Chapter 7: **Surfaces of terrestrial objects: cratering & other exogenic processes; meteorites**

- impacts: introduction
- dust, sputtering
- crater formation, surface ages, terrestrial craters
- meteorites
- sample problems

Impacts

Impacts happen. That may not always be obvious, especially on objects with ongoing volcanic or cryovolcanic resurfacing, such as Earth, Io, Europa, Triton, etc.. On the Moon or Mercury or Callisto, i.e., on objects without much recent resurfacing, it's a lot more obvious. Or, at least it's more obvious today. In the early 1960s geologist Eugene Shoemaker made some of the first significant efforts to bring the principles of geology to bear on the study of extraterrestrial surfaces. Shoemaker could be considered one of the first planetary geologists, in large part for his work with impact craters and his realization that most of the craters on the Moon were of impact origin rather than being volcanic structures. One area of research in these recent decades has been to characterize the population of impactors and how that population has changed over the history of the solar system.

There are many more small objects in the solar system than large ones. It makes sense to expect that trend to continue all the way down to dust, meaning that in terms of the number of impactors, we expect a lot of dust and very few 10-km-sized asteroids. It might also be reasonable to expect that there's a finite number of large impactors and that over the history of the solar system, the rate at which the Earth, Moon, etc., have been hit by large objects has declined. That might not be a valid assumption if, for instance, the solar system regularly encountered interstellar clouds of rock that served to re-populate the numbers of km-sized impactors. Samples of interplanetary dust, meteorites, and lunar rocks show some evidence of influence from outside the solar system but not a lot. We can also look at crater sizes, erosion, and ages, where we find that the largest craters (which presumably come from the largest impactors) tend to be older. In other words, we're fairly safe assuming that there are more small impactors than large and that the number of things we might run into has declined over the age of the solar system.

Solar system dust

Let's consider the small stuff first. Dust grains in the solar system range from large molecules up to particles a millimeter or so in size. There are no firm distinctions on that at either end, neither between large gas molecules and small dust grains nor between large dust grains and small meteoroids. Dust grains might be ancient, dating from the origin of the solar system, but recall that radiation pressure and Poynting-Robertson drag act to remove dust grains over timescales that are short with respect to the age of the solar system (generally less than 1 billion years), so we expect that the population of dust grains has to have been replenished. We know from meteor showers that comets are one source of dust. Another, more significant source of dust, is collisions. Asteroids collide, short-period comets break up (think Shoemaker-Levy-9 interacting with Jupiter), meteoroids colliding with small moons can easily kick off small particles. Sputtering, in which airless surfaces are hit by energetic photons or solar wind particles, can kick off dust grains. Studies of interplanetary dust grains show that some of them, ~0.1%, are interstellar grains that have been swept up by the solar system as we pass through the local interstellar medium. Most of the dust lies relatively near the ecliptic (recall the zodiacal light, where we see sunlight reflected from interplanetary dust). The dust also emits in the infrared, which both helps to constrain the grain sizes and to estimate the total amount of dust. Estimates of that total amount of dust in the solar system today suggest a mass of $\sim 10^{16}$ kilograms, or about the equivalent of a modest asteroid, perhaps 10-20 km in radius. That may be an underestimate and may not adequately capture the amount of both dusty and icy grains in and beyond the Kuiper Belt.

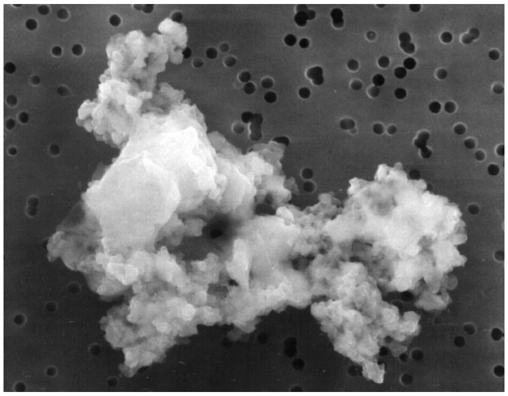


Figure 7.1: Interplanetary dust grain. This 10-micron grain was collected in Earth's stratosphere by a U2 aircraft. It is composed of silicates and carbon, meaning that it resembles primitive meteorites.

http://stardust.jpl.nasa.gov/science/sd-particle.html

How much dust hits the Earth every day? That's hard to determine. Estimates range from fewer than 10 metric tons to several hundred metric tons of dust per day. Dust grains are usually fluffy, as shown in the image above. When they hit the Earth's atmosphere they tend to slow rapidly to a terminal velocity that's low enough that the grains, fragile though they are, don't disintegrate. Instead, they float gently to the ground like so many silicate snowflakes. In other words, interplanetary dust grains don't tend to make observable meteors and they don't tend to look any different from any other bits of dust once they hit the ground.

Dust grains hitting airless objects don't slow down and they hit hard enough to erode sharp edges, meaning that older craters will look a bit soft compared to newer craters. By way of example, here's an image of the lunar crater Tycho, which is one of the youngest large craters on the Moon – it's estimated to be a bit more than 100 million years old – and next to it the crater Pictet, very much older and worn down.

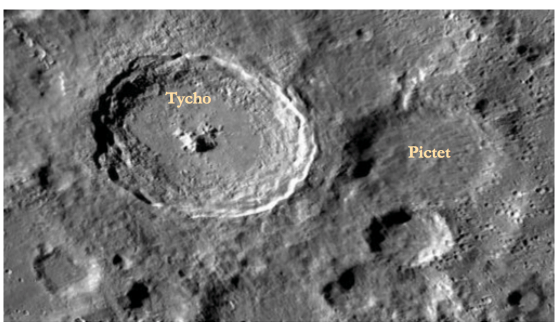


Figure 7.2: Young and old lunar craters.

NASA / ASU – Lunar Reconnaissance Orbiter
http://lroc.sese.asu.edu/posts/298

The dust grains build up on the surface and, along with the general rubble created from the broken remnants of surface rocks and larger impactors, make the *regolith*, a loosely compacted layer of surface material. Prior to the first spacecraft landing on the Moon it wasn't clear whether the regolith would be compacted at all or whether the spacecraft would sink, as if hitting quicksand.

One of those early spacecraft was the unmanned Surveyor 3, which bounced on landing. It transmitted television pictures for about two weeks before getting too cold during the long lunar night. Two and a half years later, the Apollo 12 mission landed near enough to the Surveyor 3 site for astronauts Alan Bean and Charles "Pete" Conrad Jr. to visit the Surveyor on a moonwalk and retrieve a few pieces to study the effects on the spacecraft of long exposure to space. The image below shows the way the regolith compacted slightly when the Surveyor 3 bounced.

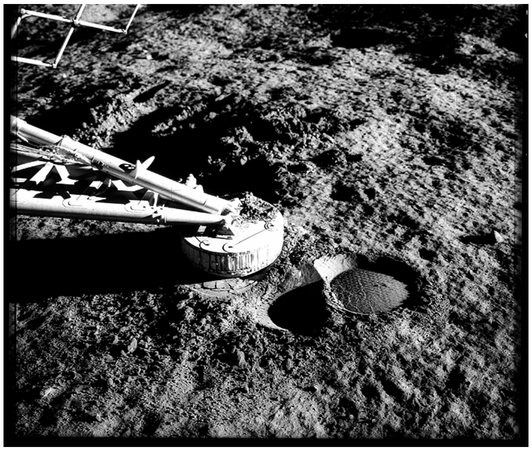


Figure 7.3: Lunar regolith
In November 1969 Apollo 12 landed near the site where the Surveyor 3 spacecraft had landed in April 1967. This photograph was taken by astronaut Alan Bean during a moonwalk.

NASA / Apollo 12
http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/a12_h_48_7110.html

The lunar dust is quite powdery and stuck to the astronauts' space suits. This is an image of Conrad, taken by Bean, during a moonwalk. Note how dusty the lower legs of Conrad's spacesuit are.

