Cosmic Chemistry: Planetary Diversity

Ouch! That Hurts!

STUDENT TEXT

IMPACT CRATERING


NASA

Craters on surface of Mars' moon Phobos.

Because obvious impact craters are not common on the Earth's surface, they were not considered of geological importance until the advent of space travel. Interest in planetary and satellite cratering increased as the Apollo program intensively explored the moon's surface and the Mariner spacecraft studied Mars' geological features.

Over the last few decades, it has become apparent that impact cratering has played a major role in the formation and subsequent history of the terrestrial planets and satellites. Spacecraft images show that most of the solid surfaces of planets and satellites are scarred by many impact craters. In fact, impact craters are the most dominant surface characteristic of rocky and icy bodies of the solar system.

Photographs of these craters can be found in most recent solar system publications, including NASA's Web sites and their CD-ROM, *Planetary Data System* (see References, Resources, URLs, CD ROMs at end of this module). You may find it helpful to study some of these photographs as you complete this activity's assignments, which focus on the cratering of the planets.

You will see craters that appear to be recent, having crisp rims and bright rays. These rays are great streaks of debris, ejected from the crater, that have fallen back to the planet's surface. In some cases these rays, which are the most conspicuous features formed by the ejecta, extend from the craters to form great circles across the surface of the planet.

Other photographs show evidence of buried craters, with broken rim segments or with ragged rings of peaks being the only clue to previous impacts. Erosion of impact craters can result from:

- Volcanism, which creates surfaces that are more sparsely cratered by covering old craters with lava.
- Wind, water, and tectonic processes that erase craters shortly after they are formed.
- Many small impacts which can wear away the surface of the planet.

The surfaces of the Earth and Mars show evidence of all these processes.

We now know that all terrestrial planets are cratered. During the first 600 million years of their existence, cratering was such a constant phenomenon that heavily cratered terrain is thought to represent the oldest surface of a planet. Impacts were especially important during the growth of the planets from planetesimals (see Student Text "Solar Nebula Supermarket" for a more complete description of the formation of planetesimals from the solar nebular disk).

Collisions between planetesimals ranging in size from 1 to 10 km occurred at velocities that resulted in the formation of larger planetesimals, rather than in many smaller fragments. Subsequently, gravitational force increased the velocities of small bodies in the immediate vicinity of the large planetesimals, resulting in more destructive collisions between those small bodies. Consequently only the largest bodies continued to grow.

The final stages of growth into terrestrial planets appear to have been quite violent. During this period, most bodies were probably struck several times by others that were approximately half their size. These impacts resulted in temperature increases, accounting at least in part for the evidence that all the terrestrial planets have been at least partially melted at some time in their geological history.

Low-velocity impacts may add mass to a planet, but high-velocity impacts may result in a mass loss. One theory that explains how the Earth's moon formed was by a truly great impact in which a Mars-size protoplanet struck the protoEarth, ejecting vapor and debris that eventually condensed into its moon. There also is evidence that most meteorites falling to Earth today are fragments produced by impact of bodies in the asteroid belt.

In Part 1 of the Student Activity, 'Ouch, That Hurts!" you modeled the impacts of solid objects on different types of surfaces. You may have observed what planetary geologists have found—that, among other factors, the size of a crater depends upon the following:

- The velocity and angle at which the projectile impacts a planet's surface.
- The composition of the projectile.
- The composition of the planet's surface.

After impact, the crater's size is usually modified by loose debris sliding down the interior walls and gathering on the floor of the crater's depression.

ATMOSPHERIC INFLUENCES

Cratering has most often been studied on Mars, Mercury, and the moon, solid bodies whose very thin atmospheres play a very small part in the process (see Data Table 5 in the Student Activity, "Are We Related?"). A planet's atmosphere, however, is involved in the formation of impact craters in two ways:

1) It influences the flight of a meteoroid as it approaches the surface of the planet.
2) It interacts with the gaseous and solid matter ejected from the crater after the projectile has struck the surface of the planet.

EFFECT ON APPROACHING METEORITES

A meteoroid must be traveling in excess of the planet's escape velocity (see Table 1 below), when it encounters the planet's atmospheric gases. Whether or not it will maintain sufficient velocity to impact the planet's surface depends upon the size of the object and the density of the planetary atmosphere.

Escape Velocities of Solar System Planets Table 1

Planet	Escape Velocity	
	km/sec	**mi/sec**
Mercury	4.3	1.7
Venus	10.3	6.4
Earth	11.2	7.0
Mars	5.1	3.2
Jupiter	60	37
Saturn	35	22
Uranus	22	14
Neptune	25	16
Pluto	unknown	

Escape velocity is the speed a body must achieve to break away from the gravity of another body and never return to it.

