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Iron Meteorites as the Not-So-Distant Cousins of Earth

--- Numerical simulations suggest that some iron meteorites are fragments of the long lost precursor material that formed the Earth and other terrestrial planets.

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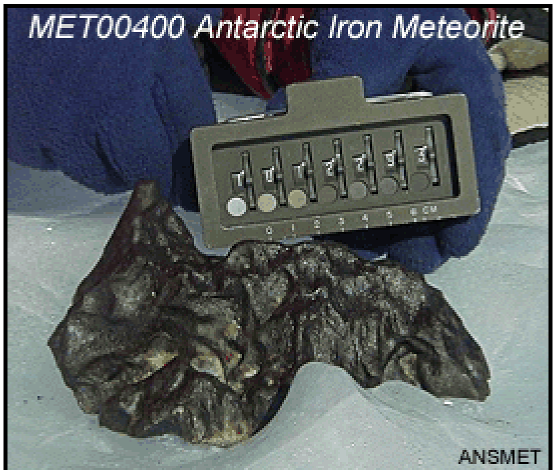


Photo of meteorite found by the '00-'01 ANSMET team in Meteorite Hills, Antarctica. Approximately 18 cm across.

Iron meteorites are fragments from the cores of small differentiated asteroids (20-200 kilometers in diameter) that formed very early in Solar System history. They are commonly assumed to have originated in the same region as most stony meteorite parent bodies, namely the main asteroid belt located between Mars and Jupiter. A new paper in the journal *Nature* by William Bottke, David Nesvorný, and Robert Grimm (Southwest Research Institute, Boulder, Colorado) along with Alessandro Morbidelli and David O'Brien (Observatoire de la Cote d'Azure, Nice, France), however, finds that the iron meteorites may have come from a different and possibly much more intriguing place. According to their numerical simulations that tracked the dynamical evolution of Moon- to Mars-sized planetary embryos interacting with tens of thousands of test bodies during the first 10 million years of Solar System evolution, many iron meteorite parent bodies formed and fragmented in the same region where Mercury, Venus, Earth and Mars are found today. The fast accretion times of planetesimals in this zone allowed heat produced by the decay of short-lived radioactive isotopes like ^{26}Al to melt and differentiate many of these objects into core, mantle, and crust. At the same time, gravitational interactions with planetary embryos increased their mutual impact velocities, enough that these planetesimals broke apart when they struck one another. The net result was the production of millions of fragments continually jostled about by planetary embryos. Over millions of years, a small fraction of this differentiated debris was scattered into the innermost region of the main belt, where it then stayed for billions of years until chance collisional and dynamical events sent it on a crash course to Earth. Bottke and colleagues' prediction of these asteroid main belt gatecrashers could mean that some of the iron meteorites we hold in our hands today are pieces of the same precursor fabric that formed the Earth and other terrestrial planets.

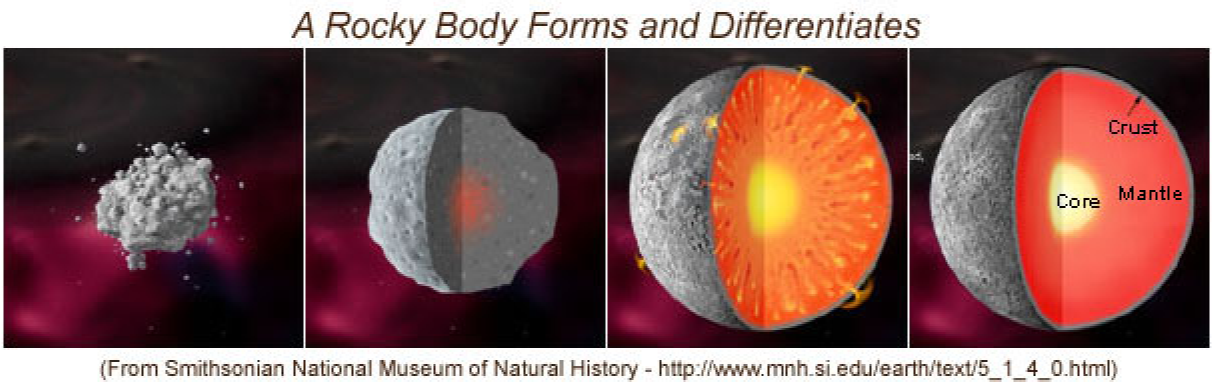
Reference:

