Lunar Cratering and Surface Composition

Earth vs. Moon

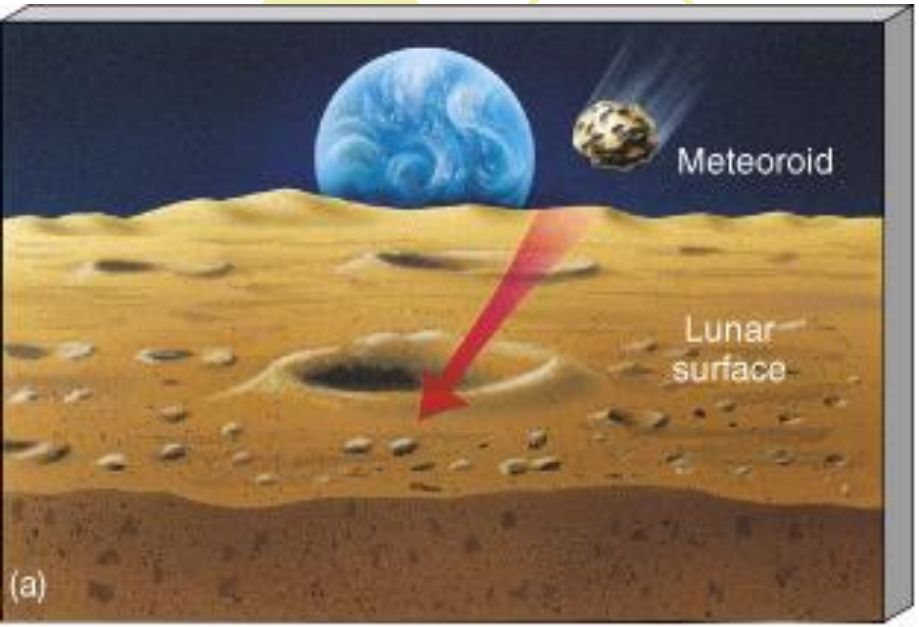
- On Earth, the combined actions of wind and water erode our planet's surface and reshape its appearance almost daily
  - Most of the ancient history of our planet's surface is lost to us
- The Moon has no air, no water, no plate tectonics, and no ongoing volcanic or seismic activity
  - Features dating back almost to its formation are still visible today

