Lecture Ten
Craters, Impacts, and Cataclysms

Scope: Impact craters exist on all the solid bodies of the solar system, from asteroids to moons to planets. Their ubiquitous nature and ancient history indicate an epoch of continuous bombardment during the formation of our planetary system. Such impacts continue to this day with reduced frequency but sometimes devastating consequences. We have witnessed one such massive collision on Jupiter, and we find geologic evidence for such events in Earth's past. The global reach of a major impact on Earth can include fires, earthquakes, tidal waves, and global dust clouds. The combined effect can produce a mass extinction that would wipe out nearly all the species on our planet. Future impacts are not a question of if they will happen, but rather when they will happen.

Outline

I. Impact craters are the most abundant surface feature in the solar system.

- **A.** Hundreds of impact craters have been found on Earth.
  - **1.** The rule of thumb is that the crater is about 20 times larger than the impacting body.
  - **2.** Easily recognizable craters are found for the most recent impacts (from tens of thousands of years ago).
  - **3.** Older impact structures can be recognized from aerial and satellite imagery, though erosion can make them hard to spot.
- **B.** The bowl shape of a crater derives from a high-energy impact.
  - **1.** The speed of impact is comparable to the Earth's speed through the solar system: about 100,000 kilometers per hour.
  - **2.** Generally, several megatons (or more) of energy are released in the impact.
  - **3.** The material excavated from the crater is strewn across the surrounding region.
- **C.** Craters are a significant feature on all of the rocky planets.
  - **1.** Venus has similar numbers of craters as Earth, but those on Venus are better preserved.

  - **2.** Craters on Mars are heavily concentrated in the southern hemisphere—which features Hellas Basin, one of the largest impact structures known.
  - **3.** Mercury and the Moon appear similar, as both are heavily cratered over most of their surface.
  - **4.** The near side of the Moon shows many large impacts that filled in with lava flows, while the far side shows only a few.
- **D.** Many moons and asteroids show abundant cratering.

II. The historical record of cratering can teach us the history of the solar system, planets, and the evolution of life.

- **A.** Dating the craters on the Moon shows an epoch of intense cratering following the formation of the solar system.
  - **1.** The heavy bombardment era lasted until about 3.5 billion years ago, and the cratering since that time has been relatively constant.
  - **2.** The fact that cratering has not slowed down means that new Earth-crossing asteroids and comets must be continually created.
- **B.** An explosion in Tunguska in 1908 was the most powerful recent impact on Earth.
  - **1.** A roughly 50-meter-sized impactor exploded about 8 kilometers above Earth's surface.
  - **2.** The explosion was about 1000 times more powerful than Hiroshima and Nagasaki combined.
- **C.** In 1994, we were lucky enough to witness an impact event on Jupiter.
  - **1.** Comet Shoemaker-Levy 9 was captured by Jupiter's gravity and broke up while in orbit.
  - **2.** A collection of 2-kilometer sized fragments of a comet crashed into Jupiter, creating Earth-sized dark spots in Jupiter's atmosphere that dissipated over a few months.
- **D.** On Earth, an impact event is the probable explanation for the end of the age of dinosaurs.
  - **1.** Tektites are beads of once-molten mineral glass that solidified in midair after an impact. Finding them is evidence of a nearby impact structure.
  - **2.** The Chicxulub impact structure, on the Yucatán Peninsula of Mexico, is about 200 kilometers across.

3. Chicxulub dates to 65 million years ago, the time of the mass extinction at the end of the Cretaceous period.
4. The geologic record shows a worldwide layer of iridium and other rare elements deposited at the KT boundary.
5. Some volcanologists disagree with the impact hypothesis. They argue that the gases released by extensive volcanoes in India changed the climate and caused the Cretaceous-Tertiary mass extinction.

E. Impact events appear to be associated with other mass extinctions on Earth.

1. Metal enrichments occur in the strata associated with mass extinctions 11, 35, 65, and 91 million years ago.
2. Three layers of impact melt are found in sediments associated with the mass extinction 35 million years ago.