- Bottke, W. F., D. Nesvorný, R. E. Grimm, A. Morbidelli, and D. P. O'Brien (2006) Iron Meteorites as Remnants of Planetesimals Formed in the Terrestrial Planet Region. *Nature*, v. 439, p. 821-824. [pdf link opens in a new window]

The Story Told by Iron Meteorites and Main Belt Asteroids

Numerical simulations have demonstrated that most of the stony and iron meteorites found today in worldwide collections came from asteroids in the main belt. For this reason, it is often taken as a given that their parent bodies formed there as well. This assumption, while reasonable for many meteorite types, does not do a very satisfying job of explaining the origin of the iron meteorites.

Most irons are pieces of the cores of distinct, small (20 to 200 kilometer-diameter) differentiated asteroids. We know this from chemical, petrographic (mineralogical and textural), and cooling rate studies of iron meteorites performed in laboratories. Very few irons are thought to be impact melts or fragments from a few, larger (>500 kilometer-diameter) differentiated bodies.



This series of graphics from the Smithsonian depicts the process of differentiation. Pictured left to right: Dust and grains clump together until a small body forms. The growing body heats up inside and begins to melt. Dense molten metal pools and sinks towards the center core of the body. Less dense silicate liquid, or magma, rises towards the surface, leaving dense residues of solid minerals in the mantle. The result is a differentiated body with a core, mantle, and crust. [Click image to view the source page.]

The fact that we have iron core fragments attests to the powerful collisions that repeatedly shattered their parent bodies during the early history of our Solar System. In our meteorite collections today, irons represent over two-thirds of the unique parent bodies sampled among all meteorites. This large percentage would suggest that differentiated parent bodies and their fragments are common in the main asteroid belt. The problem is there is little observational evidence to support this idea, and it's not for lack of looking.

Despite intense searches with telescopes equipped with cameras and spectrographs, the only clearly intact differentiated asteroid identified so far is (4) Vesta, the second largest asteroid in the main belt at 530 km diameter [see images from NASA's Hubble Space Telescope; link opens in a new window]. Spectroscopic observations of asteroid families (clusters of asteroid fragments with similar orbits produced by catastrophic collisions over the last several billion years) show few signs that their parent bodies had a distinct iron core nor a mantle/crust derived from melted rock. Instead, we see the opposite; most of the asteroid families investigated to date are made up of members with remarkably similar spectroscopic signatures.

While some main belt asteroids do look like fragments from differentiated bodies, the total number is relatively small when compared to our expectations based on the iron meteorite record. For example, only one asteroid is known to sample the crust of a Vesta-like but non-Vesta differentiated asteroid. It is called (1459) Magnya, and is a 20-30 km asteroid located in the outer main belt. Note that this body could also be an intact differentiated body. Similarly, main belt spectroscopic surveys have only identified 22 A-type asteroids, which many believe are mantle fragments from Vesta-like bodies, out of a sample of 950 objects. This material, which is likely composed of olivine-rich metal-free silicates, is mostly missing from our meteorite collection; this deficiency is often referred to as the "great dunite shortage." There have also been spectroscopic searches for the exposed cores of differentiated asteroids. The majority of the bodies with the right spectroscopic signatures to be iron cores (a set with diameter > 60 km), however, also show evidence for hydrated minerals, low densities, and/or radar signatures inconsistent with iron-rich material.

