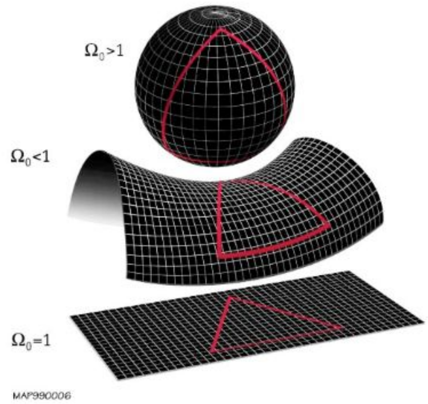
Unit 1

Chapter 1: scientific theory and the Big Bang

- The scientific theory
  - Hypothesis
    - An educated guess based upon observation
    - Can be supported or rejected through experimentation but it cannot be proven to be true
  - Theory
    - A scientific theory summarizes a hypothesis that is supported by repeated testing and observation
    - It is valid as long as there's no evidence to dispute it
  - Law
    - Explains a body of observation
    - Explains things but do not describe them
- The big bang
  - The theory
    - An effort to explain what happened at the very beginning of the universe
    - At the birth of the universe, time and space were created in a gigantic expansion that emanated from a "singularity"
      - A singularity is an area in space-time where gravitational force is so high that all known laws of physics break down and do not apply
  - The observations (evidence)
    - Three pillars of proof
    1. Recession of stars/galaxies (as described by Hubble's Law)
    2. The characteristics of cosmic microwave background radiation
    3. The abundance of light element
- Hubble's law
  - Edwin Hubble
    - Demonstrated that there were many galaxies in the universe - not just the Milky Way
    - He proved that the universe is expanding
    - He showed us how to measure distances in space
  - Light's redshift and Hubble's Law
    - Doppler shift or Doppler effect - when an object coming toward you makes a sound, the sound waves are compressed by the motion of the noisy object and sounds different to you than when the same sound waves are being carried off away from you
    - Waves of light behave somewhat the same
    - If the light source is moving toward the observer the light wavelength appears to shorted (blue-shifted)
    - If the light source is moving away from the observer the light wavelength appears to lengthen (red-shifted)
    - The more distant a galaxy is from us, the longer its light takes to arrive, thus more "red-shifted" it appears when it finally arrives
    - Hubble law: $v = H_o d$
      - v - velocity (km/s)
      - d - distance of the star/galaxy away from earth in parsecs (1 parsec = 3.46 times the distance light travels in one year)
      - H_o - Hubble constant or speed of expansion of the universe (somewhat wrong)

- Cosmic microwave background radiation
    - It is estimated that it was extremely hot in the first seconds of the universe and as it expanded, it cooled
    - Hot light photons lost energy and dropped from visible light to microwave
    - The cosmic microwave background (CMB) represents the very last remnants of the light/heat energy of the Big Bang's initial expansion
    - Supported by the fact that while the general temperature of space should be 0 K, the actual temperature is 2.726 K
- Abundance of light elements
    - Ratio of all the various atoms of the three lightest elements: hydrogen (75%), helium (25%), and lithium (trace)
    - They originated from one single ratio of the first subatomic particles of matter that can be formed from a super hot environment
- Shape of the universe
    - The universe might have a positive curvature, like a sphere
        - It's called a "closed" universe
        - The universe would be finite in size but without a boundary
        - Closed universes are also closed in time: they eventually stop expanding, and then contract in a "big crunch"
    - The universe might be "open", or have negative curvature
        - Saddle-shaped
        - They are infinite and unbounded, parallel lines eventually diverge
        - Open universes expand forever. With the expansion rate never approaching zero