III. The effects of asteroid and comet impacts on Earth can be global.

A. It is interesting to contemplate how a 10-kilometer-sized impactor can have global effects on a 13,000-kilometer-sized planet.

B. The energy released in such a large impact is equivalent to 100 million nuclear bombs.

1. The impact excavates a crater up to several hundred kilometers across.
2. The ejecta from the crater rain down over a wide region.

C. The speed of the impact creates a fireball while streaking through the atmosphere and a blast wave upon impact.

1. The searing blast wave will instantly incinerate the nearby landscape.
2. Interaction with nitrogen in the atmosphere and sulfur in the ground can lead to widespread acid rains.
3. Earthquakes from a large impact could be about 100 times more powerful than the largest ever recorded.

D. Two-thirds of all impacts would be in the oceans.

1. Tidal waves kicked up would be kilometers in height and sweep across continents.
2. Impacts in the oceans can throw enough water into the atmosphere to create a temporary increase of greenhouse warming of up to 10°C (18°F).

E. Atmospheric effects are difficult to calculate but can be particularly deadly.

1. Dust clouds kicked up by the impact can circulate globally.
2. Fires ignited by the blast wave and friction-heated ejecta would exacerbate the problem.

F. Disruption of the climate and the food chain can lead to global mass extinctions.

IV. Future impacts are only a matter of time.

A. Meteors are tiny impacts that burn up in the atmosphere and occur daily.

B. A Tunguska-level event should occur every few hundred years.

C. An impact large enough to wipe out a city should occur every 10,000 years.

D. Country-wide or regional destruction events are estimated at every million years.

E. Impacts with global consequences are predicted to occur about once every 100 million years.

F. Currently, no large asteroids are coming close. The previously sparse monitoring programs are improving steadily.

G. Given sufficient advance warning, we could nudge the potential impactor into a safe orbit.

Suggested Readings:

Beatty, Petersen, and Chaikin, *The New Solar System*, chap. 6.

Benson, *Beyond: Visions of Interplanetary Probes*.

Hey, *Solar System*.

Lewis, *Rain of Iron and Ice*.

Light, *Full Moon*.

McFadden, Weissman, and Johnson, *Encyclopedia of the Solar System*, chap. 43.

Near-Earth Asteroid Tracking. http://neat.jpl.nasa.gov/

Near Earth Object Program. http://neo.jpl.nasa.gov/

Verschuur, *Impact!*

Questions to Consider:

1. How would Earth's surface look if there were no erosion to erase craters?

2. Some craters on moons are a quarter (or more) of the size of the moon. How do you think large impacts have affected the number and sizes of moons?
3. Given that impacts are a long-term consideration with low probability of immediate consequences, how large of a budget should we devote to monitoring the threat of asteroid or comet impact?

Lecture Eleven

Journey to the Centers of Planets

Scope: The composition, topography, and motions on Earth's surface indicate a dynamic interaction with the interior that is encapsulated in the ideas of plate tectonics. For Earth, and the rest of the rocky planets, the surface we see is a thin crust layer whose depth is roughly 1% of the radius of the planet. Nearly all the volume is in a rocky mantle and an iron core. This differentiated structure is replicated for the larger moons and perhaps the large asteroids, but the smaller and lower-mass bodies are expected to be roughly the same mixture of materials throughout. The giant planets, while gaseous on the exterior, are actually more liquid in the interior. Only at the very core is a chunk of rock comparable to several or many Earths. Charged particles in the interiors of some planets, coupled with the planet's rotation, create planetary-scale magnetic fields extending from the interior to well beyond the surface.

Outline

I. Earth's surface provides many clues about its interior.

A. The three main types of rocks imply a cycling of material between surface and interior.

1. Igneous rocks are those that cooled from molten lava or magma.
2. Sedimentary rocks are deposited by wind, water, and/or snow (or ice) over time.
3. Metamorphic rocks are igneous or sedimentary rocks that have been subjected to high pressure and temperature and changed their structure.
4. The implications from these rock types is that magma must flow up from the interior and that surface rocks must flow down into the interior.

B. The topography of the ocean floor reveals a system of interconnected features.

1. The deepest parts of the oceans are trenches that generally occur along the edges of continents.