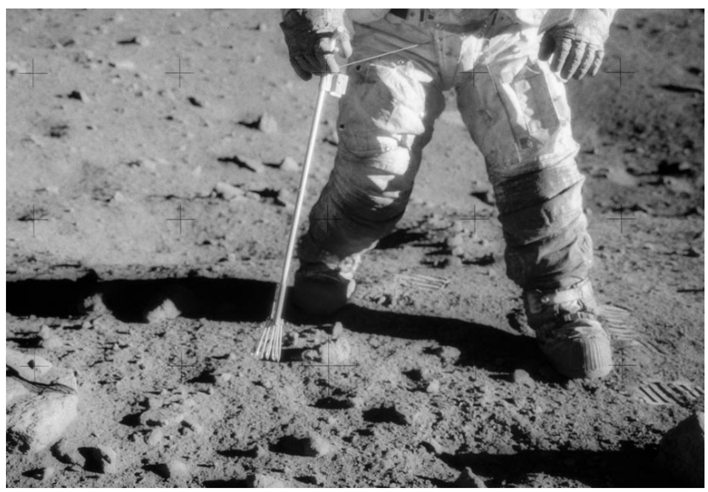


Figure 7.4: Lunar dust.

NASA / Apollo 12
http://www.nasa.gov/multimedia/imagegallery/image_feature_955.html

Phoebe, shown in the image below, is the largest of Saturn's outer satellites, at a bit more than 200 km diameter. Its orbit is fairly eccentric ($e = 0.16$) and it's inclined ~150 degrees to Saturn's equator (i.e., it's retrograde). Phoebe is on average very dark (albedo ~ 0.06) but some of the features have bright spots, suggesting the presence of clean ice not too far below the surface. Phoebe's irregular orbit, albedo, battered surface, and rock : ice ratio (its density is 1.64 g/cm^3) suggest to some that it could be a captured Centaur, i.e., an object that has migrated inward from the Kuiper Belt. Phoebe orbits Saturn at a distance of about 13 million km. So does a ring. The Phoebe ring was discovered through its infrared emissions by the Spitzer Space Telescope. The ring shares Phoebe's orbital inclination and may have been created by particles knocked off of the surface of Phoebe that have spread out into a tenuous but widely extended ring. (The Phoebe ring extends from ~100 to ~270 Saturn radii – Phoebe, given its orbital eccentricity, ranges between ~180 to 250 Saturn radii – and vertically ~40 Saturn radii, larger in both dimensions than any of the inner rings.)

Figure 7.5: Phoebe

NASA / JPL / Space Sci. Institute – Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA06073

As with dust in the inner solar system, dust grains in the Phoebe ring experience drag and will migrate inward toward Saturn, quite possibly colliding with the next innermost moon, Iapetus.

It's an appealing picture, Phoebe's dust making Iapetus' leading side dark, but it may be too simple. The low-albedo side of Iapetus is a bit too red to match the color of Phoebe. It's possible that dust from Phoebe contributed to lowering the albedo on the leading side of Iapetus and that low albedo in turn, by absorbing more sunlight, contributed to the sublimation of surface ice, leaving a mix of dust from Phoebe and Iapetus' own dark, reddish, rocky material. The ice molecules might not have had enough energy to escape from Iapetus but rather energy enough to bounce / hop to the colder poles and build up on the bright trailing side.

Dust grains, hitting an airless surface with nothing to slow them down, leave miniature impact craters. Rocks brought back by the Apollo astronauts and sample surfaces left exposed to space for known lengths of time (e.g., pieces of Surveyor 3 mentioned above, or the Long-Duration Exposure Facility (LDEF) which spent nearly 6 years in space) show impact craters left by micrometeorites. Here, for instance, is a micrometeorite crater on a lunar rock.

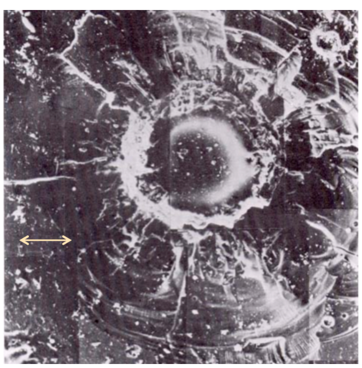


Figure 7.6: Microcrater and surrounding fractures on Apollo lunar basalt sample 12054. The line is 100 microns.

http://curator.jsc.nasa.gov/lunar/lsc/12054.pdf

Crater formation

An impactor will hit with a speed equal to the escape speed of the target plus any extra speed due to differences in orbital velocity minus any speed lost to air resistance. Earth's escape speed is 11 km/sec; for the Moon, it's 2.4 km/sec. Our orbital speed around the Sun is ~30 km/sec; an object in a retrograde orbit could be going as fast as escape speed from the Sun at 1 AU (any faster and it should already have escaped) which is ~42 km/sec, so the maximum impact speed with the Earth should be ~72 km/sec. The sound speed in surface rock, or surface ice, is less than 10 km/sec. Impacts that form substantial craters are thus generally going to be hypersonic, meaning that the impactor hits the surface moving faster than the local speed of sound. Shock waves result, creating an explosion in which both the surrounding target material and the impactor are compressed and shattered, resulting in debris that behaves much like a fluid and a crater that is much larger than the size of the impactor. Exactly how much energy is released in the impact depends on the collision speed and on the densities of the impactor and the target. So does the morphology of the final crater. Crater morphologies fall into roughly four types:

– The tiniest craters, called microcraters or zap pits, such as that shown above, are round, not much modified after the impact, and only found on airless objects.

– Simple craters are bowl shaped. Material falls back into the initial hole, leaving a crater that's approximately 5 times wider than it is deep, with a rim height ~1/25th the crater diameter.

– Complex craters are larger, ranging in diameter from tens to hundreds of kilometers. A sizeable portion of the crater floor is fairly flat, there's a rebound peak, or ring of peaks, in the center, and the crater rim is likely to have slumped into a series of terraces. The transition from simple to complex craters occurs in the 10-20 km size range, although exactly where that transition occurs depends inversely on the target gravitational acceleration – higher gravity means a higher-energy collision for a given size impactor and thus a more complex crater than we'd get with lower surface gravity.

– Even larger impacts result in multi-ring basins, in which waves have rippled outward from the impact site and frozen in place. We will look at some examples below.

Crater formation begins with the compression phase that follows the contact between the impactor and target; that's followed by the ejection of debris and excavation of the crater; the last phase is post-impact modification. The following two sets of sketches from the Lunar and Planetary Institute illustrate these steps for simple (left-hand side) and complex (right-hand side) craters.

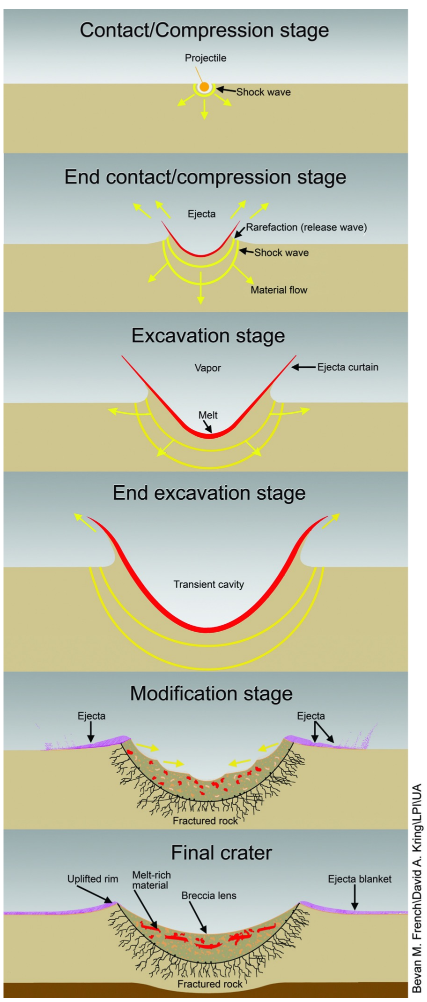
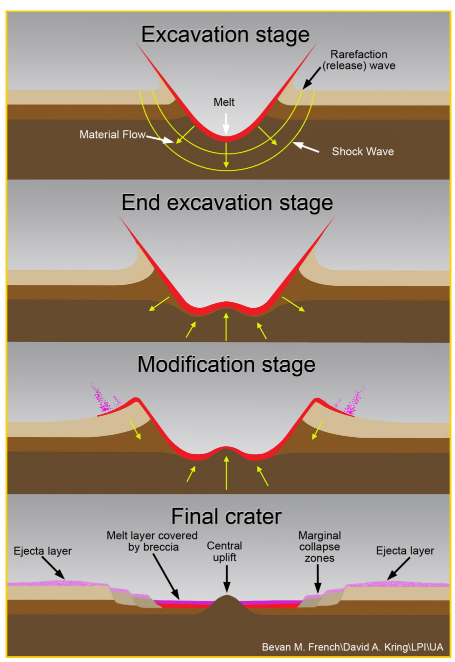


Figure 7.7: Formation of simple (left) and complex (below) craters.
A *breccia* is rock made of broken rock fragments that have been cemented together.

http://www.lpi.usra.edu/exploration/training/illustrations/craterFormation/



The size of the transient crater, before any slumping, depends on the strength of the material making up the impactor and the target surface as well as the impactor size, speed, surface gravity of the target; the diameter tends to scale approximately with impact energy as $D \propto E^{1/3}$. Because of the explosive nature of the impact, craters tend to be round for a wide range of impact angles, although grazing impacts will make elliptical craters. On Earth, craters formed by rocky meteoroids will make craters that are about 10 times the size of the impactor. Complex craters on the Moon have central peaks that rise up to about 3 km above the crater floor; peak height is normally lower than the crater rim.

