ASTR-1010: Astronomy I
Course Notes
Section VIII

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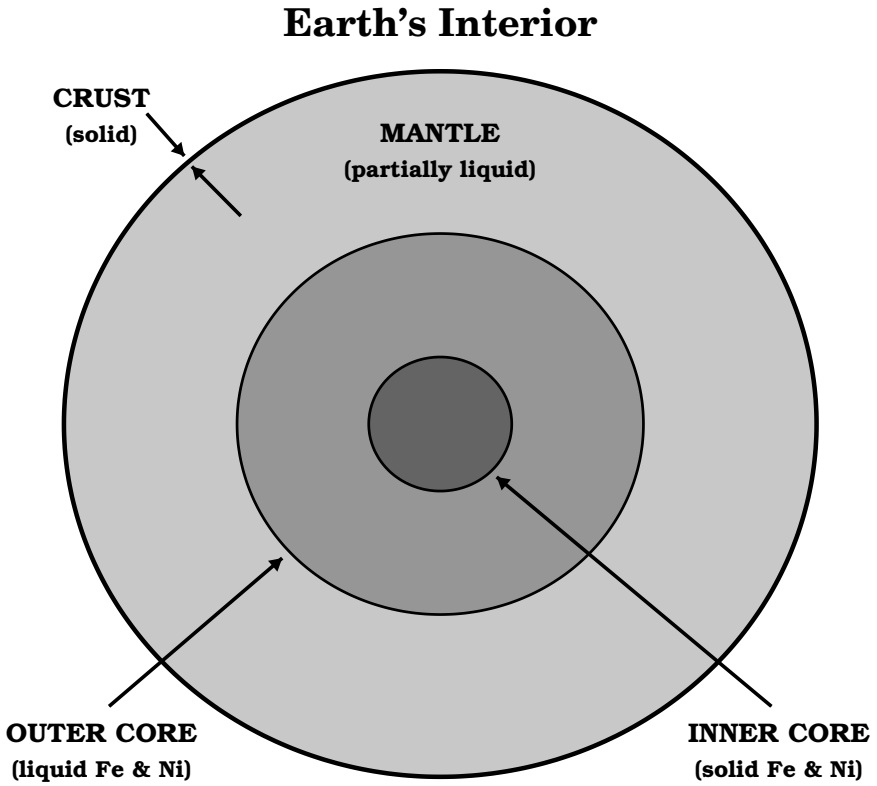
Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1010: Astronomy I taught by Dr. Donald G. Luttermoser at East Tennessee State University.

VIII. The Earth-Moon System

A. The Earth's Interior

1. The Earth's interior is layered into 4 distinct zones:



a) Inner core (radius of 1200 km) which is solid and composed primarily of Fe & Ni.

b) Outer core (thickness of 2270 km) which is liquid and composed primarily of Fe & Ni.

c) Mantle (thickness of 2900 km) which is partially liquid and composed primarily of O, Si, Mg, and some Fe.

d) Crust (thickness of 8-70 km) which is solid and composed of the lightest elements (H, C, N, & O) with traces of heavy elements.

2. We know the interior structure through **seismology**: using sound waves from Earthquakes as a probe.

a) Seismic waves travel at different velocities through different types of materials.

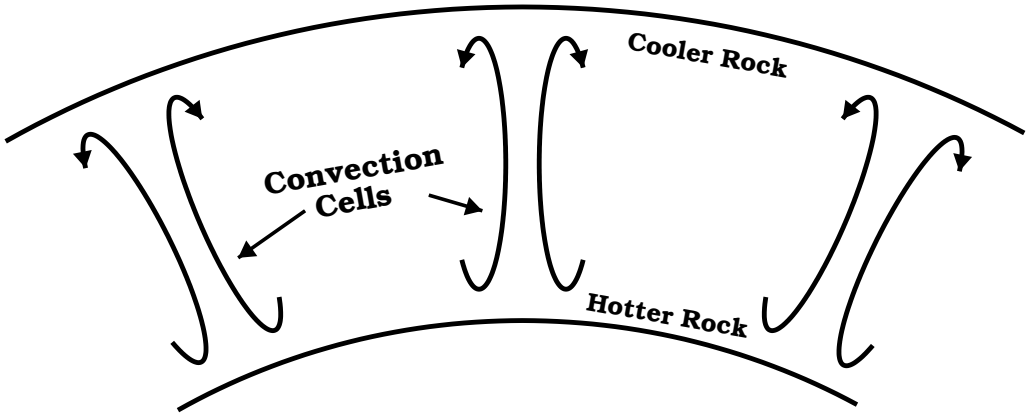
b) Density, composition, and even temperature can be deduced from seismic waves.