The story is further complicated by the very early formation age of iron meteorites. Researchers using hafnium-tungsten and aluminum-magnesium isotoptic dating techniques have reported the very interesting (and perplexing) result that core formation in iron meteorite parent bodies was nearly contemporaneous with the formation of the Ca-Al inclusions, some of the first solids to form in the Solar System. Iron meteorite core formation also predates the formation of those chondrules found in ordinary and carbonaceous meteorites by one to several million years. (See, for example, **PSRD** article: Dating the Earliest Solids in the Solar System.) Bottke and colleagues argue that if small asteroids differentiated in the main belt at such early times, it is reasonable to expect that larger bodies forming nearby would also differentiate, leaving the inner main belt literally teeming with such bodies. According to their numerical results, there is simply no reasonable way to get rid of all of this evidence.

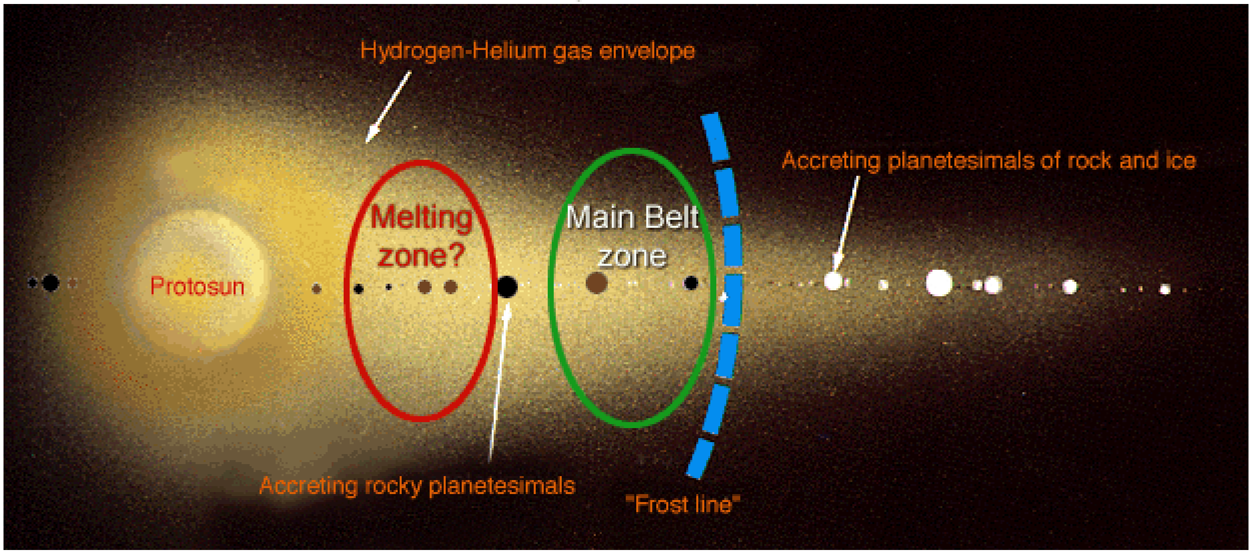
To sum up, the iron meteorites tell us that small differentiated asteroids were once common and they formed very early, while asteroid observations suggest that little differentiation ever occurred in the main belt region. Somehow, we have to reconcile these different stories.

Formation Location Closer to the Sun than the Main Asteroid Belt

Bill Bottke and his colleagues are tackling the puzzle of iron meteorites using their expertise in modeling the formation and evolution of asteroids and meteoroids. By considering the ways that asteroid parent bodies formed, heated, collided, fragmented, and scattered, they make the case that the formation location of most iron meteorite parent bodies was outside the asteroid main belt, and most likely in the terrestrial planet region. It is an idea that was first postulated in 1979 by John Wasson (UCLA) and George Wetherill (Carnegie Institution) based on meteorite evidence and has now been updated using models of the collsional, dynamical, and thermal evolution of asteroids.