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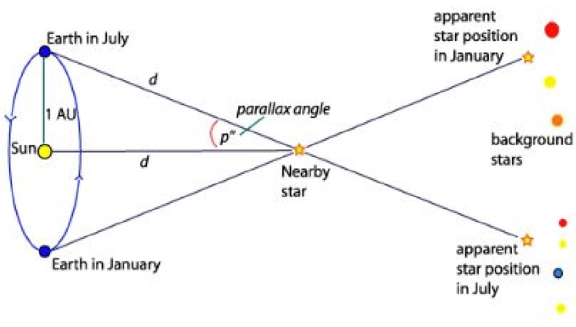
    - The universe might be flat
        - They are infinite in spatial extent and have no boundaries, parallel lines are always parallel
        - They expand forever, but the expansion rate approaches zero
    - For all 3 models, a density parameter is critical
        - Positive curvature - there is more than enough matter around to allow gravity to pull everything back ($\Omega o>1$)
        - Negative curvature - there is insufficient matter around to allow gravity to act and stop the expansion
            - Density parameter is less than 1 ($\Omega o<1$)
        - Flat - there is exactly the critical value of matter around that will prevent the universe from pulling back together or from expanding indefinitely to oblivion ($\Omega o=1$)
    - What affects gravity
        - Conventional matter: stars, planets, asteroids, comets, etc
            - Only less than 5% of the universe
        - Dark matter: matter we have never seen because it gives off no electromagnetic energy but we know it exists because we can detect its gravitational attraction to conventional matter
            - Only 27% of the universe
        - Dark energy: repels matter and acts in opposition to gravity and controls the expansion of space

- Age of the universe
  - Radioactivity
    - Elements that are radioactive breakdown to form other components and give off energy
    - We can figure out the age of the universe by observing the compositions of gases around old stars, knowing the exact radioactive processes required to produce these gas compositions from the very first elements, and knowing all the time factors involved in breaking down one component to yield others
  - Hubble's expansion constant
    - H_o - constant for the expansion rate
    - There have been many refinements to H_o but it's possible to use Hubble's equation to determine the age of the most distant light sources we can find
    - The Hubble Space Telescope found white dwarf stars that gave dates between 12 and 13 billion years
    - It was found that the age of the universe had to fall between 13 and 14 billion years
  - Cosmic microwave background radiation
    - Offers the most accurate view to date of conditions in the early universe
    - Assuming the right model has been developed, the universe is 13.80 +/- 0.04 billion years old
- Neil Turok
  - Claims that there have been many Big Bangs and universes, and that there will be many more
  - The Big Bang represents just one stage in an infinitely repeated cycle of expansion and contraction, and that neither time nor the universe has a beginning or eng
  - A universe consists of two infinitely extensive sheets, separated by a very thin layer of energy
    - Once in a while, the intermediate layer becomes unstable, gravity starts pulling things together, the layers bounce together, and - from the point of the contact - sufficient energy is generated to produce another Big Bang

Chapter 2: time and space

- Light years
  - A light year is the distance that light travels in one year
  - Light travels at about 300,000 km/sec, there are 31,500,000 seconds in a year, so light travels 9.4608 x 10^{12} km per year
- Measuring light years
  - Up to 500 light years distant
    - Trigonometric parallax - relies on an object appearing to be at a different place relative to the background, depending on your viewpoint
    - Kinda like when you hold out a finger while looking with one eye and when you switch eyes, the finger jumps from one position to another
    - As earth rotates around the sun, the nearby star appears to "wobble" relative to the distant stars
    - Looking at the star in January vs July, the telescope would've moved a tiny angle and measuring the angle, and knowing the distance that earth has traveled in 6 months (2 astronomical units/300 million km), we can calculate the distance of the star



- 500 to 500 million light years distant
  - First technique is using the brightness/luminosity of stars using the Hertzprung-Russell diagram that relates the luminosity of stars to their temperature
    - Using a calibrated colour chart to determine the temperature and then measuring the intrinsic brightness (true brightness) as well as apparent brightness
    - Apparent brightness = intrinsic brightness/(4 × π × distance^2)
    - Called the main sequence fitting
    - Good for distances up to 150,000 light years away
  - Second technique uses “marker stars” that have a special property - they have a pulsing brightness that peaks with absolute regularity which is completely related to the star’s brightness
    - Aka Cepheids
    - Once you find a Cepheid and carefully measure the time between one brightness peak and the next, it gives you the intrinsic brightness value
    - After that, you use the first technique
    - Good for distances up to 500 million light years away
- Beyond 500 million light years
  - Using Hubble Law

- The scale of space
  - In our immediate environment is a group of about 40-50 galaxies, together called the Local Group
    - Andromeda Galaxy is the largest, and the Triangulum Galaxy is the smallest
    - Andromeda Galaxy is hurtling toward the Milky Way Galaxy at around 500,000 km/h and is expected to crash in about 3 billion years

