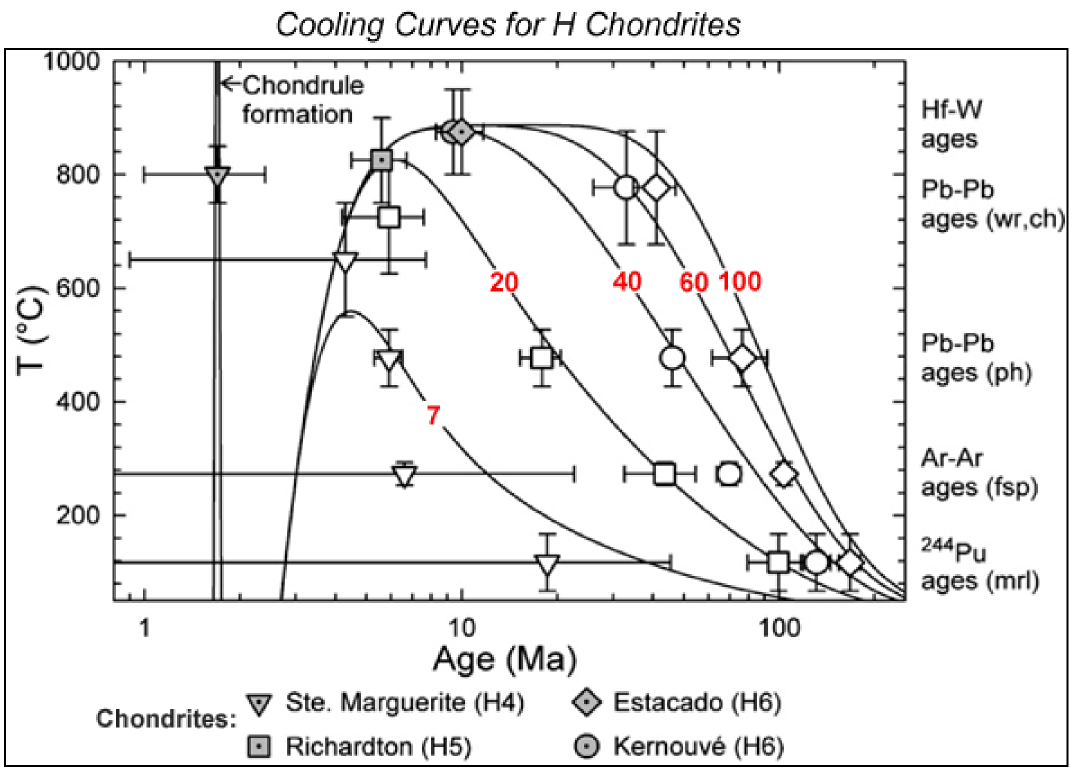


(PSRD graph made with data from T. Kleine.)

Calculations by Thorsten Kleine indicate that an asteroid 100 kilometers in radius will heat up rapidly by decay of aluminum-26, remain at a peak temperature dependent on the depth, and then cool slowly. Shown here is the cooling rate during the slow cooling, estimated for 500 degrees Celsius, the temperature where metallographic cooling rates apply. Note that the cooling rates in the regions deeper than 40 km are all the same, but vary substantially above 20 km. (We thank Thorsten Kleine for providing the output from his calculations, which we used in constructing this graph.)