3. The outer core is hot which ionizes much of the liquid Fe & Ni. The core rotates just as the surface does.

a) Charged particles in motion produce a magnetic field.

b) The spinning outer core produces the Earth's *dipole* magnetic field that we measure at a strength of 0.5 gauss at the surface.

4. The mantle is also hot. Energy (heat) must flow outward towards cooler regions. This heat flow happens via **convection**.



a) This convection breaks the thin crust into plates and moves the plates about the surface.

b) This plate motion is called **plate tectonics**.

B. Activity on the Earth.

1. Over its 4.6 billion year history, the interior of the Earth should have completely cooled.

a) Should be a solid body throughout, but it is not.

b) Radioactive decay of certain elements (U for instance) continually warms the interior of the planet.

c) This is the main driving force of the Earth's surface activity!

i) Earthquakes.

ii) Volcanos.

iii) Shape of the crust through plate tectonics.

2. The effects of plate tectonics.

a) Approximately 200 million years ago, all of the continents were together which formed a supercontinent called **Pangaea**.

i) Before this time, Pangaea didn't exist and separate continents existed, but moved towards each other.

ii) The Appalachian Mountains formed during the continent collision that formed Pangaea!

b) The mantle's convection broke Pangaea apart forming the present day continents.

i) Pangaea broke apart at a line which is now called the **Mid-Atlantic Ridge**.

ii) At this ridge, new rock is brought up from the mantle to form new crust.

iii) This pushes the American continents away from Europe and Africa at nearly 5 cm/yr.

iv) Such a plate boundary is called a **divergent plate boundary**.

c) This sea-floor spreading pushes North America toward and northward of the Pacific plate, which is moving southward.

i) These 2 plates slide along each other in opposite motions $\Longrightarrow$ **transform plate boundary**.

ii) These plate motions are not uniform, but occur in sporadic lurches due to friction between the plates.

iii) Each *lurch* that occurs causes an **earthquake** to occur!

$\Longrightarrow$ Lurch causes vibration which propagates through the rock in waves.

$\Longrightarrow$ The measurement of these waves is the science of **seismology**.

d) The Indian plate is running head-on into the Eurasian plate $\Longrightarrow$ **convergent plate boundary**.

i) This collision causes the Himalayan Mountains to form.

ii) One plate can sink below another plate (called **subduction**) $\Longrightarrow$ the rock that sinks, heats up to

a molten state and rises through the rock of the other plate causing **volcanos** to form.

e) Convection *hot spots* can form under the centers of some plates pushing mantle material through the crust causing **shield volcanos** (*e.g.*, Hawaii).

C. The Earth's Atmosphere

1. Four distinct layers exist:

a) **Troposphere** (weather sphere): Temperature decreases with height due to a density, hence heat capacity, decrease.

i) **Heat capacity** is a measure of the ability of a material to absorb heat.

ii) It is defined as the constant of proportionality between the amount of heat and the change in temperature that the heat produces in the material.

iii) C = heat capacity = $\dfrac{\text{change in heat energy}}{\text{change in temperature}}$.

b) **Stratosphere**: Temperature increases with height due to ozone (O_3) absorption of solar UV light.

i) Radiation $\rightarrow$ Heat (kinetic energy).

ii) Prevents Sun's UV radiation from reaching the ground.

c) **Mesosphere**: Temperature decreases again due to a sharp decrease in air density and heat capacity.

d) **Thermosphere**: Sharp increase in temperature due to

X-rays from the Sun being absorbed by nitrogen and oxygen.

i) Causes these 2 atoms to ionize.

ii) Higher levels called the **ionosphere** $\Longrightarrow$ atoms completely ionized.

iii) Although temperatures are high ($T > 1000°$C), air density is very low so total heat content is low.