Chapter 3: matter and the nebular hypothesis

- The chemical elements
  - Element: a substance that cannot be broken down to anything simpler by any chemical means
  - Atom: a particle of matter that has the unique properties of an element
    - Contains a central nucleus, protons, neutrons, and electrons
  - Ions: an atom with either a negative charge or positive charge
  - Isotope: all atoms of a particular element have the same number of protons but may contain different numbers of neutrons
  - Radioactivity: the spontaneous breakdown of unstable atoms with the production of energy and other particles
    - Fission - a breakdown of the nucleus of a relatively heavy atom into 2 other lighter particles plus energy
    - Fusion - the combination of two lighter atoms/isotopes to make one heavier atom/isotope plus energy
  - Supernova: the explosive death of a massive star
  - The periodic table of elements: an arrangement of all the known chemical elements in a table according to a defined order of increasing atomic number
  - The elements - from first to last
    - The first seconds and minutes after the big band, it resulted in the production of hydrogen, helium, and lithium

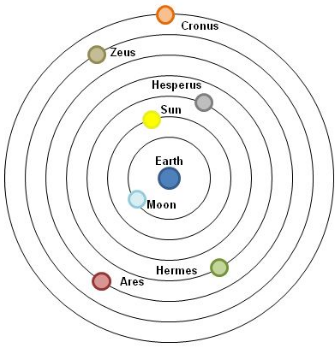
- The nebular hypothesis
  - Suggests that the solar system formed over a relatively brief span of time and all as a unit, from a nebula, or cloud, of interstellar gas
  - ~5 billion years ago, a dark, formless nebula floated within the Orion Arm of the Milky Way
  - The enormous, low-density gas cloud spread out over a large volume of space and contracted under its self-gravity
  - The cloud began to shrink and flatten and collapsed under its self-gravity
  - Not all gas clouds collapse but this one did probably due to the recoiling from the shock wave produced by a nearby supernova
  - The collapsed region increased in density when the contraction started; atoms were banging about vigorously, generating heat in the process
  - Eventually, the particles became densely packed that heat can no longer escape
  - The particles near the center wind up moving at very high speeds which provided enough pressure to stop any further collapse and fusion reactions can take place
    - A star is born
  - Conservation of angular momentum
    - Momentum: a measure of an object’s tendency to move at a constant speed along a straight path
    - Angular momentum: a measure of the amount of spin of an object
    - Conservation of angular momentum: if no outside force acts on a spinning object, the object's angular momentum will not change with time, no matter how the object interacts with other objects
  - Condensation of the planetary disk
    - The center of the disk was very how and the outer parts were cool
    - The nebula had the same composition everywhere both before and after the slow collapse and flattening into a disk
    - Homogeneous composition - suggests that the planets should all form with closely similar compositions but they do not because of the temperature gradient
    - In the cooler outer parts, the temperature was low enough the everything condensed
    - Closer to the sun, where it was much hotter, not everything could condense
      - Substances like hydrogen, water vapour, etc would boil off
      - The refractory elements (elements that do not readily respond to heat like metals) could condense and freeze
  - From pebbles to planets
    - The small grains of refractory materials quickly grew to the size of pebbles
    - These pebbles moved in the same direction, orbiting the sun, and when 2 pebbles collided it was more gentle fashioned and wound up sticking together (accretion)
    - As they grew, the gravitational forces would increase
    - They accumulate into larger lumps to create stones, boulders, planetesimals, and protoplanets
  - The leftover gases were sept out of the solar system towards the end of the formation of the planetary system
    - Evidence of this is:
      - Solar winds from the sun that gives off charged particles

        - A class of stars called T Tauri stars is believed to be similar to how the sun would have looked at the time of its formation and it has been determined that these stars have very strong winds
        - The atmospheres we now find around the rocky inner planets are almost not what they were when the planets first formed
            - They were completely swept off at some early stage which resulted in outgassing of the planets (the release of volatile substances by volcanoes)
    - Predictions
        - The bombardment rate (number of collisions) should have been very high early on, but fallen off fairly precipitously as time passed
        - Late in the formation process, there must have been some large lumps moving around the solar system
            - Not all would have been orbiting in completely parallel paths, so there may occasionally have been really vigorous collisions between enormous fast-moving lumps of rock
        - The collisions influenced
            - Why Uranus is tipped on the side
            - Why the rotation of Venus is retrograde
            - How Earth's mood came to be (Earth was clobbered by a Mars-sized planet early in its life)
            - Why Mercury's orbital inclination varies chaotically