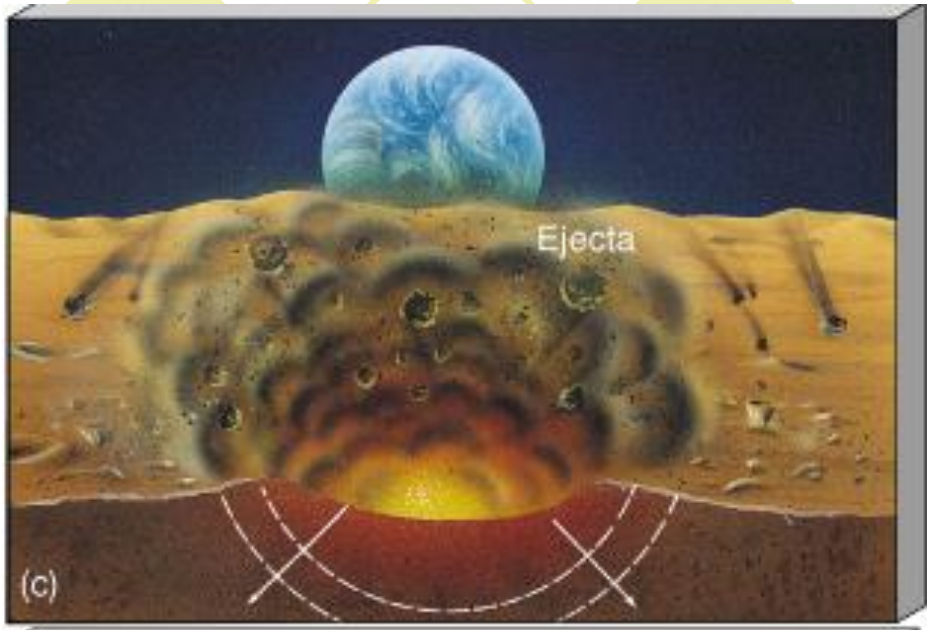
Meteoroids

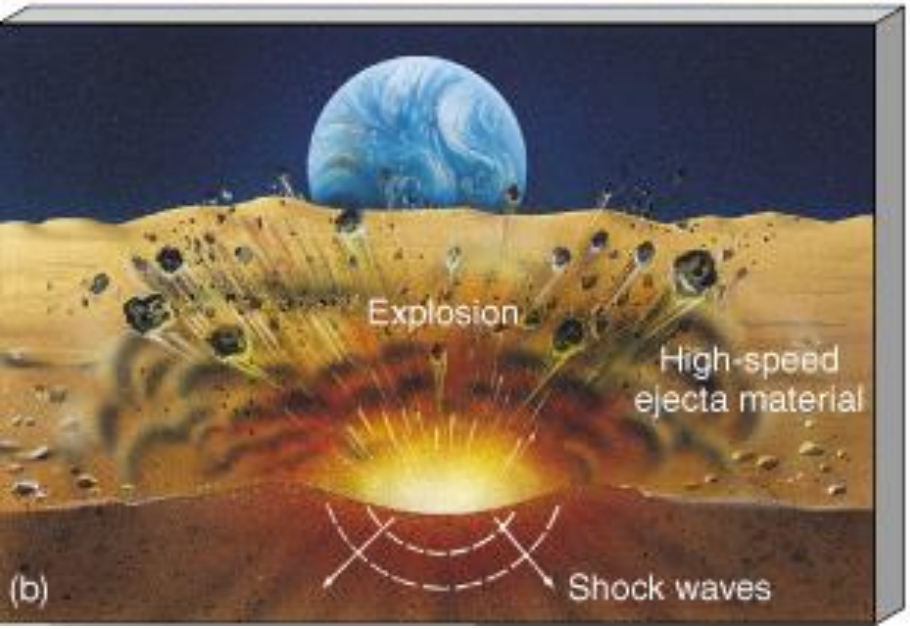
- The primary agent of change on the lunar surface is meteoroids
- The Moon has no atmosphere to protect against impact
- Large and small meteoroids zoom in and collide with the surface, sometimes producing huge craters
- Over billions of years, these collisions have scarred, cratered, and sculpted the lunar landscape
- Craters are still being formed today

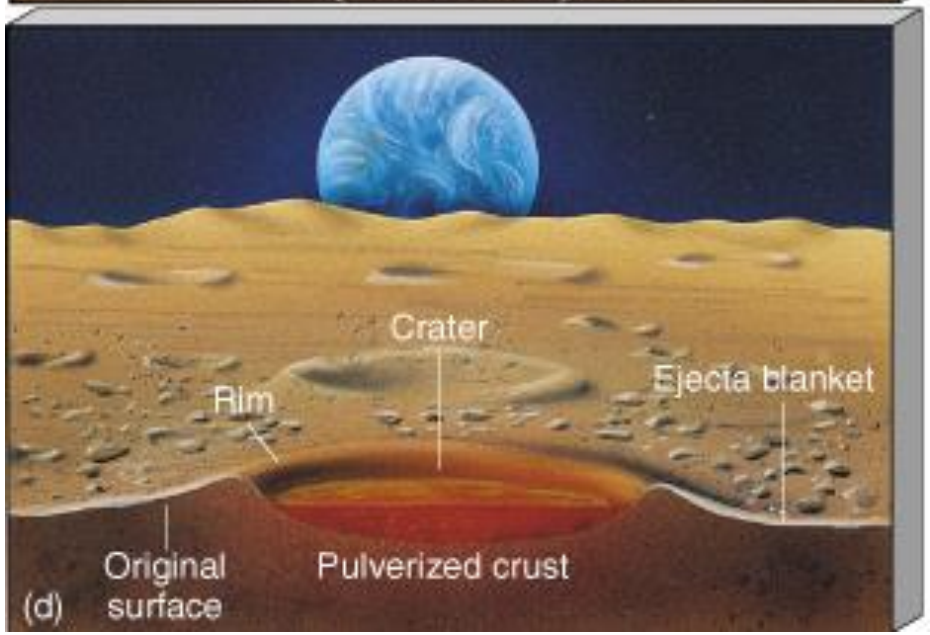
Meteoroid Impact

- Meteoroids generally strike the Moon at speeds of several kilometers per second
- Even a small piece of matter carries an enormous amount of energy
- Impact of a meteoroid with the surface causes sudden and tremendous pressures to build up, heating the normally brittle rock and deforming the ground like heated plastic
- The explosion pushes previously flat layers of rock up and out, forming a crater