To address the formation the iron meteorite parent bodies, we first need to understand why small bodies differentiate and where this is most likely to take place. According to various studies, planetesimals are predominantly heated by the decay of short-lived radionuclides like ^{26}Al (and ^{60}Fe.) (See **PSRD** article: Asteroid Heating: A Shocking View for more about heating with ^{26}Al.) Because ^{26}Al decays rapidly (half-life = 0.73 million years) and small bodies lose heat quickly, only the fastest-growing bodies have a chance to melt. According to planetesimal formation models, growth is a function of distance from the Sun and swarm density. This means that until we reach the snowline (the orbital distance beyond which water ice is stable), the fastest-growing bodies are closer to the Sun than farther away from the Sun. Combining these ideas with the very early core formation times of the iron meteorite parent bodies, Bottke and colleagues deduced that the iron meteorite parent bodies may very well have formed in the terrestrial planet region.

Solar System Formation



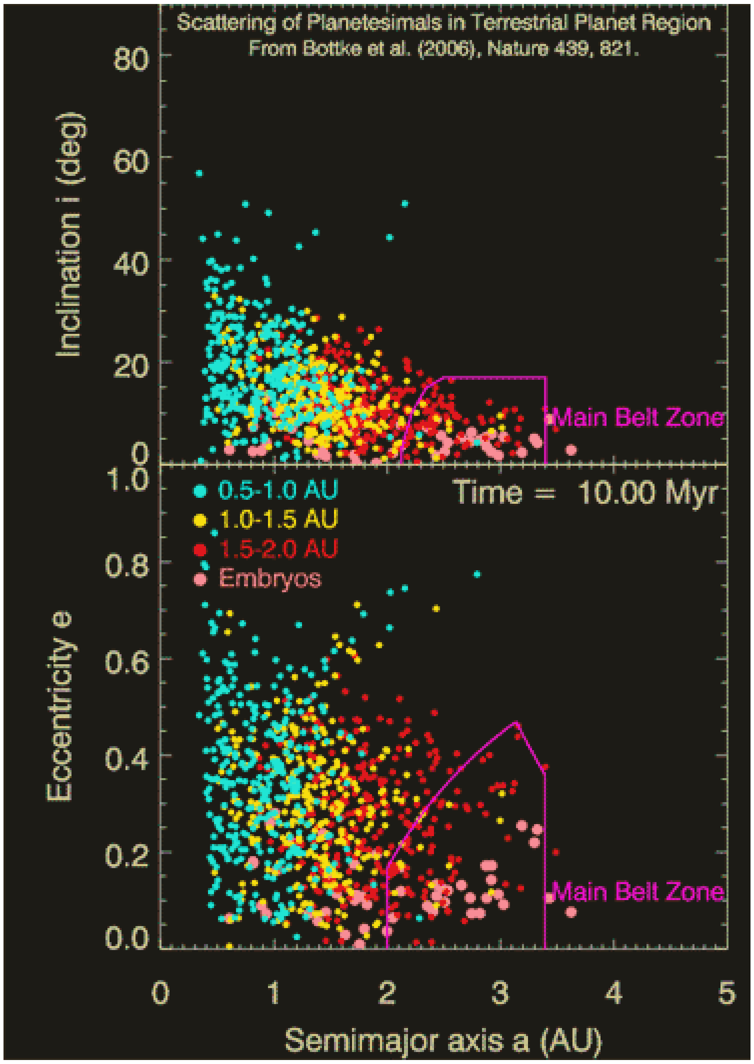
(Background graphic courtesy of Windows to the Universe, http://www.windows.ucar.edu
Ellipses added for emphasis.)

During early Solar System formation, iron meteorite parent bodies may have formed in a zone where melting and differentiation were likely to take place; a zone closer to the Sun than the asteroid main belt zone.