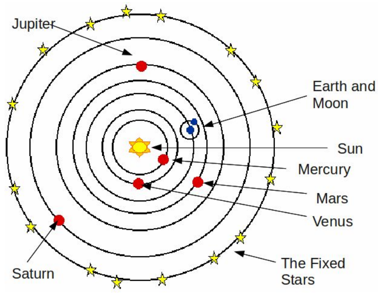
Unit 2

Introduction - the solar system

- Geocentric model: Earth is at the center of the solar system
- Heliocentric model: the sun is at the center of the solar system
- The pioneers and their models



    - Pythagorus/Plato (530 BC)
        - One of the earliest models where the Earth is a stationary object in space surrounded by a sphere which contained everything else
        - The objects inside the sphere rotated slowly east at speeds depending upon how far they were from Earth
    - Aristarchus (310-230 BC)
        - He experimented with placing the sun at the center instead of the Earth and the geometry seemed o work and seemed to be able to predict events in the solar system

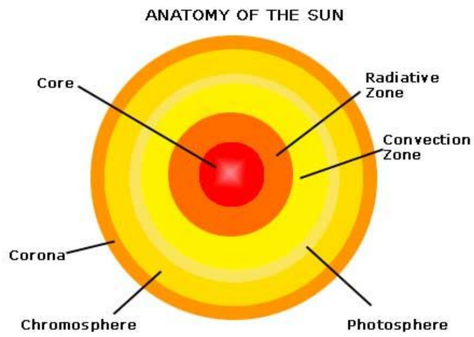


    - Ptolemy (85-170 AD)
        - Church boy put Earth back in the center and other objects he could see on moving spheres
        - Accepted by the church but totally wrong
    - Copernicus (1514)
        - Put the sun at the center of the system, had Earth rotate about the sun, and had Earth revolve on an axis once per day
        - He published a book with his friends and his friends inserted a preface that indicated that the contents were handy for calculating planetary position but should not be taken as anything representing reality

- Tycho Brahe (1546-1601)
  - He witnessed a supernova one night and was amazed that the light could be seen even during days and appeared at exactly the same spot no matter where it was observed
  - He concluded that it was very much further away and it lead the King of Denmark to give him gold to build the world's first state-of-the-art observatory
  - He acknowledged Copernicus' model and proposed a system that kept Copernicus' best results while avoiding finding an explanation for a moving Earth
    - The sun moves around Earth, dragging the rest of the planets with it
- Johannes Kepler (1571-1630)
  - It seemed to him that the planets were not sitting upon a whole series of celestial spheres, but that they had somehow been pushed into their orbits by the sun
  - He figured that there was a magnetic force that was strongest near the sun
  - Developed three laws
    - The construction of an ellipse where the sun was at one focal point
    - The imaginary line joining a planet and the sun sweeps equal areas of space during equal time intervals as the planet orbits
    - The squares of the orbital periods of the planets are directly proportional to the cubes of the semi-major axes of their orbits
  - Perihelion: the point of nearest approach of a planet to the sun
  - Aphelion: the point of greatest separation
- Galileo (1546-1642)
  - He improved the existing telescope by polishing the lenses and magnifying the view 8-fold and then later 33 times
  - He observed the moon, sunspots, and Jupiter
  - He published a book promoting the Copernicus theory

Chapter 4: a star called the sun

- Anatomy of the sun
  - The sun is made of gas that becomes denser as you move toward the center of the sun
  - The photosphere (visible outer layer) - the depth within the gas at which we can see no deeper toward the core
  - The chromosphere is the irregular layer of gases surrounds the photosphere and is invisible to the eye
  - The corona merges into the chromosphere and it extends for millions of km into space