Meteoroid
Lunar surface
(a)


Ejecta
(c)


Explosion
High-speed ejecta material
(b)
Shock waves


Crater
Rim
Ejecta blanket
Original surface
Pulverized crust
(d)

Meteoroid Impact

- The diameter of the eventual crater is typically 10 times that of the incoming meteoroid
- The crater depth is about twice the meteoroid's diameter
- Shock waves from the impact pulverize the lunar surface to a depth many times that of the crater itself
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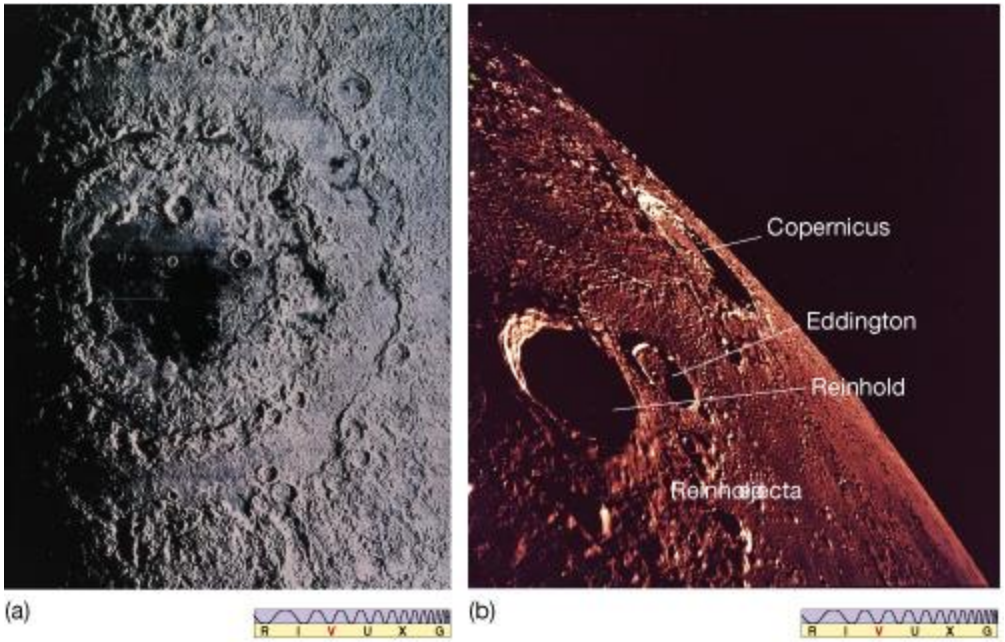
Ejecta

- The material thrown out by the explosion surrounds the crater in a layer called an ejecta blanket
- The ejected debris ranges in size from fine dust to large boulders
  - The larger pieces of ejecta may themselves form secondary craters



Micrometeoroids

- Masses ranging from a few micrograms up to about 1 gram
- Eat away at the structure of the lunar surface
- Fresh large craters are scarce, but small craters are very common
  - One new 10-km (diameter) lunar crater is formed roughly every 10 million years
  - A new meter-sized crater is created about once a month
  - Centimeter-sized craters are formed every few minutes

Cratering History

- Astronomers can use the known ages of Moon rocks to estimate the rate of cratering in the past
- Astronomers now believe that the Moon, and presumably the entire inner solar system, experienced a sudden sharp drop in meteoritic bombardment about 3.9 billion years ago
- The rate of cratering has been declining slowly ever since

Lunar Dust

- Meteoroid collisions with the Moon are the main cause of the layer of pulverized ejecta—also called lunar dust, or regolith
- Covers the lunar landscape to an average depth of about 20 m
- The regolith is thinnest on the maria (10 m) and thickest on the highlands (over 100 m deep in places)
- The steady buildup of dust due to innumerable impacts has smoothed the outlines of craters, and will probably erase them completely in about 100 million years