Pro-Onion Chondrites

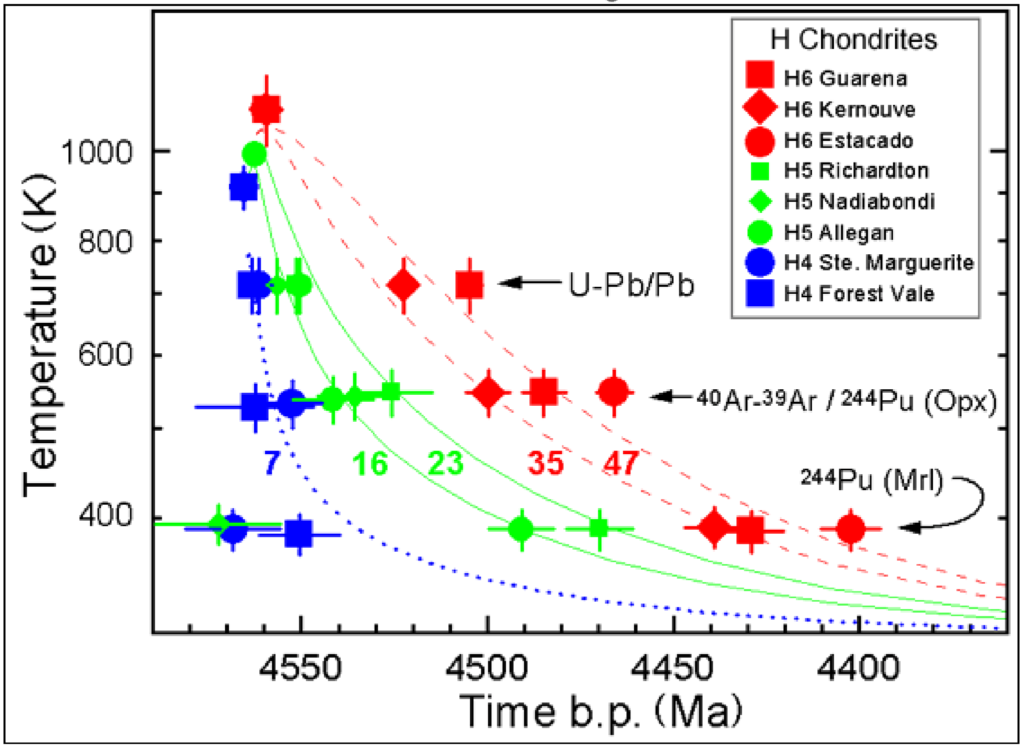
The papers by Trieloff and Kleine and their coworkers make a strong case for the validity of the onion shell model. Kleine's results are shown in the diagram below, which plots closure temperature against age. The four meteorites were also studied by Trieloff and his colleagues, but this diagram includes data for the hafnium-tungsten system as well. Note that the apparent burial depths (labeled in red, given by the calculated curves) and the closure temperatures for different isotopic systems are consistent with cooling in an onion shell body. The two type 6 chondrites (◈,⊙) are deepest, the type 5 (⊡) is shallower, and the type 4 chondrite (▽) cooled fastest. In fact, the type 4 chondrite has a hafnium-tungsten age offset by 2 million years from the more metamorphosed chondrites. Kleine suggests that this reflects the time of formation of chondrules in the chondrite and that the rock was not heated enough during metamorphism to erase that original record of chondrule formation in the solar nebula.



(From Kleine, T. *et al.*, 2008, *Earth and Planetary Science Letters*, doi:10.1016/j.epsl.2008.03.013.)

This graph shows cooling curves calculated from Kleine and colleagues. Numbers on the curves (in red) refer to depth from the surface of the asteroid in kilometers. Data points are ages and closure temperatures for different isotopic systems. Shorter times mean faster cooling, hence shallower burial. These four chondrites are consistent with the onion shell model for asteroids.

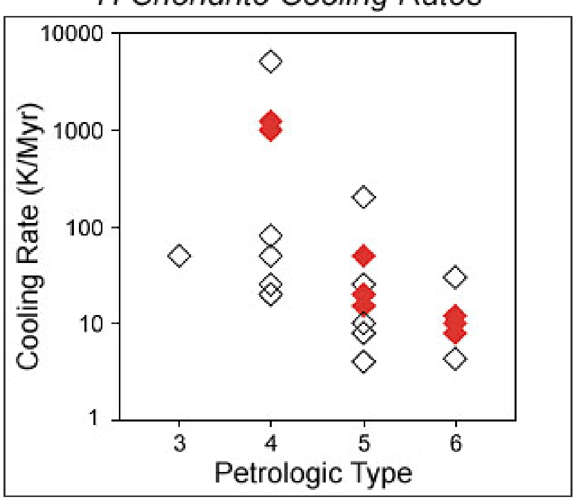
Trieloff and his colleagues measured argon-argon and plutonium-244 fission track ages and compiled data for other systems, and plotted eight chondrites on a similar diagram, including three type 6, three type 5, and two type 4 chondrites (see graph below). Their results are also strikingly consistent with the onion shell model.



(From Trieloff, M. *et al*, 2003, *Nature*, v. 422, p. 502-506.)

Mario Trieloff and his colleagues plotted closure temperature against age (linear scale in this case) for type 6 chondrites (red symbols), type 5 chondrites (green), and type 4 chondrites (blue). Numbers on the curves refer to depth from the surface of the asteroid in kilometers. The least metamorphosed chondrites cooled significantly faster than more metamorphosed samples, consistent with the onion shell model.

Metallographic cooling rates on the same set of meteorites are also consistent with an onion shell model. The diagram below is from a paper my colleagues and I published in 1987. For now, pay attention to the symbols colored in red, which are from the set studied by Trieloff and Kleine. They make a good, consistent story with the age data. Cooling rates increase from type 6 to 5 to 4, as called for by the onion shell model.