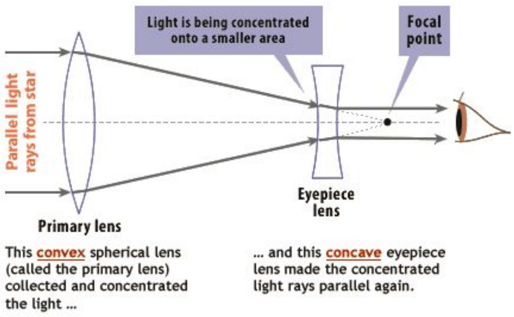
- Sun physical facts
  - Diameter about 1.4 million km (*about 109 times the diameter of Earth*).
  - Volume about 1.3 million times that of Earth.
  - Mass is about 330,000 times that of Earth (99.8 % of the Solar System's mass).
    - Age is just over 4.6 billion years
    - Rotation period (because the Sun's body is not rigid, as it rotates, mass is transferred to its middle, giving the whole body a slightly oblate shape
      - **Oblate**: an equatorial diameter greater than that between the poles of rotation)).
    - At the Sun's equator: 25 Earth days
    - At the Sun's poles: 35 Earth Days

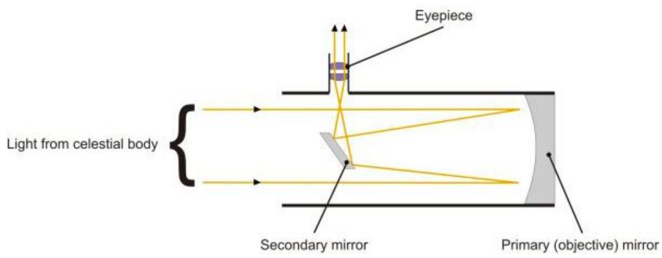
    - Temperature: **Kelvin** (**K**) is a scale of temperature, like Celsius; each division of K is equal to each division of C – but they have different zero points. Zero for Celsius is the point where water freezes (0 °C); zero for Kelvin is the point where all motion within an atom ceases (0K = -273 °C). You can calculate K from °C simply by adding 273.
        - Interior: 15,000,000 K
        - Surface: 5800 K
- Distance measurements inside the solar system
    - Distance between Earth and sun is ~150 mil km
    - One anatomical unit (1 AU) = the mean average distance between the sun and Earth
        - Mars is 1.5 AU from the sun, Pluto is 39.5 AU
- Chemical composition
    - Spectroscopy
        - The measurement and analysis of energy spectra to determine the composition of matter
        - The device used is a spectrometer or spectrograph, which records the spectrum of light emitted (or absorbed) by a given material
        - W. H. Wollaston passed sunlight through a prism and saw dark lines crossed the rainbow band
        - Scientists found that the dark lines were characteristic of particular elements
    - The genesis experiment
        - Scientists have thought that samples of material streaming out from the sun, caught within the solar wind would not only be a direct sample of the sun's composition but also would closely resemble the original dust, gas, and ice from which the bodies of the solar system evolved
        - NASA's Genesis mission was set out to capture particles of the solar wind and return them for study on Earth
        - To capture the solar wind, they constructed collection tiles or foils of materials such as gold, sapphire, and even diamonds
        - When the spacecraft returned to earth, its parachute failed to open and it slammed into the desert
        - They were able to separate the samples and found that the isotopic compositions of oxygen and nitrogen implanted in the wafers were significantly different to those in most of the solar system objects
- The sun in action
    - In the chromosphere, there are prominences - arcs of gas that begin on the bright surface and soar to as much as 10,000 km into the corona
    - Even more dramatic are flares - short-lived gas eruptions that generally last for no more than 20 min
- Magnetic fields
    - Earth has a strong magnetic field produced by an interaction between the solid and liquid metal core
    - The sun also has a magnetic field generated by the interaction of the unique properties of matter in the different layers inside the sun
    - The magnetic fields are like giant bar magnets with a north and south pole
    - The poles switch on earth irregularly and on the sun every 11 years or so
    - Right now we are emerging from solar maximum

        - The clearest manifestation of switch time for the sun is the development of a great number of sunspots (a region of the sun's photosphere marked by lower than average temperature appearing black)
- The solar wind
    - Made up of plasma (ionized gas) that escape because of their high kinetic energy
    - The magnetic field volume around a body like Earth is called the magnetosphere
    - The solar particles interact with the molecules of gas in the upper atmosphere creating aurora borealis in the north and aurora australis in the south
- Life and death of the sun
    - At about 4.6 billion years along, the sun is halfway through its cycle and has fused hydrogen into helium, yielding great amounts of energy
        - The sun has grown 30% brighter and bigger and will expand into a red giant
    - Once the helium is fused into carbon and oxygen it will blow off its outer envelope leaving its core to cool and become a white dwarf
    - When it stops altogether it ends up as a black dwarf