Erosion Rate

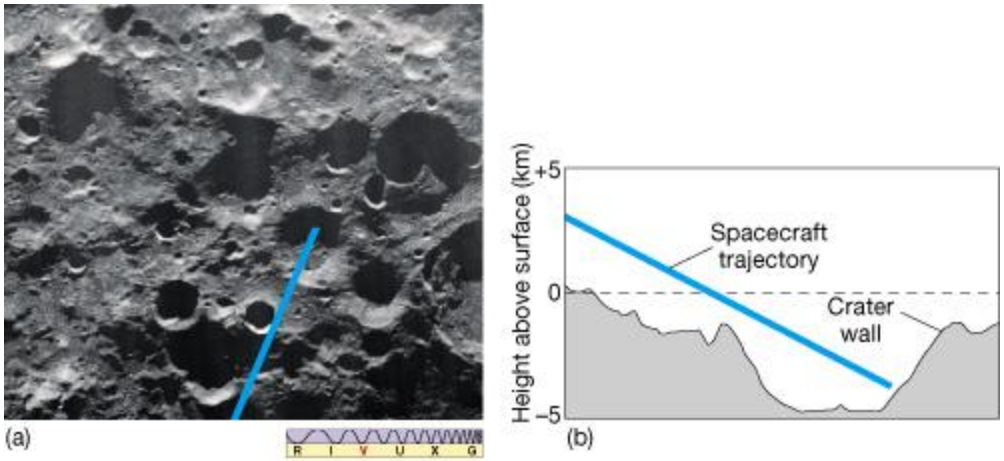
- The current lunar erosion rate is very low because meteoritic bombardment on the Moon is a much less effective erosive agent than are wind and water on Earth
- The Barringer Meteor Crater in the Arizona desert will probably disappear completely in a mere million years
  - If a crater that size had formed on the Moon even 4 billion years ago, it would still be plainly visible today
  - Even the shallow bootprint is likely to remain intact for several million years

Lunar Ice

- Some regions of the Moon are thought to contain water in the form of ice
- In November 1996, mission controllers of the *Clementine* spacecraft reported that radar echoes captured from an old, deep crater near the lunar south pole suggested deposits of water ice at a depth of a few meters
- In early March, 1998, NASA announced that sensitive equipment on board the *Lunar Prospector* mission had confirmed *Clementine*'s findings
- Large amounts of water ice—possibly totaling trillions of tons— was detected at both lunar poles
- However, the *Lunar Prospector* discovery of lunar ice was indirect
  - The instruments on board the spacecraft actually detected the presence of hydrogen (H), whose existence was taken as evidence of water (H_2O).

Lunar Prospector

- In an attempt to gain more direct information about lunar ice, NASA scientists decided to end the *Lunar Prospector* mission in a very spectacular way
  - It was directed to crash into one of the deep craters in which the ice was suspected to hide
  - The hope was that the *Hubble Space Telescope* and ground-based telescopes on Earth might detect spectroscopic signatures of water vapor released by the impact
  - No water vapor was seen
- Lunar ice remains a strong possibility, but its existence has not yet been definitively proven



Lunar Volcanism

- An intriguing alignment of several craters in a *crater-chain* pattern so straight that it is very unlikely to have been produced by the random collision of meteoroids with the surface
- The crater chain probably marks the location of a subsurface fault—a place where cracking or shearing of the surface once allowed molten matter to well up from below
  - As the lava cooled, it formed a solid “dome” above each fissure
  - The underlying lava receded and the centers of the domes collapsed, forming the craters we see today
- There is good evidence for surface volcanism early in the Moon’s history, and volcanism explains the presence of the lava that formed the maria
- Whatever volcanic activity once existed on the Moon ended long ago
- The maria solidified over 3 billion years ago and the Moon has been dormant ever since

Moon's Evolution

- The Moon formed about 4.6 billion years ago
- At formation, the Moon was already depleted in heavy metals compared with Earth
- During the earliest phases of the Moon's existence—roughly the first half billion years or so—meteoritic bombardment must have been frequent enough to heat and remelt most of the surface layers of the Moon
- If the Moon has a small iron core, that core also formed at this time
- About 3.9 billion years ago, around the time that Earth's crust solidified, the heaviest phase of the meteoritic bombardment ceased
- The Moon was left with a solid crust, which would ultimately become the highlands, dented with numerous large basins, soon to flood with lava and become the maria
- As the Moon cooled, the volcanic activity ended as the thickness of the solid surface layer increased
- The Moon is dead now, and it has been dead for a long time

(a) 4 billion years ago

(b) 3 billion years ago

(c) Today