The three images below are of lunar nearside craters illustrating these various morphologies. Rosse, on the left, is a simple crater with a diameter of 12 km. Theophilus, center, is 104 km across; note the central peaks and the slumped terraced rim. On the right is Mare Orientale; its outer ring has a diameter of ~930 km, although there are hints of a larger ring, ~1300 km across, not shown in this image.

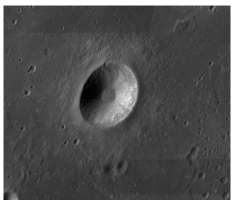
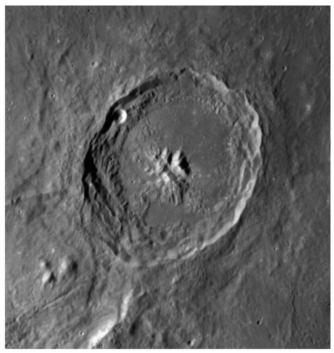
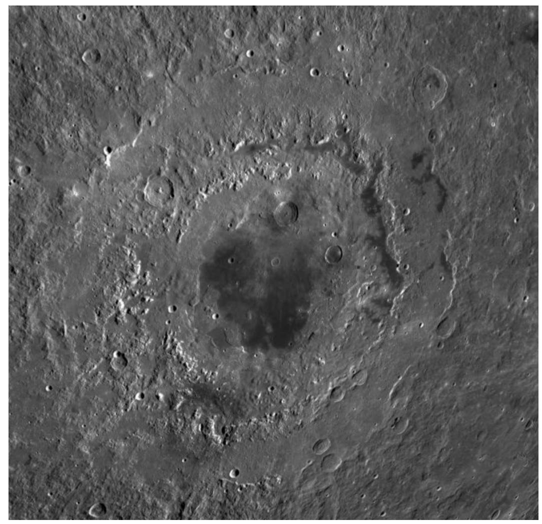


Figure 7.8: Lunar craters Rosse and Theophilus, and multi-ring basin Mare Orientale

http://photojournal.jpl.nasa.gov/catalog/PIA14011



NASA / GSFC / ASU – Lunar Reconnaissance Orbiter



Ejecta from crater excavation flops over the crater rim into an ejecta blanket; some pieces may themselves get thrown some distance and, if large enough, make secondary craters. Hokusai is an 85-km-wide complex crater on Mercury displaying a central ring of mountains. The smaller pits in radiating outward in streaks away from Hokusai are secondary craters.

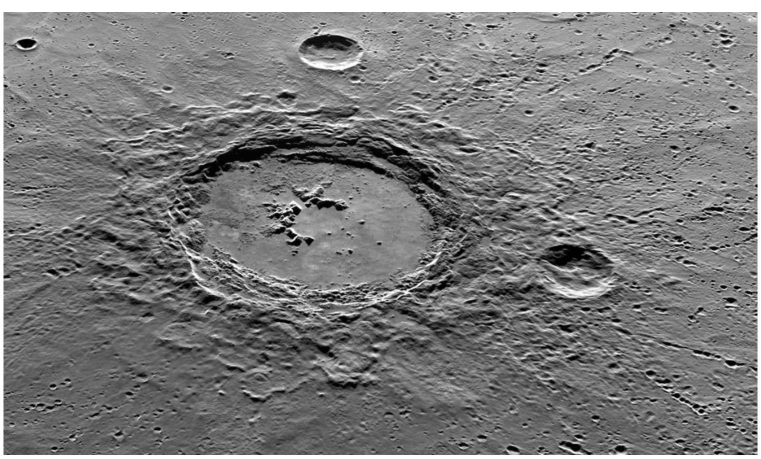


Figure 7.9: Crater Hokusai on Mercury

NASA / Johns Hopkins APL / Carnegie Inst. – MESSENGER spacecraft

http://photojournal.jpl.nasa.gov/catalog/PIA18683

Crater rays are formed when relatively recent broken rock catches the sunlight. Crater ejecta, and some of the surface rock hit by the ejecta, fractures, exposing clean sharp new crystal faces. Over time these surfaces darken, as the minerals are hit and damaged by solar UV or fractured or simply covered by micrometeorite impacts. Moderately large young craters can have rays that extend many hundred of kilometers, or about 10 times the crater's diameter. The following is an image of Mercury including the crater Xiao Zhao. It's about 24 kilometers diameter, large enough to have a central peak but clearly not the largest crater in this field. Xiao Zhao's rays (and crisp rim) indicate that it's a relatively young crater.

Figure 7.10: Crater Xiao Zhao, Mercury

NASA / Johns Hopkins APL / Carnegie Inst. – MESSENGER spacecraft

http://photojournal.jpl.nasa.gov/catalog/PIA10668

Impactors don't always hit rock. Mars has enough subsurface water, particularly at high latitudes, that the impact energy turns the target material into mud. The resulting crater is called a rampart crater, or, less formally, a splosh crater. A classic example is the crater Yuty, seen here in a Viking 1 Orbiter image.

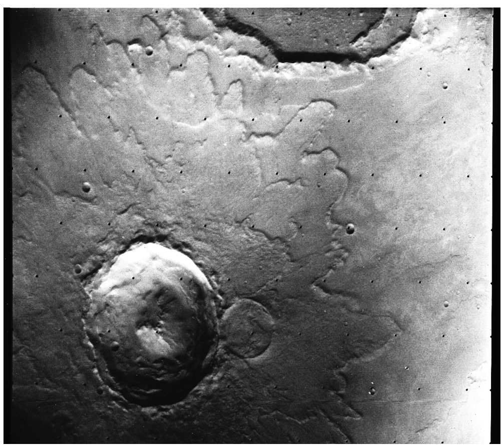


Figure 7.11: Yuty, Martian rampart crater, showing the lobate ejecta characteristic of rampart craters.

NASA / JPL - Viking 1 Orbiter

http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vo1_003a07.html

Craters on icy objects such as Ganymede and Callisto display evidence that their surfaces are not as rigid as, say, the Moon or Mercury. Some of the largest craters on Ganymede have relaxed – the ice is soft enough to flow, leaving only an albedo feature known as a palimpsest, such as the one called Memphis Facula shown in the following image.

Figure 7.12: Memphis Facula on Ganymede; this bright palimpsest is ~344 km diameter.

NASA / JPL – Voyager 2
http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vg2_2063702.html

Also faintly visible in this image are ripples from a long-ago multi-ring basin. Valhalla, on Callisto, is a good example of a multi-ring basin on an icy object.

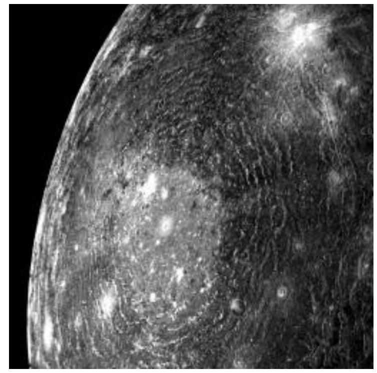


Figure 7.13: Valhalla, multi-ring impact basin on Callisto; the diameter of the ring system is ~3,800 km.

NASA / JPL – Voyager 1

http://photojournal.jpl.nasa.gov/catalog/PIA02277

In ice, the ripples are close together and fairly evenly spaced. Compare this to the image of Mare Orientale, on the Moon. In rock, the ripples get farther apart.

Not all icy objects' craters will relax – here are some sharp-looking craters on frigid Charon.

Figure 7.14: Charon's craters; image is ~260 km wide.