Evolution, Delivery to Main Belt, and Survival

The formation of the terrestrial planets started with the accretion of roughly kilometer-sized planetesimals out of the solar nebula. Some of these bodies experienced "runaway growth," a phase where the largest body in a given feeding zone takes advantage of its larger gravitational cross section to rapidly agglomerate all of the remaining nearby planetesimals. Over time, this leads to a period where the inner Solar System, which includes the main belt region, is shared by both Moon- to Mars-sized planetary embryos and planetesimals whose size distribution has roughly the same shape as that found in the main asteroid belt.

The dynamics of how these bodies evolved and where they went in the early phases of Solar System history can be modeled using computer simulations. Bottke and coauthors tracked tens of thousands of bodies that evolved amid a swarm of protoplanets spread between 0.5-3.0 AU (where 1 AU is defined as the average distance between Earth and Sun). Some of the intact bodies, and certainly their fragments, are shown to have scattered to stable regions in the asteroid main belt (located ~2.1 to 3.4 AU.) See the animation shown below.



The plots on the left show 10 million years of evolution for 1,000 test bodies at a time when Jupiter had not yet formed. [The animation repeats.]

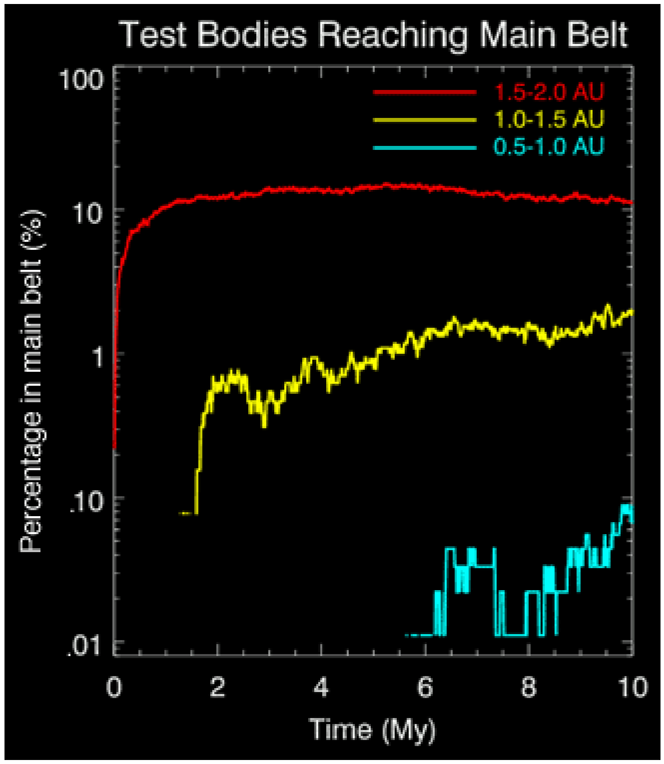
The test bodies were initially placed in three zones away from the Sun, indicated on the x-axis as Semimajor axis a (AU): **0.5-1.0 AU**, **1.0-1.5 AU**, and **1.5-2.0 AU**. In addition, planetary embryos (colored pink) were initially placed between 2.0-3.2 AU. The y-axis describes the eccentricity and inclination of the bodies. Eccentricity e defines the orbit's shape, and can be thought of as the ellipticity of the orbit where the Sun is placed at one focus. Circular orbits have e = 0, while parabolic orbits have e = 1. Inclination is defined as the angular distance of the body's orbital plane from the reference plane of the Solar System (often considered the ecliptic plane) in degrees. The asteroid main belt zone is outlined in bright purple.

Watch how the test bodies move over time due to their gravitational interactions with the embryos. The test bodies are assumed to have no mass. Encounters with embryos scatter the test bodies away from their initial zones and spread their semimajor axis distribution.

Almost immediately, we see test bodies from the **1.5-2.0 AU** region enter the stable, main belt zone through gravitational interactions with planetary embryos. Bodies from the **0.5-1.0 AU** and **1.0-1.5 AU** regions also reach the main belt zone, but not until several millions of years have passed.