2. Ozone depletion.

a) Ozone (O_3) in the stratosphere absorbs solar UV light.

b) UV light has higher energy than visible light $\Longrightarrow$ enough energy to break apart complex molecule chains.

i) UV light can alter the structure of the DNA molecule $\Longrightarrow$ gives rise to **mutations**.

ii) Most mutations are bad (*i.e.*, harmful) to living organisms $\Longrightarrow$ cancer results.

c) Ozone reacts with hydrofluorocarbons (a common refrigerant):

i) $CH_3CHF_2 + O_3 \rightarrow CO_2 + H_2O + CH_2F_2$
(ethylidene fluoride) + (ozone) $\rightarrow$ (carbon dioxide) + (water) + (a hydrofluorocarbon radical).

ii) The ozone disappears! The resulting molecules have no absorption lines in the UV $\rightarrow$ the solar UV radiation is able to reach the ground.

3. The Greenhouse Effect.

a) How a greenhouse works.

i) Visible light from the Sun is able to pass through the glass of a greenhouse and heats the inside of the greenhouse.

ii) The insides warms to a temperature which emits IR light $\Longrightarrow$ radiates like a blackbody.

iii) The glass is *opaque* to IR light $\Longrightarrow$ the IR photons cannot escape into the outside environment — the greenhouse heats up!

b) CO_2 and H_2O gas in the Earth's atmosphere works the same way as the glass in a greenhouse.

i) Solar visible light passes through the atmosphere unimpeded.

ii) Heats the ground so that it radiates IR light.

iii) IR light then radiates outward back into space, however, the CO_2 and H_2O absorb this light which heats the atmosphere.

c) If it wasn't for CO_2 and H_2O, the Earth's atmosphere (and surface) would be too cold for liquid water to exist early in the history of the planet $\Longrightarrow$ life would not have formed or evolved.

d) The burning of fossil fuels releases tremendous amounts of gaseous CO_2 into the atmosphere.

i) CO_2 abundance has increased by over 20% over the past 100 years due to the industrial revolution.

ii) The average temperature of the Earth also has increased (by about 3 K = 3°C) over this same time period.

iii) The hypothesis has been made that the increased CO_2 abundance has caused this temperature increase.

e) Venus has experienced a **runaway greenhouse effect** which we will discuss later.

D. The Moon's Surface

1. The Moon's surface can be subdivided into 2 main type of topology:

a) **Highlands**: Mountainous regions with numerous craters (the brighter regions, the oldest surface of the Moon).

b) **Maria**: Smooth lava plains with relatively few craters (the darker regions).

2. The Moon is in **synchronous orbit** with the Earth $\Longrightarrow$ rotation period = revolution period.

a) One side always points towards the Earth.

b) The *near* side has many maria.

c) The *far* side has no maria.

d) **The far side is <u>not</u> the same as the dark side!**

3. The craters are a result of impacts, most of them resulted from the final epochs of the planetesimal bombardment.

a) The largest impact basin on the Moon is Mare Imbrium.

b) Some of the more recent impact craters show bright *rays* of material radiating from them (*e.g.*, Tycho and Copernicus).

E. The Moon's Interior

1. We have learned much about the Moon from the rocks returned and seismographs left on the Moon by the **Apollo** manned-Moon missions (*i.e.*, Apollo 11 – 17 [13 never landed]).

2. We have learned that the oldest rocks from the Moon (from the highlands) are 4.6 billion years old — the same age as the meteorites.

