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.

2. From the deepest ocean trenches to the highest mountains is about 20 kilometers of vertical relief, but that is still only about 0.3% of Earth's radius.
3. Mid-ocean ridges are like undersea mountain ranges rising a kilometer or two above the ocean floor.

C. We interpret the ocean's topographic features as boundaries of large plates.
1. Earth's crust is divided into 8 large plates and a few smaller ones.
2. Trenches are regions where one plate is subducting underneath another plate.
3. Ridges are regions where magma rises from the interior to create new plate material.
4. The number of and strength of earthquakes are highest at the plate boundaries.
5. Volcanic activity is associated with trenches.
6. The long chain of undersea mountains leading to Hawaii is an example of hot-spot volcanism that tracks the motion of the Pacific Plate over many millions of years.

D. The history of plate motions shows that Earth's continents are floating atop a fluid interior layer.
1. The idea of continental drift is easily imagined by noting that the bulge of the east coast of South America would fit neatly into the west coast of Africa.
2. About 180 million years ago, all the continents were together in one supercontinent called Pangea.
3. Where a continent is today has little to no correlation with where it was a few hundred million years ago.

II. Our detailed knowledge of Earth's interior serves as the template for understanding other worlds.

A. Differentiation is the gravitational separation of materials of differing densities.
1. For differentiation to occur, the body must have been molten at some point during its formation.
2. We expect planets and larger moons to be differentiated, while the smaller moons, asteroids, and comets should be undifferentiated.

B. Seismology measurements probe Earth's interior.
1. Earthquakes trigger seismic waves that pass along Earth's surface and through its interior.
2. The properties of seismic waves, notably their speed of propagation, depend on the medium through which they are traveling.

C. The interior structure of Earth has three main layers.
1. The crust is roughly 60 kilometers thick and is about 1% of Earth's radius.
2. The crust is composed of low-density materials and contains only 0.4% of Earth's mass.
3. The rocky mantle extends about halfway down and contains about two-thirds of Earth's mass.
4. The upper mantle contains the asthenosphere, a region that acts like a fluid on geologic timescales.
5. The core is composed of iron and nickel and holds about 30% of Earth's mass.

III. The interiors of other large rocky and icy worlds are comparable to Earth's interior structure.

A. The other rocky planets are all differentiated, but each shows distinct variations in interior structure and motions.
1. Venus's interior structure is thought to be similar to Earth's, with the major difference being that it is a one-plate planet.
2. Surface features on Venus are likely due to convective motions in the mantle and episodic volcanic resurfacing.
3. Mercury's small size and high density point to a large iron core extending more than two-thirds of the planet's radius.
4. Long faults, called scarps, on Mercury indicate compression of its crust during solidification.
5. Mars has a lower density that indicates a lower percentage of iron in its composition.
6. The uplifted and volcanic regions on Mars are confined to two major areas that likely indicate sustained regional motions in the mantle.
7. Compared to Earth's plate tectonics, the other rocky planets' surfaces show relatively mild expressions of their interiors.

B. The large moons and minor planets illustrate a sequence from differentiated to undifferentiated bodies.

1. The Moon is differentiated, but its lower density means it probably does not have a core.
2. The Moon shows evidence of ancient crustal extension and contraction but no major internally generated geologic activity for the past 2.5 billion years.
3. The largest asteroids are likely to be differentiated. The existence of iron meteorites provides evidence of the complete breakup of some differentiated bodies.
4. With some exceptions, the Galilean moons of Jupiter are thought to have iron cores surrounded by rock, with icy surfaces.
5. Europa, Ganymede, and Callisto show potential evidence for having subsurface oceans.
6. Titan is believed to have a differentiated rock and ice interior with a subsurface ocean of water and ammonia.
7. Other large bodies of the outer solar system, like Triton and Pluto, have densities indicative of undifferentiated ice and rock.

IV. The giant planets (sometimes called "gas giants") are actually more liquid in their interior.

A. Like the Sun, the giant planets have an interior structure determined by hydrostatic equilibrium.

B. Jupiter and Saturn have roughly the solar composition of hydrogen and helium.
1. The outermost layer is gaseous molecular hydrogen.
2. At higher pressures, hydrogen breaks down into a liquid called metallic hydrogen.
3. Jupiter is predominantly liquid hydrogen (by volume), whereas Saturn is more gaseous hydrogen (by volume).

C. Uranus and Neptune are significantly smaller and resemble the cores of Jupiter and Saturn.
1. They probably have a small rocky core of a few Earth masses. They form farther out in the solar system, and instead of accreting gas, because they didn't have enough mass, they instead accreted "ices."
2. The dominant component is a hot, highly compressed liquid of "ices": a mixture of water, ammonia, and methane, along with various chemical species derived from these.
3. The outer 15% of these planets is molecular hydrogen gas.

V. Magnetic fields are generated in the interior of most planets. They are an external manifestation of interior structure, and one which, as we'll see in a later lecture, provides protection from interplanetary storms.

Suggested Readings:

Beatty, Petersen, and Chaikin, *The New Solar System*, chaps. 12, 14.

Bennett, Donahue, Schneider, and Voit, *The Cosmic Perspective*, chap. 9.

De Pater and Lissauer, *Planetary Sciences*, chap. 6.

Hey, *Solar System*.

McFadden, Weissman, and Johnson, *Encyclopedia of the Solar System*, chaps. 8, 10, 16, 21.

Shu, *The Physical Universe*, chap. 17.

Questions to Consider:

1. How does the composition of an object, from rocks to ices to gases, affect its formation and its interior structure?
2. What role might the impacts of the heavy bombardment era play in creating differentiated worlds?
3. Anything falling into a giant planet would be crushed by high pressure well before it hit any sort of solid surface. Would the giant planets qualify as a practical version of a bottomless pit?