NASA / JHUAPL / SRI – New Horizons spacecraft
http://pluto.jhuapl.edu/Multimedia/Science-Photos/view.php?gallery_id=2

As previously mentioned, the near and far sides of our Moon have had different impact histories. The majority of the lunar maria, huge lava-filled basins, are on the Earth-facing side. The largest impact basin, though, is on the far side and is not filled with flood basalts: the South Pole - Aitken Basin (SPA) is so named because it stretches from the lunar south pole to the crater Aitken, a distance of roughly 2,500 km. In the image below, SPA shows up as a distinctly darker roughly circular patch. Why the difference, i.e., what combination of impact ages, impactor trajectories, surface compositions, crustal thicknesses, etc., could account for the lack of extensive volcanic regions on the lunar far side, generally, and SPA, more specifically, is an ongoing area of lunar research. In an effort to help address the nature of SPA, in early 2019 a Chinese spacecraft, Chang′e-4, landed in the Von Kármán crater within SPA and deployed a rover, Yutu-2, equipped to perform several types of observations of surface and near-surface rock. Early spectroscopic results suggest the presence of olivine and a low-Ca form of pyroxene, minerals that are expected to be part of the lunar mantle. Rocks from the near-side highlands, in comparison, are rich in lower-density plagioclase feldspars. This suggests that the SPA impact may have penetrated the lunar crust, bringing mantle material to the surface. And if that's the case, we still have the question of why SPA didn't fill with flood basalts as so many of the major near-side impact basins did. Sample return missions from various regions on the lunar far side would undoubtedly help clarify the Moon's impact history.

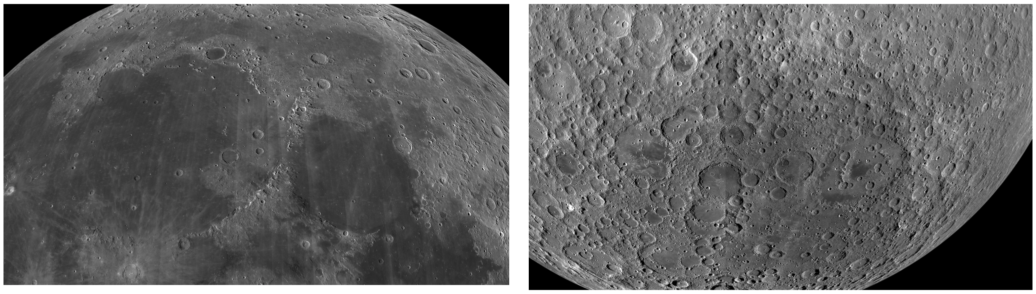


Figure 7.15: Mare Imbrium and Mare Serenitatis on the near side (left) and the South Pole - Aitken basin on the far (right) side of the Moon. Credit: NASA / GSFC / Arizona State University. Lunar Reconnaissance Orbiter mosaics. http://lroc.sese.asu.edu/posts/298

Crater density and surface age

As examples of the extremes of possible surface ages, compare volcanic Io, continually resurfacing itself, with Callisto, whose surface is totally saturated with impact craters. On any given objects, regions with lots of craters are relatively older than regions with few craters. The following image is of Enceladus' northern hemisphere. The region near the limb is more heavily cratered than the region on the left-hand side of the image. It may be the case that some satellites tidally locked on a planet do get hit preferentially on one side, but here it's a more reasonable explanation that the smoother plains have been resurfaced more recently than the cratered regions.

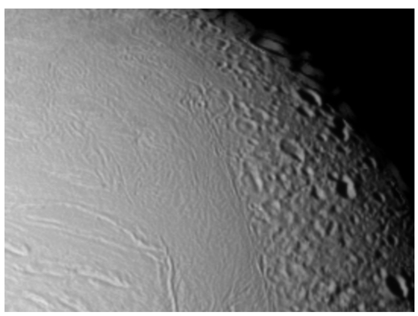


Figure 7.16: Enceladus – resurfacing on the left, craters on the right.

NASA / JPL / Space Sci. Institute – Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA12673

At some point the number of craters on the surface of a cold object, i.e., one where there is no resurfacing, should reach an equilibrium. On such a saturated surface, making a new crater means obliterating an older crater. Callisto is close to saturated, as are the lunar highlands; the following image is of the heavily cratered trailing hemisphere of Saturn's moon Tethys.

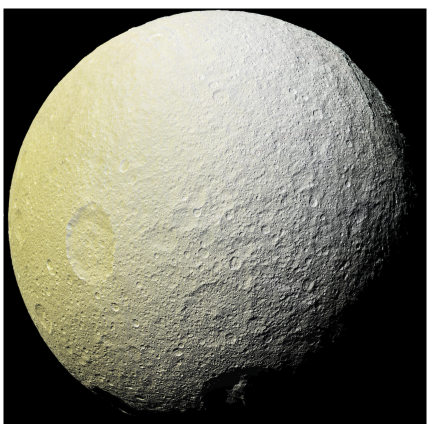


Figure 7.17: Tethys

NASA / JPL / Space Science Institute – Cassini spacecraft
http://photojournal.jpl.nasa.gov/catalog/PIA19636

Saturated surfaces seem to be at least 3.5 billion years old, and possibly 3.9 billion, although it is not easy to get a definitive picture of the cratering history of the solar system in its first billion years. The dominant view is that during and just after planet formation the cratering rate was high, that it falls with time, and that the rate of cratering today is nearly constant.

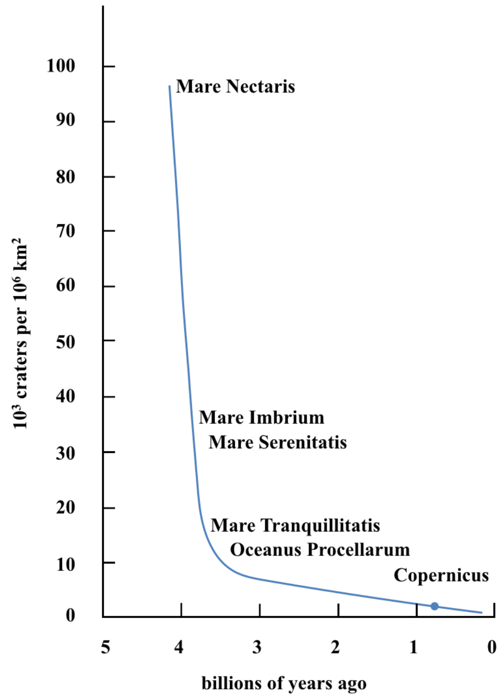


Figure 7.18: Estimated rate of lunar cratering, along with approximately the times at which several of the maria were formed and the crater Copernicus.

A topic of current research and debate among planetary geologists is the question of whether there was a "late heavy bombardment" at ~3.9 billion years ago. There is agreement about the fact that there were many impacts occurring at that time. There are, for instance, lunar rock samples that show evidence of melting from the shock heating during impacts. What is unclear is whether there was a spike in the impact rate at around 3.9 billion years ago or whether there was simply a generally high level of cratering occurring for the first roughly half a billion years of the solar system.

A standard method for displaying the cratering density on a surface is to plot the number of craters per square kilometer in diameter increments vs. crater diameter, i.e., construct a size-frequency distribution. For the Moon we can compare the crater density in various regions – e.g., the maria vs. the highlands – with the measured ages of Apollo rock samples. We can also compare the size-frequency distribution for craters with the size-frequency distribution for asteroids and meteoroids, as that should represent the likely population of impactors (recognizing the fact that large impactor produces multiple craters, in that a large impact yields ejecta blocks that produce a field of smaller secondary craters). A source of error on objects with at least some atmosphere is dust. Those dust storms on Mars, for instance, will tend to fill in craters somewhat, possibly obliterating smaller ones. William Hartmann is an expert on crater size-frequency distributions and one of the first to use lunar farside images in the 1960s to count craters in the oldest ("uplands") regions on the surface of the Moon. The following sketch of a size-frequency distribution for the oldest farside regions of the Moon is based on some of his work from the 1980s. The numbers of large craters, more than ~5 km diameter, are ~30 times the number of large craters on the nearside maria.

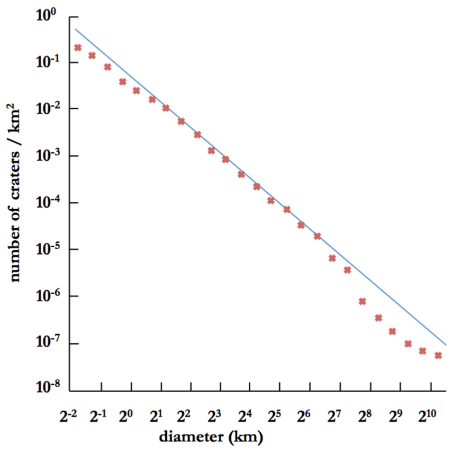


Figure 7.19: Lunar farside uplands crater size-frequency distribution. The blue line represents crater saturation.