(From Taylor, G.J., *et al.*, 1987, *Icarus*, v. 69, p. 1-13.)

Metallographic cooling rates for each petrographic type of H-chondrites. (We offset some points by a few degrees per million years because they plotted on top of one another.) Those in red are the set of chondrites studied by Trieloff and Kleine and their colleagues, and are consistent with an onion shell model. Other chondrites also seem to be consistent with the onion shell model, but quite a few samples appear inconsistent. There are type 6 chondrites that cooled too fast and type 4 chondrites that cooled too slowly. This complicates the story of the H-chondrite asteroid.

Anti-Onion Chondrites

The age data are certainly consistent with the classic, and logical, onion shell model for heating and cooling of the H-chondrite parent asteroid. Unfortunately, while some metallographic cooling rate measurements are also consistent with this model, not all are, as shown in the diagram above. What's going on? Paul Pellas always argued that the metallographic cooling rates must be wrong, partly because he, like most of us, was enamored with the onion shell model. In a debate I had with him at a Lunar and Planetary Science Conference, he defended his interpretation, based on fission track data, that the H chondrite had an onion-shell structure. As with many things, including his wonderful zest for life, Paul was passionate about the onion shell. Perhaps he did not like the idea of it being disturbed before metamorphism was finished. At the end of our friendly debate, he held up a bumper sticker that said "I love asteroids," with the word "love" replaced by ♥, of course.

So, what is the cause of the larger range of metallic cooling rates for the H chondrites? One explanation is that there is more than one H-chondrite parent asteroid. While we cannot rule that out, the uniformity of many properties of H chondrites, such as oxygen isotope compositions and clustering of cosmic-ray exposure ages, suggests a single source. Another possibility is that shock caused by impacts messed up the metallographic cooling rate record. This is also unlikely because the chondrites we have measured do not have shock effects in either the silicates or the metallic minerals. In addition, shock heating would have distinctive effects on the metallic minerals and their compositions, which we do not observe. Nevertheless, this could use some more detailed study.

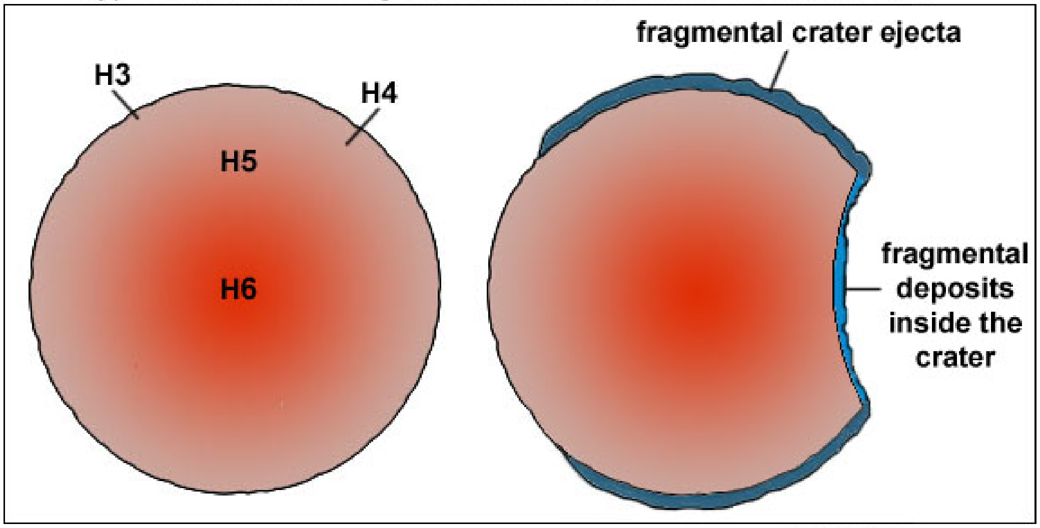
It seems to me that the metallographic cooling rates are likely to be correct. This does not mean that the onion shell model is wrong. In fact, internal heating by aluminum-26 is almost certain to have occurred and that must have lead to a period in which an onion shell existed. The question is why there seems to be some variation in the cooling rates beyond what we expect from a well-behaved onion shell asteroid. Part of the solution is to determine high-precision ages of the chondrites that have metallic cooling rates that do not conform to the onion shell model. If such data agree with the metallic cooling rates, something happened to the onion shell structure. We also ought to measure additional metallic cooling rates to determine how many chondrites do not seem to fit the onion shell model and what other characteristics they might have, such as higher or lower peak temperatures measured by the two-pyroxene or olivine-spinel thermometers. In short, we need a more comprehensive study of H chondrites.