When small meteoroids first encounter a planet's thinner upper atmosphere, random collisions with gaseous molecules decrease the meteoroid's velocity, producing heat. Some small projectiles are completely vaporized. Others are slowed to the point that they can dissipate the heat to the environment and they remain a part of the "cosmic dust" in the planet's upper atmosphere.

Larger meteoroids, some traveling at speeds exceeding Mach 50 (50 times the speed of sound), reach the more dense planetary atmospheric layers and produce a bow shock as atmospheric gases are compressed and heated in front of the meteoroid. At these high velocities, a shock wave not only can emit bright light, but it can also cause great damage to the planet's surface even if the meteoroid does not reach the surface itself.

The energy dissipated by a meteoroid is determined by the drag force and the length of its trajectory through the atmosphere. The surface of the meteoroid is melted and, perhaps, even vaporized from the heat of friction with the atmosphere. If its velocity is decreased to ten percent of its initial value, it is considered to be "stopped" and it falls to the planet's surface subsonically. If, however, the projectile is large enough, it can survive the passage through the atmosphere, remaining intact and striking the planet's surface at a high velocity. The minimum size for survival of a meteoroid depends upon the material's strength, the body's density, and its velocity when it encounters the planet's atmosphere. Table 2 below shows the results of mathematical modeling of these variables.

Minimum diameters of meteoroids that can penetrate an atmosphere. Table 2

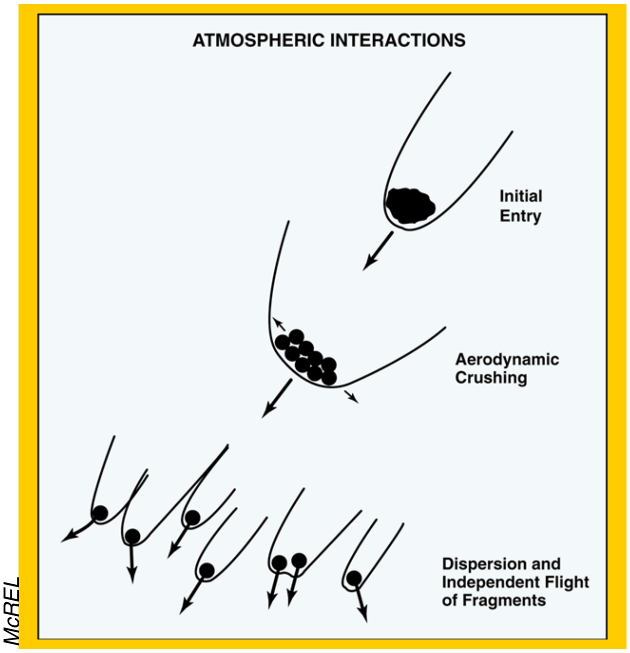
Planet	Surface acceleration/ gravity (m/sec^2)	Surface pressure (Mpa)	Minimum diameter of meteoroids of different densities		
			Ice (m)	Stony (m)	Iron (m)
Venus	8.6	9.0	16,000	3,800	2,000
Earth	9.8	0.1	150	60	20
Mars	3.7	0.0006	2.4	0.9	0.3

Note. The data in Table 2 are from "Impact Cratering: A Geologic Process," by H. J. Melosh, 1989, Oxford Monographs on Geology and Geophysics No. 11, Table 11.1, p. 206, New York: Oxford University Press.

When a meteoroid strikes the surface of a terrestrial planet at high speed, shock waves are propagated not only into the target rocks and but also into the impacting meteoroid. A compression wave spreads out from the point of impact, followed by a decompression wave. The colliding meteoroid melts and partly vaporizes. The shock wave and the heat resulting from the collision cause material to move sideways and to be ejected from the cavity. Part of the rocky fragments ejected form the crater's rim.

The above description assumes that a meteoroid remains intact during its flight through the planet's atmosphere. However, their is evidence that, because of aerodynamic stresses, many meteoroids *fragment* in the atmosphere before striking the planetary surface. Figure 1 is a schematic representation of the atmospheric entry and possible fragmentation of a large meteoroid.

Figure 1



McREL

Figure 1. Schematic representation of atmospheric crushing and fragmentation of a meteoroid. Note. The data in Figure 1 are from Impact Cratering: A Geologic Process (Figure 11.3, p. 209) by H. J. Melosh, 1989, New York: Oxford University Press.

Stress on the meteoroid increases rapidly as it encounters a denser atmosphere, breaking it up into small pieces and expanding it outwardly. This increases the drag and separates the single bow shock into separate ones for each fragment. Surprisingly, it is structural strength of the meteoroid, not it size, that determines whether or not it fragments or remains intact.