Based on W.K. Hartmann 1995, "Planetary cratering 1. The question of multiple impactor populations: Lunar evidence", *Meteoritics*, **30,** pp. 451-467.

Note that there are many more small craters than large craters.

Hartmann has applied the size-frequency distribution analysis to many of the solid solar system surfaces and suggests ages for those surfaces based on how far they are from saturated. Here are examples of the crater distributions for two more regions on the surface of the Moon, the dark and light regions on Ganymede, Callisto, and Venus:

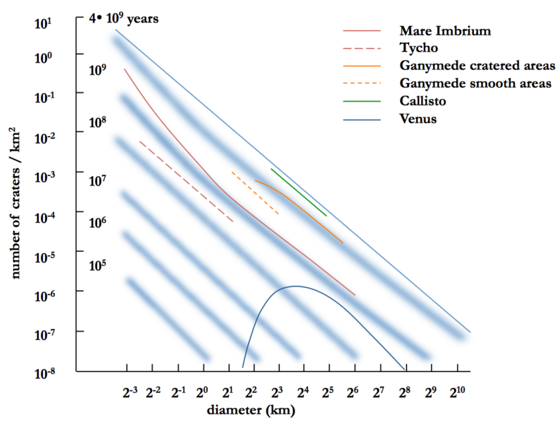


Figure 7.20: Ages of selected surfaces.

For more examples see, for instance, W.K. Hartmann 2005 *Moons and Planets*, 5th ed., pp. 262-3.

Mare Imbrium is older than the crater Tycho but younger than the saturated regions of the lunar surface. Ganymede's dark cratered areas are older than the smooth lighter regions, and neither of them are saturated; Callisto's surface is pretty much saturated. Io, with approximately zero impact craters, doesn't even make it onto this plot. Look at the differences between the distributions on these airless surfaces and the distribution for Venus – on Venus, the atmosphere breaks up small impactors before they can hit the ground to leave craters. The numbers of large craters on Venus tell us that resurfacing has occurred. The terrestrial crater distribution looks a lot like the distribution for Venus, although we have a few more smaller craters because our atmosphere is less thick and less able to destroy incoming meteoroids.

Terrestrial craters

Yes, Earth has impacts, although craters tend to disappear fairly quickly due to erosion, subduction, volcanic resurfacing; the fact that 70 percent of Earth's surface is covered in water means that the majority of impacting meteoroids are likely to hit water and not leave a crater in the first place. The following are images of some of the Earth's impact craters.

Figure 7.21: Meteor Crater, Arizona

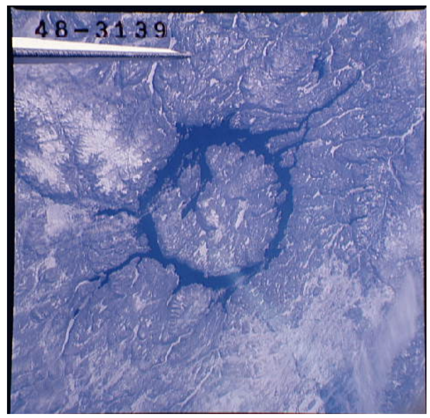
This crater is ~50,000 years old; its diameter is ~1.2 km and depth ~170 m. The rim rises ~45 m above the surrounding plains. The impactor was a nickel-iron meteoroid ~50 m in diameter.

NASA image.
http://spaceplace.nasa.gov/craters/en/

Figure 7.22: Lake (and crater) Manicouagan

This crater is in Quebec. It's relatively old for terrestrial craters, at ~215 million years. It's a ringed basin ~100 km diameter; the lake that has filled part of the central region is ~70 km across. The probable impactor would have been an asteroid ~5 km across.

NASA / STS-9 Space Shuttle mission.
http://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=STS009&roll=48&frame=3139



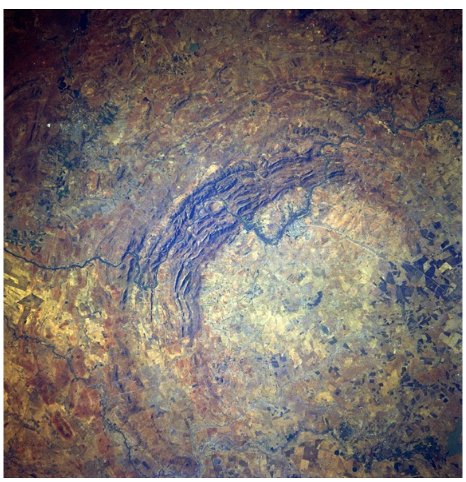


Figure 7.23: Vredefort crater

This ring of hills around an eroded domed center in South Africa is what remains of one of the largest and oldest preserved impacts on Earth. The original crater rim, well outside this field of view, is estimated to have been ~300 km across. The ring of hills shown here is ~70 km across. The impact age is estimated to be ~2 billion years.

NASA / Space shuttle image STS51l-33-56AA
https://eol.jsc.nasa.gov/searchphotos/photo.pl?mission=STS51I&roll=33&frame=56AA

Meteorites and other remnants

Meteorites are divided roughly into three groups: stones, irons, and stony-irons. The overwhelming majority (90+ %) of *falls*, i.e., those seen to fall, are stones, which suggests that most meteoroids (the objects in space) are rocky. *Finds* are those meteorites found on the Earth's surface but not having been observed to fall. Iron meteorites are preferentially represented among finds, in part because they are more obviously different from terrestrial rocks and in part because irons are more resistant to weathering than stony meteorites. Meteorites are named for the general locale where they were collected.

In November 1492 residents near the town of Ensisheim, in Alsace, observed a fireball. The stony meteorite, originally ~127 kg, dug a crater of ~1 meter depth.

Figure 7.24: Woodcut of the Ensisheim fireball.
http://miac.uqac.ca/miac_frames_e.html

Clearly documented events such as the Ensisheim fall helped, slowly, convince people that stones really could fall from the sky. When Ernst Chladni (1756 – 1827) published a work on meteorites in 1794 proposing an extraterrestrial origin many in Europe still thought that these stones must be volcanic.

Incoming objects often explode in the atmosphere, leading to a shower of meteorites that fall across what's called a *strewn field*. Several thousand meteorite fragments, of approximately 37 kg total, fell in and around the town of L'Aigle, in Normandy, in April 1803. Jean-Baptiste Biot (1774 – 1862) went to investigate this event; his conclusion was that many stones had in fact fallen from the sky at the same time and that they must be extraterrestrial.

There are a number of web sites with good descriptions or images of various meteorite falls and finds, including the Meteoritical Society (http://www.lpi.usra.edu/meteor/metbull.php), Encyclopedia of Meteorites (http://www.encyclopedia-of-meteorites.com) and the Smithsonian National Museum of Natural History Mineral Science collections (http://collections.nmnh.si.edu/search/ms/).

Figure 7.25: A fragment of the L'Aigle meteorite.

Photo: Peter Marmet
http://www.encyclopedia-of-meteorites.com/meteorite.aspx?id=12434

Ice makes a good backdrop against which to detect meteorites and quite a few finds, including some that are scientifically important, have been made in Antarctica. Glaciers carry ice, and meteorites, downslope until they encounter a mountain. Here the ice sublimates or is *ablated* by the wind, leaving the meteorites exposed. Most falls, of course, are likely to hit the oceans. Meteorites that are a fraction of a millimeter in size will melt entirely as they pass through our atmosphere and, if they survive, form tiny glassy *cosmic spherules*, which show up in samples dredged from the ocean floor. The following image by researchers at the University of Washington shows a collection of micrometeorites that have been fully melted.

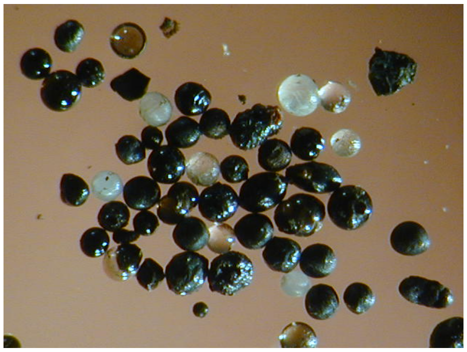


Figure 7.26: Cosmic spherules.

https://catalyst.uw.edu/workspace/idp/40208/285084

A meteorite large enough to survive passage through the atmosphere will show a smooth glassy *fusion crust*; the outer ~1 mm will have melted from the friction with the air. Some loose drops of molten rock and/or metal will fly off the surface (the process of ablation) leaving the meteorite much reduced in size and looking as though someone had pushed into a soft pliable surface with their thumbs. The following image shows a fragment of the Campo del Cielo iron, which fell 4-5,000 years ago in what is now northern Argentina.