Messing with an Onion Shell

Data on peak temperatures recorded by the olivine-spinel system also demonstrate the complexity of the thermal record. As Renit Kessel and her colleagues report, olivine-spinel temperatures are surprisingly similar among petrologic type 4-6 chondrites, ranging from about 700 to 725 Celsius. Given the range in metallographic cooling rates, which reflect cooling at lower temperatures that these, Kessel concludes that the onion shell thermal model must be an oversimplification. She suggests, following an idea by Glen Akridge and coworkers (University of Arkansas), that some chondrites were located near a boundary where heat conductivity varied dramatically over short distances. One way this can happen is to produce by repeated impacts a thick, low-conductivity fragmental layer (regolith) at the surface of the asteroid.

Another way to make boundaries is to remove a chunk of an asteroid. My colleagues and I calculated that a big impact could excavate down to 20-30 kilometers on an asteroid 100 kilometers in radius without disrupting it. This would result in an increase in cooling rate of some of the type 6 chondrites that were cooling slowly before the impact. A region cooling slowly 50 kilometers beneath the surface would suddenly be only 20 kilometers beneath the surface, doubling its cooling rate. (Readers can get an idea of the effects by playing around with the cooling rate versus depth graph above.) It might also cause burial of some areas of the body by fragmental material, thus slowing the cooling of less-metamorphosed rock. On top of that, the amount of loose, fragmental deposits inside the crater might vary in thickness, giving an even greater range of cooling rates for the exposed rock.

Hypothetical Cratering Event of H-chondrite Parent Asteroid



(PSRD graphic)

The view on the left depicts a slowly-cooling asteroid, with the intensity of red proportional to temperature. In such a body, cooling rate is related to depth, with deeper areas cooling slower than shallower ones. This results in an onion-shell structure with the most metamorphosed rock most deeply buried. One way of disturbing this is for an impact to make a big hole, as shown on the right. Rock formerly deeply buried is now closer to the surface and cools faster. The ejecta from the crater forms an insulating layer around the asteroid, slowing the cooling of the rock beneath it. If fragmental, its thermal conductivity would be much lower than that of rock, so a thin layer has a big effect on the rate of heat loss and cooling.

This picture is not as orderly as the onion shell model, but it may be more realistic. In its own way it has a certain amount of order to it. The hypothetical cratering event would have happened during slow cooling, so within the first few tens of millions of years. The early history of the solar system was a time when objects whacked into one another, including in the asteroid belt. It would not be surprising if one such collision messed up the nice onion shell H-chondrite parent asteroid, producing the baffling thermal record we are trying to unravel.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** Heating, Cooling, and Cratering: One Asteroid's Complicated Story --Short Slide Summary (with accompanying notes).

- Göpel, C., Manhès, G., and Allègre, C. J. (1994) U-Pb Systematics of Phosphates from Equilibrated Ordinary Chondrites *Earth and Planetary Science Letters*, v. 121, p. 153-171.
- Kessel, R., Beckett, J. R., and Stolper, E. M. (2007) The thermal history of equilibrated ordinary chondrites and the relationship between textural maturity and temperature, *Geochim. Cosmochim. Acta*, v. 71, p. 1855-1881.
- Kleine, T., Touboul, M., Van Orman, J. A., Bourdon, B., Maden, C., Mezger, K., and Halliday, A. N. (2008) Hf-W thermochronometry: Closure temperature and constraints on the accretion and cooling history of the H chondrite parent body, *Earth and Planetary Science Letters*, doi:10.1016/j.epsl.2008.03.013.
- Lindsley, D. H. (1983) Pyroxene thermometry, *American Mineralogist*, v. 68, p. 477-493.
- Scott, E., Yang, J., and Goldstein, J. (2007) When Worlds Really Did Collide. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/April07/irons.html.
- Slater-Reynolds, V., and McSween, H. Y., Jr. (2005) Peak metamorphic temperatures in type 6 ordinary chondrites: An evaluation of pyroxene and plagioclase thermometry, *Meteoritics and Planetary Sci.*, v. 40, p. 745-754.
- Taylor, G. J., Maggiore, P., Scott, E. R. D., Rubin, A. E., and Keil, K. (1987) Original structures, and fragmentation and reassembly histories of asteroids - Evidence from meteorites, *Icarus*, v. 69, p. 1-13.
- Trieloff, M., Jessberger, E. K., Herrwerth, I., Hopp, J., Fiéni, C., Ghélis, M., Bourot-Denise, M., and Pellas, P. (2003) Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronometry, Nature, v. 422, p. 502-506.
- Zinner, E. (2002) Using Aluminum-26 as a Clock for Early Solar System Events. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Sept02/Al26clock.html