3. The maria are a bit younger from 3.1 to 3.8 billion years old.

4. The Moon has virtually the same average density as the Earth's mantle $\Longrightarrow$ composition must be similar.

5. The Moon's interior is subdivided into 3 distinct layers:

a) Small, solid **iron-rich core** ($R < 700$ km).

b) Plastic **asthenosphere** (650 km thick).

c) Solid **lithosphere** (800 km thick) which includes the solid mantle and a solid crust.

i) Moon's crust is thicker on the far side (100 km).

ii) Moon's crust is thinner on the near side (60 km).

iii) This is why the maria is only seen on the near side.

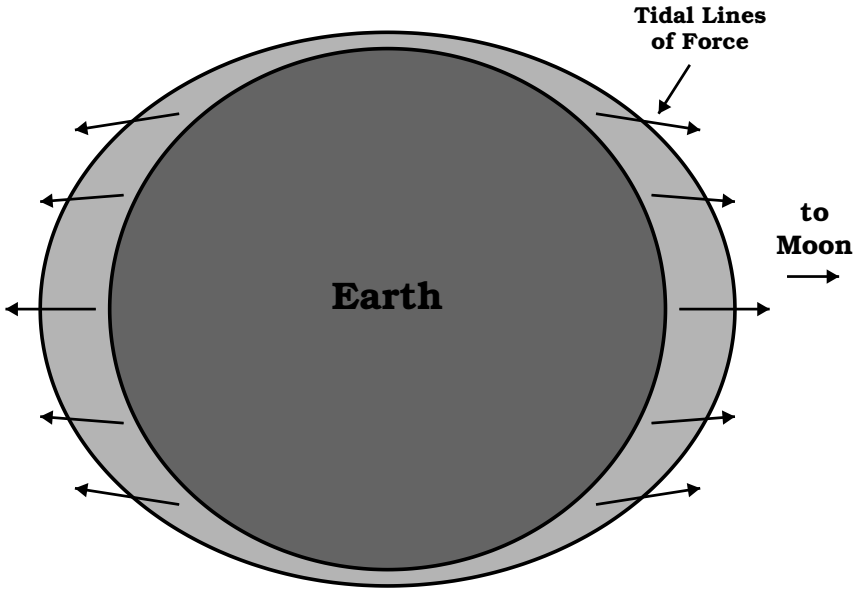
6. The maria lava plains are made up of denser material than the highlands. As a result, the Moon is a bit more massive on the side towards the as compared to the far side. This is the reason the Moon is tidally locked to the Earth (*i.e.*, synchronous rotation).

7. Since the Moon's interior is solid and spins slowly (once every 27.3 days), the Moon doesn't have a magnetic field.

F. The Earth's Tides

1. Just as the Earth has tidally locked the Moon into always pointing one face towards it, the Moon's gravitational field rises tides on the Earth.

2. **Tidal forces** are the differences in the gravitational pull at different points on an object.



3. The Sun also causes tides on the Earth.

a) When the Sun and Moon are co-aligned with the Earth (new or full phase), **spring** or high tides are produced.

b) When the Sun and Moon are at quadrature (90° angles,

1st or 3rd quarter phase) with each other, **neap** or low tides result.

4. Due to the Earth's rapid rotation, the tides are a little ahead of the overhead position of the Moon.

a) The tidal bulge on the leading side of the Earth produces a small forward force on the Moon that causes it to slowly spiral away from Earth (4 cm per year), which has been confirmed by instruments left on the Moon by the Apollo astronauts.

b) Since angular momentum must be conserved, as the Moon's orbital period increases, the Earth's spin rate must slow down (0.0016 seconds per century).

c) As a result, early in its history, the Moon was closer to the Earth and the Earth spun much faster in the past.

Example VIII-1. What was the distance of the Moon in 3000 BC and how long did the day last?

$\Delta T = 5000$ yrs = 50 centuries

$\Delta P_\oplus = 0.002$ sec/cen * 50 cen = 0.1 sec $\Longrightarrow$ tenth of a second shorter day!

$\Delta r = 4$ cm/yr * 5000 yr = 20,000 cm = 200 m = 0.2 km closer to the Earth!