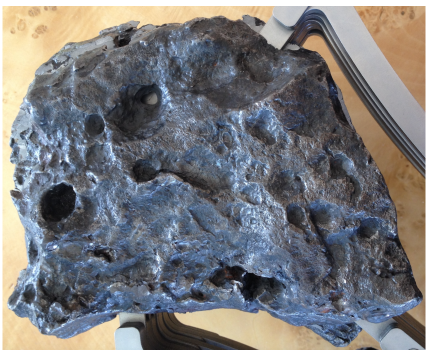


Figure 7.27: Campo del Cielo iron

photo by AKD

A useful way of thinking about types of meteorites is to ask how metamorphosed the rock is: how has it been altered by heat, pressure or shock, chemical reactions such as interacting with water, etc.. For instance, some meteorites were part of asteroids that were differentiated and subsequently broken apart by collisions. In the process of differentiation heavy elements such as iron and nickel and other *siderophilic* ("iron-loving") elements including gold, cobalt, iridium, and several others, that have a chemical affinity for iron will sink toward the asteroid's core.

Iron meteorites, such as the one shown in the image above, are remnants of the cores of differentiated asteroids. Iron meteorites also contain nickel; most are in the range between ~5 and ~25% Ni. There are two dominant iron-nickel crystal forms are found in irons, taenite and kamacite. Taenite occurs at higher temperatures and / or higher nickel content; kamacite is lower nickel. In taenite the atoms are arranged in a face-centered cubic pattern and in kamacite the arrangement is body-centered cubic:

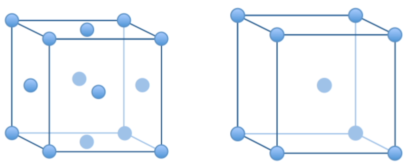


Figure 7.28:
Face-centered cubic (far left) and body-centered cubic (left) crystal structures.

The originally molten core of the asteroid might have an iron to nickel ratio of 9:1. As it cools below about 1,800 K crystals of taenite will start to form. Once the temperature is down around 1,000 K kamacite crystals will have started forming. These form in planes on the corners of the taenite cube. Cutting the corners off of a cube leaves a structure that looks like an octahedron and iron meteorites containing more than ~5% Ni are usually octahedrites. Some, with more than ~18% Ni, don't form noticeable kamacite plates because once they are cool enough to do so nickel doesn't diffuse very well; these are called ataxites. At low nickel concentrations, less than ~5%, kamacite dominates. Since kamacite crystals are basically just cubes, these are called hexahedrites (for six-sided). A phase diagram for a mix of iron and nickel at the relevant temperatures and nickel concentrations looks like this:

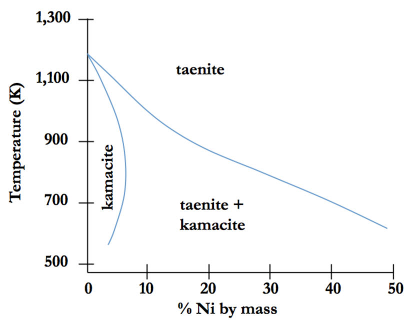


Figure 7.29: Taenite – kamacite phase diagram, based on a diagram in *Thunderstones and Shooting Stars* by Robert T. Dodd.

Does the structure show? Yes, at least if the iron is cut, polished, and etched lightly with acid. The structure thus revealed is called the Widmannstätten pattern, after one of the men who first noticed it.

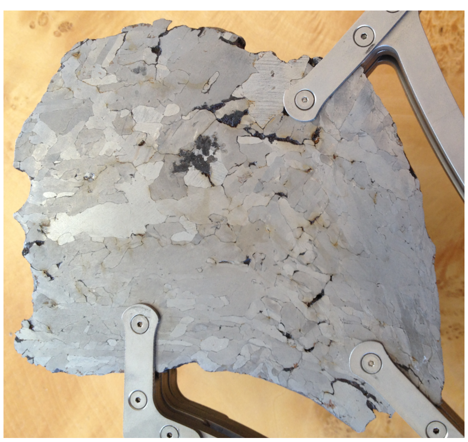


Figure 7.30: The interior of the Campo del Cielo iron fragment shown above.

Photo by AKD

Any given asteroid could fragment into iron meteoroids with a range of nickel content. Recall for discussing cooling magma that once crystals start to form and sink or float out of a melt the composition of the remaining melt differs from its initial composition. The same principle works here – crystals of taenite form, leaving behind a nickel – iron melt with a slightly different nickel percentage out of which the next round of crystals form. Trace elements will also solidify out at different temperatures. For a given nickel percentage, the more slowly an asteroid core cools, the more the kamacite crystals have a chance to grow. All of these pieces – crystal size, trace elements, nickel content – are a part of the puzzle of reconstructing the history of an individual iron meteorite. As early meteoriticists studied the range of iron meteorites it became clear that, even allowing for the fact that one asteroid could yield meteorites with a range of crystal structures, more than one parent body is required.

Pallasites. At the core-mantle boundary of one of these subsequently to-be-fractured differentiated asteroids we expect there to be a region in which olivine has crystallized and settled out of the mantle magma on top of a layer of still-molten liquid metal in the core. In other words, we expect to have meteorites that sample the core-mantle boundary. These are the pallasites, one of two main subgroups of the stony-iron meteorites. They aren't named for Pallas, the second asteroid to be discovered, but rather for Peter Simon Pallas, a German naturalist who, while examining an interesting rock sample in 1772, recognized that he had something deserving of further study. The following image of a slice of a pallasite shows light coming through the translucent olivine crystals surrounded by the nickel-iron matrix.

Figure 7.31: Slice of the Esquel pallasite, found in Argentina in 1951.

http://spacemath.gsfc.nasa.gov/weekly/7Page24.pdf

The second major group of stony-irons is the mesosiderites, a group of meteorites about which there is still much debate. Unlike the pallasites, with their distinctly separate silicate crystals embedded in a metal matrix, mesosiderites are a mix of nickel-iron and igneous silicates and appear to be impact breccias, i.e., rocks formed from broken bits of other rocks and buried deeply enough to solidify. They may, or then again they may not, be related to the howardites (see below).

Achondrites. The mantles and crusts of differentiated objects are also sources of meteorites. Typically these are relatively depleted in the siderophilic elements and relatively enriched in *lithophilic* elements, those with a chemical affinity for oxygen and silicon. Stony meteorites are primarily categorized based on whether or not they contain *chondrules*, small glassy inclusions that we'll discuss further below. The stony meteorites most likely to originate at or near the surface of a differentiated object are those without chondrules, called the achondrites. Because we don't necessarily have to destroy an object to eject a rock from its surface, there are many more potential parent objects for these meteorites.

The HED meteorites (howardites, eucrites, and diogenites) are quite similar to igneous rocks on Earth. The general consensus, based on their compositions, is that they are from Vesta. Radioisotopic tests show that these rocks crystallized roughly 4.43 – 4.55 billion years ago. The southern hemisphere of Vesta shows evidence of an enormous impact, the basin now known as Rheasilvia, that reached through Vesta's crust and into its mantle less than a billion years ago. With the HED meteorites we appear to be sampling impact breccias, surface basalts, and the mantle from Vesta.

Over 100 meteorites have compositions consistent with having originated on Mars. The major groups here are the SNC (shergottites, nakhlites, and chassignites) meteorites. Most Martian meteorites are shergottites, which are igneous, mafic - ultramafic rocks. The may be as young as ~180 million years, which is odd because there's not much evidence of magma solidifying that recently on Mars. One additional Martian meteorite, Allan Hills 84001, was collected in Antarctica in 1984. Dating suggests that it crystallized about 4.09 billion years ago, at a time when liquid water was present on the surface of Mars. An impact ejected it from the surface of Mars ~17 million years ago. This meteorite shot to fame in 1996 when NASA scientist David S. McKay argued that certain features of this meteorite – e.g., carbonate globules and tiny (20-100 nm) tube-shaped structures – were evidence of fossilized life. The weight of scientific opinion is that he's probably wrong, but no one has proven it conclusively.