Most **meteorites** entering the Earth's atmosphere break up due to aerodynamic stress. Most meteorites survive the much less dense Martian atmosphere without fragmenting. On the other hand, very few, if any, meteoroids would be expected to reach Venus' surface intact (see Table 2 for a comparison of these planets' atmospheric pressures).

When meteoroids are crushed before impact, the craters they produce have very different forms from those produced by a single solid meteoroid, which have symmetrical bowl-shaped interiors with raised rims. The single crater produced by a cluster of fragments is not so deep as one produced by a single object and the crater may have a flat floor. Tight clusters of fragments also may produce craters with central mounds. If the fragments disperse before impact, they fall in a group or cluster of small meteorites, forming an elliptical crater field (see Figure 2 below).

Figure 2

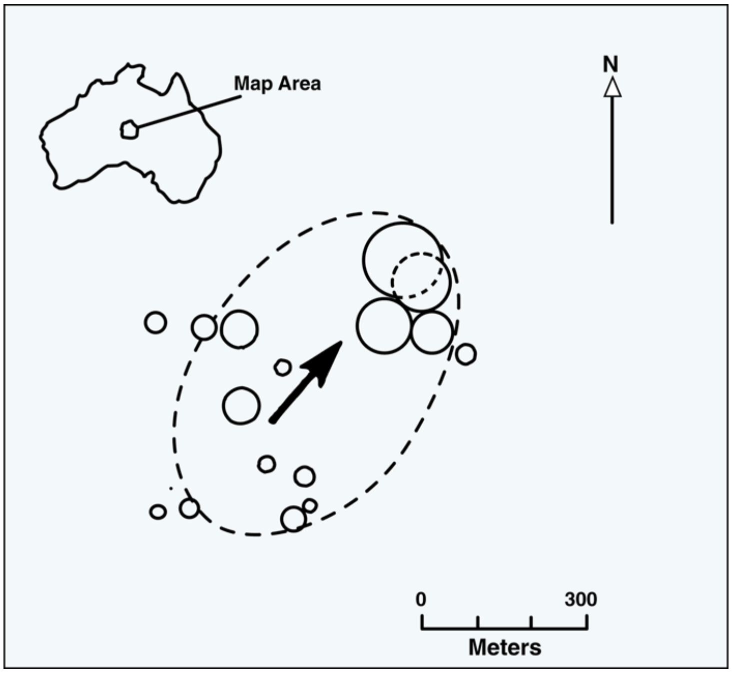


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Figure 2. A schematic drawing of an elliptical field formed by a cluster of small meteorites. Note. The data in Figure 2 are from Impact Cratering: A Geologic Process (Figure 11.1, p. 208) by H. J. Melosh, 1989, New York: Oxford University Press.

INTERACTION WITH EJECTA

The density of a planet's atmosphere also determines how it reacts with the plume of vaporized meteoroid and surface material that is ejected as any of the above types of craters form. If the impact is small enough, the plume of hot vapor expands until its pressure equals that of the surrounding atmospheric pressure. It forms a mushroom-shaped cloud which rises until it stabilizes and disperses as dust and debris at some level in atmosphere. (See Figure 3a.)