Note that many of the gatecrashers go to the inner main belt (2-2.5 AU), the region where dynamical models indicate the vast majority of meteorites come from.

The figure below shows the fractions of test bodies, from different initial zones in the inner Solar System, that reach the main belt by gravitational interactions with planetary embryos. Bottke and colleagues conclude from this that it is plausible that the current main belt contains samples from the feeding zones of Mercury, Venus, Earth, and Mars. Moreover, most of these bodies are injected into the inner main belt, the same region that, according to dynamical models, produces the most meteorites. This fact that meteorite delivery mechanisms are biased in favor of material from this region may help explain the unusual diversity of iron meteorites in worldwide collections.



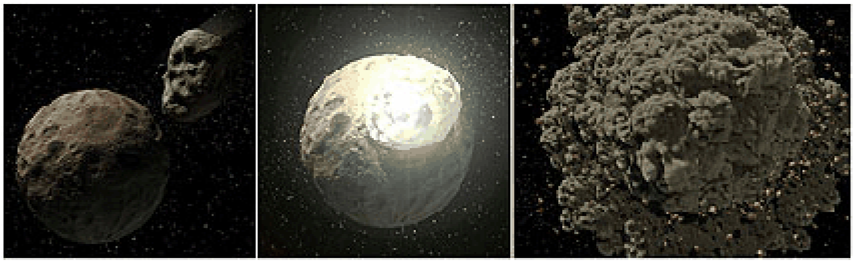
(From Bottke *et al.*, 2006, *Nature*, v. 439, p.821.)

The curves in the plot, above, were generated by tracking 17,000 test bodies for 10 million years. Ten percent of the bodies from the **1.5-2.0 AU** zone (red curve) reached the main belt after one million years. About one percent of the bodies from the **1.0-1.5 AU** zone (yellow curve) reach the main belt after a longer delay of two million years. And only 0.01-0.1% of bodies from the **0.5-1.0 AU** zone reach the main belt after six million years.

We know that collision probabilities and impact velocities of the bodies striking one another (see graphic below, left) increase closer to the Sun. Bottke and colleagues found that most 20-kilometer-diameter bodies at <1.5 AU break up quickly enough (graphic, right, lower two curves) that few reach the main belt zone. This helps explain the apparent absence of small, intact differentiated bodies in the main belt today. Because each break-up produces millions of fragments, however, it is statistically likely that some portion of the debris made its way into the main belt region. The 20 kilometer bodies scattered in from 1.5-2.0 AU have a better chance of reaching the main belt, but their distance from the Sun implies longer formation times and hence the increased likelihood that they never differentiated.

Finally, these results show that if small differentiated bodies had once formed in the main asteroid belt, a large fraction would still be around today. So far, none have been observed. This raises the bar for models that would create iron meteorite parent bodies in the main belt and then eliminate the evidence by collisional and/or dynamical processes.

Rocky Bodies Collide

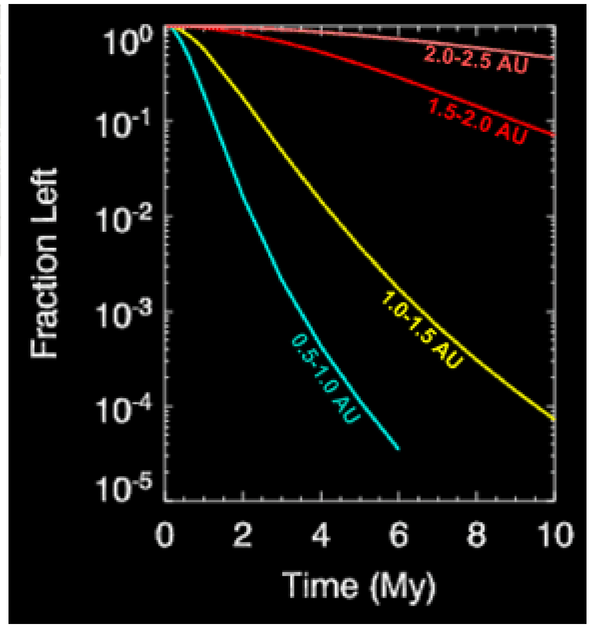


Courtesy of Spitzer Space Telescope. NASA/JPL-Caltech/T. Pyle (SSC-Caltech)

What would a catastrophic collision between two bodies look like? Pictured **above** is an artist's rendition of a collision sequence, from left to right, between two rocky bodies that produces millions of fragments.