Another 130+ meteorites are sufficiently similar to the lunar Apollo samples to warrant concluding that they are from the Moon. The oldest known igneous rocks, dating to 4.55 billion years ago, are a small group of achondrites called Angrites. Their spectra resemble those of several main belt asteroids but their origin hasn't been established definitively. There are several other distinct groups of achondrites, some with and some without well-identified parent objects.

Here are two images of meteorites from differentiated parent objects:

Figure 7.32: Cumberland Falls, a brecciated enstatite-rich achondrite that fell in Kentucky in 1919.

Figure 7.33: Allan Hills 81005, a 3-cm lunar meteorite found in Antarctica in 1981.

http://www.mnh.si.edu/earth/text/dynamicearth/6_0_0_GeoGallery/geogallery_drilldown.cfm?categoryID=2

Cosmic ray exposure ages. In many cases it is possible to tell roughly how long a differentiated meteorite spent in space between being ejected from its parent object and impacting the Earth. Cosmic rays is a catch-all term referring to high-energy particles, usually meaning particles arriving from outside the solar system and sometimes even from outside the galaxy; it could, but often does not, include the mostly lower-energy particles in the solar wind. For comparison, normal solar wind particle energies are on the order of 10^3 eV; the largest numbers of cosmic rays arrive with energies of ~300 MeV and the highest energy cosmic rays have energies of ~10^{20} eV, roughly ten million times more energetic than the Large Hadron Collider particle collisions.

As energetic as they are, cosmic rays don't tend to penetrate more than about a meter into the surface of an asteroid, meaning that a meteoroid could have been protected until the impact event that launched it into space. While it's in space, its outer meter or so is exposed to cosmic rays. The cosmic rays are energetic enough to cause nuclear reactions that create distinctive radioactive and stable isotopes. They also leave microscopic tracks as they plow into the meteoroid, although so does the decay of ^{244}Pu. Once on the Earth the exposure ceases because our atmosphere protects us from these energetic particles. The radioactive isotopes, in particular, are useful for determining the duration of the meteorite's cosmic ray exposure. The one wrinkle that you might notice is that many meteoroids fracture on impact with our atmosphere and we could be misled by meteorites that had been protected during their migration to Earth. Cosmic ray exposure ages vary a lot, but some are less than a million years, which is quite fast. The combination of gravitational perturbations and the Yarkovsky effect, though, can be very efficient at delivering meteorites to Earth from the asteroid belt.

Chondrites. The majority of meteorite falls are chondrites, which are stony meteorites usually containing chondrules, mm-scale igneous, often glassy, spherules embedded in the meteorite. Among all meteorites the chondrites most closely resemble the composition of the Sun, or of the Sun minus the most volatile elements. The rocky matrix includes grains of metal, e.g., metallic nickel-iron and sulfides and distinct individual silicate mineral crystals. Some tiny refractory grains, e.g., of silicon-carbide, diamond, corundum, and others, announce by their isotopic anomalies that they are pre-solar grains, i.e., solid bits that pre-date the formation of the solar system.

The dominant model of chondrule formation suggests rapid heating of dust grains at low pressure and temperatures on the order of 1,000 – 1,500 K. They seem to have been heated fast, because they contain moderately volatile elements that would have been lost under sustained heating, and to have cooled relatively quickly; the glassy ones may have solidified within minutes. Chondrules show enough variety, though, that they needn't all have been formed by precisely the same mechanism. What they do share is the fact that reheating by deep burial inside a large asteroid would have destroyed their structure.

Some chondrites also contain calcium-aluminum inclusions (CAIs), which, like chondrules, are roughly mm-sized, but which usually light-colored and refractory, meaning that they must have condensed at relatively high and sustained temperatures and cooled more slowly than the chondrules. Models suggest that CAIs solidified in closer to the forming Sun than did chondrules. If they condensed relatively early it makes sense that the CAIs should contain some of the oldest minerals in the solar system. One CAI, from the carbonaceous chondrite NWA 2364 (collected in northwest Africa), has been dated at 4.569 billion years.

Chondrites are subdivided into several types. Chondrites may not have been subjected to high-grade metamorphism but that doesn't mean that they haven't experience low levels of metamorphism due to heat, shock or pressure, or hydration. Despite being roughly solar, chondrites don't all show the same composition, varying for instance by the amount of iron or carbon or which silicates dominate. Structure, composition, and the extent of metamorphism shown are all factors in classifying chondrites.

Enstatite chondrites are rare, as chondrites go. As their name suggests, they contain a relatively high percentage of enstatite ($MgSiO_3$). Their minerals show evidence of forming in reducing conditions and they don't show much evidence of alteration by water, which suggests that they may have formed in the inner part of the solar system and might record conditions at the time the terrestrial planets were forming.

Carbonaceous chondrites are slightly less rare, accounting for ~5% of all chondrites. There are several subsets, each named for a specific specimen. Again, as the name suggests, these chondrites contain carbon compounds, including several that have amino acids. They contain relatively higher proportions of hydrated minerals or evidence of past modification by water. These meteorites are relatively fragile and contain relatively higher levels of volatiles.

The majority of chondrites are classified as "ordinary". They are subdivided primarily on the basis of their iron abundance and whether that iron is present as nickel – iron metal or as mafic silicates and troilite (FeS). H, L, and LL stand for relatively high iron, low iron, and low iron / low metallic iron.

Notable carbonaceous chondrites. Fragments of more recent falls are more likely to be collected with care to avoid terrestrial contamination. The Murchison meteorite made a noticeable fireball just prior to its impact in Victoria, Australia, in September 1969. Murchison (subtype CM2) provides clear evidence of an extraterrestrial source of organic material. Several amino acids, including glycine and alanine, are present, as is uracil, one of the nucleobases in RNA. Six months earlier another notable carbonaceous chondrite fall, Allende, was observed in Mexico. Allende (subtype CV3) is an example of a carbonaceous meteorite, i.e., one that must have formed at low temperature, containing calcium-aluminum inclusions, i.e., grains that must have solidified at high temperature. It's a puzzle. Allende also contains pre-solar grains, as does the Sutter's Mill carbonaceous chondrite that fell in April 2012 near Sutter's Mill, California. The Sutter's Mill meteoroid was ~2-4 m diameter. Because it created a fireball that was caught on camera, its trajectory could be determined. It seems to have entered the atmosphere quite fast, ~29 km/sec, and broken up at nearly 50 km altitude, considerably higher than the Chelyabinsk object fractured.

Here are two images of chondrites from the Smithsonian National Museum of Natural History.

Figure 7.34: Allende; note the white CAIs.

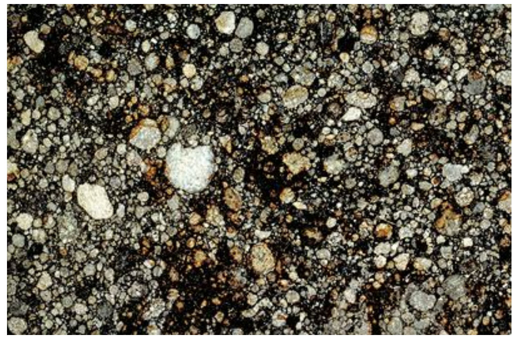


Figure 7.35: Mezö-Madaras, an ordinary L-type chondrite that fell in Romania in 1852.

http://www.mnh.si.edu/earth/text/dynamicearth/6_0_0_GeoGallery/geogallery_browse.cfm?categoryID=2&browseType=type&typeID=111&typeName=Stone,%20chondrite%20(Undefined)

An odd carbonaceous chondrite exploded in a fireball over northern British Columbia in January 2000, with many fragments falling on the icy surface of Tagish Lake. The Tagish Lake meteoroid is estimated to have been ~4 m in diameter. Collectors found about 10 kg, estimated to be about 1% of the original mass. Its trajectory and reflectance spectrum suggest that it may have originated from the asteroid 773 Irmintraud, which is a D-type asteroid. D-type asteroids are relatively dark, reddish, outer belt objects that include a number of Jupiter's trojans. There are some suggestions that these objects must have originated even farther out in the solar system and perhaps were gravitationally nudged inward from the Kuiper Belt. Tagish Lake contains chondrules and CAIs, organic compounds, pre-solar gains, nanodiamonds – all useful pieces of evidence for modeling the early history of the solar system.