Figure 3

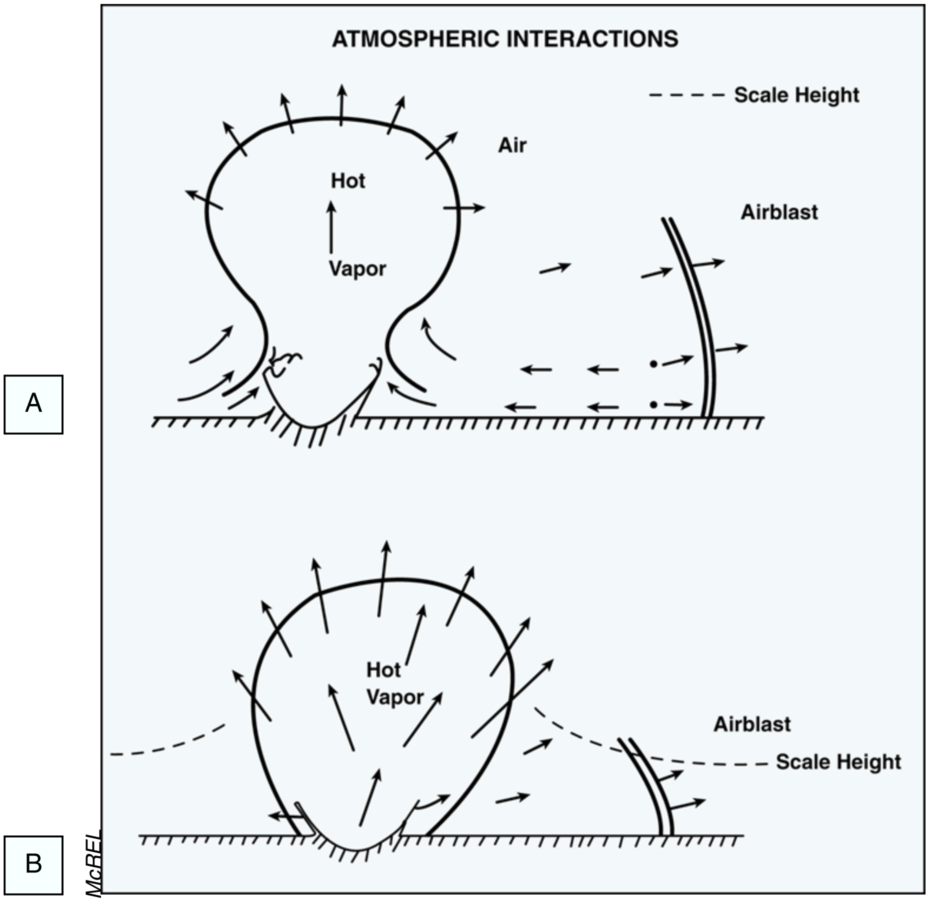
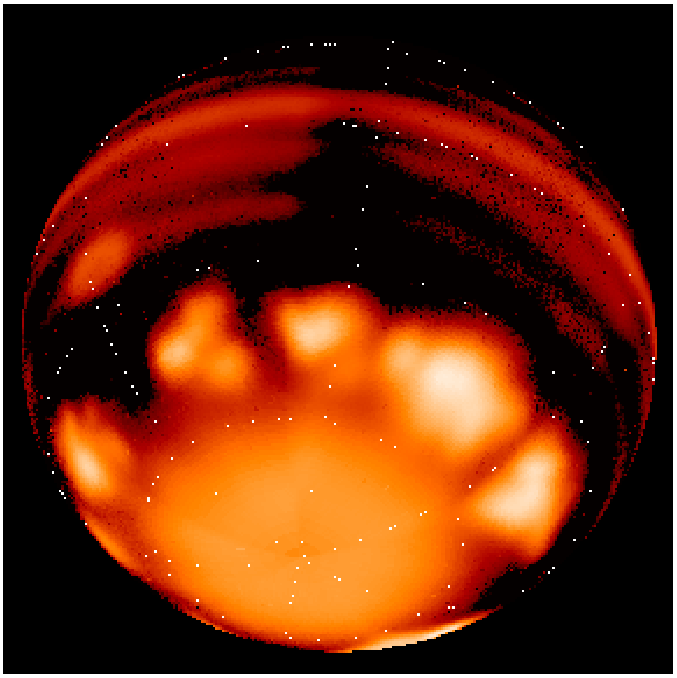


Figure 3. Atmospheric interactions with the vapor plume produced by a) a small impact and b) a large impact. Note. The data in Figure 3 are from Impact Cratering: A Geologic Process (Figure 11.6, p. 213) by H. J. Melosh, 1989, New York: Oxford University Press.

The vapor plume resulting from a large impact (see Figure 3) also carries debris with it. However, pressure equilibrium with the atmosphere is never reached, and the expanding gases explode into the low-pressure regions of the high planetary atmospheres. The contained ejecta may be restrained by gravity and the dust from both types of impacts may remain suspended for long periods of time, ultimately causing changes in the planet's climate.

IMPACT WITH A GAS GIANT

In 1994 there was a collision of Comet Sheomaker-Levy 9 with the planet Jupiter. This impact is commonly known as the "String of Pearls" because of multiple collisions with the planet. Most of the observations of this collision occurred from Earth, but the Galileo Space Probe had an ideal view because the collisions site was on Jupiter's back side, out of view of Earth. Only Galileo was able to directly see the crash sites. Questions abound from the data that Galileo sent back. List some questions you might have about a comet impacting a gas giant.



NASA/Mount Palomar

An infrared image of Jupiter at a wavelength of 2.3 microns, constructed in a computer from 5 individual images taken from Palomar Mountain on July 23rd and 24th, 1994, showing the scars left by the multiple impacts of Comet Shoemaker-Levy 9. The picture shows the planet as it would appear to an observer located above 45 S, 60 W. The prominent impact sites E, H, Q, G, and L (from left to right) are visible at 44 S, surrounding the bright South Polar Hood. The smaller spot between the Q and G impact sites is due to the R impact, which was observed directly from Palomar. The Polar Hood and the impact sites both appear bright in this image because they are composed of particulate clouds that are high above an opaque layer of gaseous methane, which obscures the underlying cloud deck at this wavelength. The fainter feature at 20 S, near the western limb of the planet, is the famous Great Red Spot.