The plot on the **right** focuses on 20-kilometer-diameter bodies. Between 0.5-1.5 AU they disrupt quickly; only their fragments reach the main belt. Bottke and colleagues say these results help explain the paucity of small intact differentiated bodies in the main belt today.

20-km-diameter Test Bodies That Survive the First 10 Myr of Collisional Evolution



(From Bottke *et al.*, 2006, *Nature*, v. 439, p.821.)

Gatecrashers: From Here to There and Back Again

Bottke and coauthors have shown using numerical simulations how the iron meteorite parent bodies and their fragments could have started here in the inner Solar System before being scattered out to the main belt. Still, the results of this model beg the following question: if it works for irons, shouldn't it also work for the stony component of the differentiated asteroids? In other words, if fragments of crust, mantle, and core were indeed main-belt gatecrashers, it is logical to ask why so few olivine and basaltic meteorites (mantle and crust material, respectively) from sources other than asteroid (4) Vesta are found in the meteorite collection.

To address this issue, Bottke and colleagues used yet another computer model to track the evolution of a hypothetical population of olivine (A-type) asteroids in the inner main belt. They concluded there are simply not enough A-type asteroids in the inner main belt to keep a healthy population of olivine meteoroids replenished by a collisional cascade over 4.5 billion years. Instead, they report these asteroids were steadily eroded over time by collisions and dynamical depletion processes, such that the current population, while non-negligible, is statistically unlikely to produce a significant number of present-day meteorites.

For iron meteoroids, which represent our core fragments, the main belt survival and delivery situation is substantially different. For example: (1) irons are roughly 10 times stronger than stones, meaning they are less susceptible to disruption and are more likely to survive atmospheric entry to Earth, and (2) irons drift roughly 10 times more slowly than stones in space by thermal radiation forces (i.e., the Yarkovsky Effect, a thermal thrust produced when small bodies orbiting the Sun absorb sunlight, heat up, and reradiate the thermal energy after a short delay produced by thermal inertia. Because iron conducts heat better than stones -- think of how your iron skillet retains heat so well -- the temperature variation across the surface of an iron meteoroid is smaller, which in turn reduces the efficiency of the Yarkovsky effect at moving these objects in space.) Taken together, the researchers surmise that the population of small iron asteroids in the inner main belt has probably not changed much over the last four billion years.

In the movies, for example "At the Earth's Core" (1976) and "The Core" (2003), humans often go to extraordinary (and mostly implausible) efforts to reach Earth's core. It is interesting to consider the possibility that our iron meteorite collection could save us the trip, in that they may actually be samples of the same kinds of materials now contained thousands of kilometers below our feet.

Movie posters of imaginary worlds and a diagram of the real world.

Accordingly, if we can place the known iron meteorites into the appropriate Solar System context, it may eventually be possible to use them as probes into the unknown and perhaps forever unreachable materials located within the deep interiors of Mercury, Venus, Earth, the Moon, and Mars. Studies like these by Bottke and colleagues show clearly the extraordinary benefits of combining laboratory analyses of meteorites, astronomical observations of asteroids, and numerical modeling of asteroid formation and evolution.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Bottke, W. F., D. Nesvorný, R. E. Grimm, A. Morbidelli, and D. P. O'Brien (2006) Iron Meteorites as Remnants of Planetesimals Formed in the Terrestrial Planet Region. *Nature,* v. 439, p. 821-824. [pdf link]

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