An additional piece of evidence comes from analysis of meteorites' isotope ratios, including the ratios of the stable isotopes ^{16}O : ^{17}O : ^{18}O. On Earth these isotopes occur in the ratios 0.99757 : 0.00038 : 0.00205 in an established reference known as "standard mean ocean water" (SMOW); rocks' oxygen value vary from the ocean. We are interested in comparing differences between meteorite isotope ratios and terrestrial values. Because these differences are going to be very small numbers they are often presented as differences in parts per thousand normalized to the dominant isotope, in this case ^{16}O. For instance, the notation $\delta^{18}O(‰)$ is defined as

$$\delta^{18}\mathrm{O}(‰) = \frac{\left[n(^{18}\mathrm{O})/n(^{16}\mathrm{O})\right]_{\mathrm{meteorite}} - \left[n(^{18}\mathrm{O})/n(^{16}\mathrm{O})\right]_{\mathrm{SMOW}}}{\left[n(^{18}\mathrm{O})/n(^{16}\mathrm{O})\right]_{\mathrm{SMOW}}} \cdot 1000,$$

where *n* indicates the number density of the isotope. This is like taking a percentage difference relative to a standard, except in this case it's per mille (i.e., per thousand, *not* per million!). Below is a three-isotope plot for oxygen for Earth basalt (blue dot) and various meteorites and meteorite inclusions. Any process that acts to separate isotopes by mass would lead to a line with a slope of ½ because ^{17}O is one neutron more massive than ^{16}O and ^{18}O is two neutrons more massive. That's the slope of the terrestrial fractionation line. Enstatite chondrites lie near the terrestrial basalt point. The Martian meteorites fall along a line that's offset a bit from the terrestrial line but also has a slope of ½, which simply indicates a slightly different initial oxygen concentration relative to the Earth. Roughly speaking, data points that are shifted up with respect to the mass fractionation line indicate formation from an oxygen reservoir containing more ^{17}O, a shift to the right implies more ^{18}O, and a shift down below the mass fractionation line and to the left implies more ^{16}O. Carbonaceous chondrites lie along a line with a slope of 1, which might mean that they formed in a region with a relatively higher amount of ^{16}O.

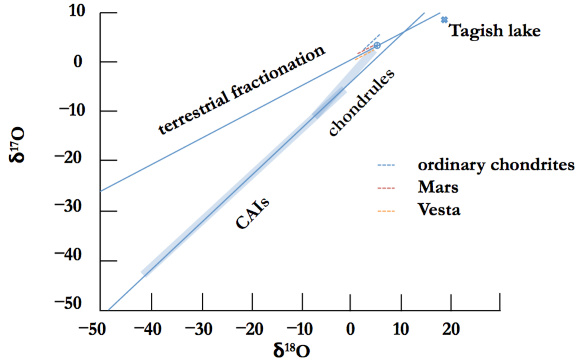


Figure 7.36: Three-isotope oxygen plot; the CAI and chondrule distributions are for carbonaceous chondrites.

Notable impacts

Did an asteroid impact seal the fate of the dinosaurs 65 million years ago? Quite possibly. Impacts leave evidence in addition to craters and meteorites. Impacts can blast terrestrial surface rock up high enough into the atmosphere that the rock is heated so much on the fall back down that it turns glassy. The result is a *tektite*, a centimeter-sized rock that's often black (although also possibly green or brown or grayish) and may have a teardrop shape. This one is round and flat-ish:

Figure 7.37: Tektite

Photo by AKD

Meteoroids are also likely to have compositions that differ from terrestrial surface rocks. In particular, impacts often leave excess iridium. There's a global layer of iridium dating from about the time of the extinction of the dinosaurs. That date also corresponds to the date of an impact in the northern Yucatán Peninsula at a site called Chicxulub.

The Chicxulub impact site is nearly 200 km in diameter and 20 km deep. It's partially underwater and partially overgrown with vegetation. It's also surrounded by a ring of sinkholes ("cenotes") and nearby there's quartz that shows evidence of having been shocked and there's a sizeable number of tektites. A scar this large suggests an impactor on the order of 10 km in diameter. That's large enough the ejecta would have been blasted high enough, possibly out of the atmosphere, that it would have been heated enough as it fell back to Earth to ignite wildfires on impact. In the ocean there would have been huge tsunami waves. In the atmosphere there would have been dust, perhaps enough to block sunlight for several years. There are some suggestions that a series of earthquakes and volcanic eruptions occurred as a result of the shock waves in the crust. There is not a definitive picture of exactly what happened and at what times or in what order following this impact, but it does seem to be large enough to have been globally destructive. The following image shows the location of the impact and the slight topographic relief (a few-meter deep trough) that still marks location of the crater rim.

Figure 7.38: Chicxulub impact site, Yucatán

NASA / JPL – Shuttle Radar Topography Mission
http://photojournal.jpl.nasa.gov/catalog/PIA03379

In 1908 there was an explosion in a sparsely populated region in central Siberia that flattened ~2,000 km^2 of trees, created an air pressure wave that was recorded in western Europe, and produced a seismic shock equivalent to a moderately strong earthquake (perhaps magnitude 5 or so). World War I interfered with attempts to study the site. Later investigations failed to find any impact crater and not much in the way of meteorites. The consensus is that a stony asteroid possibly ~100 m in diameter exploded in the atmosphere, 6 – 10 km above the ground.

Figure 7.39: The Tunguska Event
Downed trees photographed by the Kulik Expedition in 1927

http://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska/

A more recent airburst occurred in 2013 over Chelyabinsk, Russia when a bolide (a meteor, possibly explosive, that's bright enough to see in the daytime) exploded about at ~30 km altitude. At peak brightness, for those even several tens of kilometers away, the explosion was brighter than the Sun. Air pressure waves from the event travelled around the globe at least twice and were recorded by the monitoring stations of the Comprehensive (Nuclear) Test Ban Treaty Organization. Many people saw the blast, rushed to windows to look out, and were hurt by flying glass when the shock wave hit ~2 minutes later. Several hundred fragments of the impactor, the largest ~300 kg, have been recovered from the "strewnfield" along the meteoroid's trajectory. They are of a type called ordinary chondrites, about which more will be said when we look in detail at meteorites. Many people recorded the event on dashboard and other cameras, which allowed those analyzing the event to determine the impactor's trajectory. It was an Apollo asteroid, a class of asteroids whose orbits cross the orbit of the Earth. The object seems to have been about 10,000 metric tons and 17 – 20 meters diameter. A plume of debris from the blast rose several kilometers and was carried around the Earth by the jet stream. Here is an image from dashcam video posted to Wikimedia:

Figure 7.40: Chelyabinsk event.

Posted to Wikimedia Commons by Aleksandr Ivanov
https://en.wikipedia.org/wiki/File:Взрыв_метеорита_над_Челябинском_15_02_2013_avi-iCawTYPtehk.ogv

If you are interested in tracking upcoming near misses, the Spaceweather site (http://www.spaceweather.com) has a listing of upcoming encounters between the Earth and Potentially Hazardous Asteroids. On the other hand, we didn't see the Chelyabinsk meteoroid coming.

Sample problems

1. Suppose that a rocky asteroid of 500 m radius impacts the Moon at 5 km/s. Assume that half of the kinetic energy of the impact goes into ejecting material from the crater that's formed and half into shocking / heating the surface. Further assume that a round crater is formed with a depth = 1/2 its width and that to form it we need to lift the material that was in the crater by about 1 crater radius. (The volume of such a half spheroid would be $\frac{1}{2}\cdot\frac{4}{3}\pi\cdot r\cdot r\cdot\frac{r}{2}=\frac{1}{3}\pi r^3$.) Estimate the crater size. Hints: think about the potential energy of the ejected material at the height of its trajectory and about conservation of energy; for purposes of approximating, you could assume that both the impactor and the surface were roughly the same material and thus the same density.

2. Reading carefully? crater questions:

a) Explain why there are relatively few small craters on Venus.
b) What's the difference between a simple and a complex crater?
c) What is a multi-ring basin?
d) Why are crater rays bright?
e) What is a palimpsest?
f) What is a rampart (or splosh) crater?

3. Reading carefully? meteorite questions:

a) What is the difference between a meteoroid, a meteor, and a meteorite?
b) Where do we find a Widmannstätten pattern and what can it tell us about the size of the parent asteroid?
c) What are chondrites and chondrules?
d) What do we think was the parent object for HED meteorites? how about SNC meteorites?

4. Impact events: What was significant about Chicxulub? Tunguska? Chelyabinsk?

Answers to selected problems are on the next page:

1. Assuming densities of ~ 3 g/cm^3, the crater diameter would be ~ 13 km.