G. The Moon's Formation

1. There have been many hypotheses presented for the formation of the Moon.

2. Any accepted theory of the Moon's formation must take into account the following constraints:

a) Moon's composition must be matched (not much Fe & Ni, nor light elements).

b) Angular momentum problem — Moon must form with its relatively low total angular momentum of the Earth-Moon system.

c) Moon's mass must be obtained.

3. There used to be 3 main competing theories (prior to the Apollo missions) for the Moon's formation $\Longrightarrow$ none of them pass the above constraints set by the Apollo missions.

a) **Fission theory**: The Moon was pulled out of the Earth from the rapid rotation of the proto-Earth.

i) Supporting: (1) Moon's average density (3340 kg/m^3) is similar to the Earth's outer layers; (2) Perhaps the Pacific basin was the original site of the ejection.

ii) Against: (1) The Moon has no water, unlikely to have spun out of the Earth due to fission; (2) The Moon has more **refractory elements** (*i.e.*, those that melt at a higher temperature) than **volatile elements** (*i.e.*, those that melt at lower temperature) — formation occurred at high temperatures; (3) The Earth-Moon system would have a much higher angular momentum than observed; (4) The surface of the Earth is always changing due to plate tectonics, as such, the Pacific basin didn't even exist when the Earth was young.

b) **Capture theory**: The Moon formed elsewhere in the solar system and was later captured by the Earth's gravitational field during a close encounter.

i) Supporting: (1) The refractory to volatile element ratio may indicate that the Moon formed closer to the Sun than Earth; (2) The Moon's orbital plane is similar to the ecliptic plane — suggests Moon formed in the planetary disk around the Sun.

ii) Against: (1) The Moon would have to have coasted to within 50,000 km from the Earth at exactly the right speed to put it into Earth orbit from a solar orbit <u>without</u> hitting the Earth; (2) Again, the Earth-Moon system would have a much higher angular momentum than it currently has.

c) **Cocreation theory**: The Earth-Moon formed at the same time as a double planet from the solar nebula in the same location from the Sun.

i) Supporting: (1) Moon in virtually same plane as the ecliptic; (2) Water could have been baked out of small planetesimals by the early Sun before accreting into the Moon.

ii) Against: Why doesn't Venus and Mars have such a large Moon too?

4. The results from the Apollo mission has presented a new theory which is the currently accepted theory of the Moon's formation: the **collisional ejection theory**.

a) The Earth was struck by an object perhaps as big as Mars towards the end of the planetesimal bombardment, after the Earth had differentiated.

b) This collision ejected mantle debris from which the Moon formed.

c) Supporting: (1) Apollo mission found that lunar craters resulted from impacts (some very large) and not volcanos, such large impacts surely took place on Earth as well, including perhaps a Mars-sized object; (2) Collision would have vaporized any water and volatile elements from the ejected material; (3) Density of Moon similar to Earth's mantle — Moon's small amount of iron results from the Earth already being (partially) chemically differentiated; (4) Debris would lie in the same plane as the ecliptic since the colliding body would have been in the ecliptic (*i.e.*, a large planetesimal); (5) Such an impact could have given rise to the Earth's axis tilt; (6) Earth-Moon total angular momentum could be produced by such a collision.

d) Against: Planetesimal would have to be in a relatively small range of masses to eject enough material to form the Moon, yet not be large enough to completely destroy the Earth.

e) See Figure 8.33 in the textbook which shows a supercomputer simulation of such an impact that may have produced the Moon.

5. Once the material was ejected from the Earth, the rocks accreted into the Moon. As the Moon solidified from the outside in, the still molten mantle of the Moon caused much volcanism in the

regions of the Moon's crust that were relatively thin over the first billion years of the Moon's life $\Longrightarrow$ great lava plains formed in these lower basins (*i.e.*, the maria).

6. The low crater density on the maria indicates that the planetesimal bombardment ceased very rapidly during the first half billion years of the solar system's life $\Longrightarrow$ **number of craters on a planetary surface gives us some clues of the age of a surface**.