Chapter 5: geometry of the solar system

- Tools of the trade
    - Optical telescopes
        - Gathers up light and allows you to examine an image at a focal position
        - The atmosphere acts like a huge distorting lens
        - To see stars clearly, you can either devise a system that will compensate for the motion of the atmosphere or you can move the telescope outside the atmosphere
        - Two types of astronomical telescopes
            - Refractures - collect light by means of a glass lens
            - Reflectors - collect light with a curved mirror
        - World's largest optical telescopes are the two Keck telescopes mounted on Mauna Kea Hawaii





        - An example of a joint-venture instrument is the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii
        - All telescopes on Earth has to make some compensation for Earth's atmosphere and the distortion it creates
        - The Hubble Space Telescope (HST) orbits 600 km above Earth, has a 2.44 m mirror mounted inside the hollow tube, is fitted with a great array of signal detectors, and is operated 24 h/day
    - Non-optical telescopes
        - Aka invisible astronomy
        - Collects every other energy range (gamma rays, x-rays, ultraviolet rays, infrared, and radio waves)

        - If you want to insert a satellite into orbit around Earth, it may carry one or more types of non-optical telescopes, and you need a rocket which will deliver orbital velocity (velocity to place the satellite into a position that exactly balances gravity's pull on the satellite with the inertia of the satellite's motion)
        - Geostationary satellite - the satellite stays right over the same spot at the time
        - To add more power to send a telescope to Mars, you need to have it attain escape velocity (the minimum velocity needed for an object to just overcome Earth's gravitational attraction)
- Classification of planets
    - Terrestrial planets - 4 planets closest to the Sun are dense, made mostly of rock and metal, and fairly small, and Earth and Mars have satellites
    - Gas giants - 4 large planets aka jovian planets that are huge, low density, composed mostly of hydrogen and helium and surrounded by rings and many satellites
    - Between the terrestrial planets and the jovian/gas giants is the asteroid belt
        - Largest object in the belt is called Ceres
    - Pluto - too small, too dense, has a satellite that was almost as big as itself, and follows a mildly eccentric orbit rather than the nearly circular ones of other planets
    - Past pluto there's a thick band called the Kuiper Belt consisting of icy bodies
        - Eris and Sedna are large objects in the belt
    - The outer limits of the solar system is an enormous belt of icy bodies called the Oort Cloud
        - Region of comets
    - According to the International Astronomical Union there are 12 planets in the solar system
        - A planet is a celestial body that has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a nearly round shape and is in orbit about a star, and is neither a star nor a satellite of a planet
        - The 4 terrestrial planets
        - The 4 giant gas planets
        - Pluto
        - Charon
            - Pluto's satellite that was classified as a twin planet
        - Eris
            - The furthest spotted orbiting object 27% larger than pluto
        - Ceres
            - The largest of the asteroids inside the asteroid belt
    - The definition was later reduced
        - A planet is a celestial body that is in orbit around the sun, has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a nearly round shape, and has cleared the neighbourhood around its orbit
        - A dwarf planet is a celestial body that is in orbit around the sun, has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a nearly round shape, has not cleared the neighbourhood around its orbit, and is not a satellite
        - All other objects, except satellites, orbiting the sun shall be referred to as "small solar system bodies"
        - The result is that the solar system contain 8 planets and 5 officially recognized dwarf planets (Ceres, Pluto, Eris, Haumea, and Makemake)

        - Solar system bodies that orbit past the orbit of Neptune have been termed Trans-Neptunian Objects (TNO)
        - All dwarf planets located toward the outer regions of the solar system would be called plutoids; that includes Pluto, Eris, Haumea, and Makemake
- Planetary reshuffle
    - The grand tack
        - According to planetary dynamicists, the big four planets were assembled very quickly and then started interacting with one another as their orbits were pretty close and those interactions pushed them out into different positions
        - Nice model
            - Uranus and Neptune were pushed out
        - Grand tack model
            - Instead of becoming locked in to orbit tightly about the sun, Jupiter gets “caught” by Saturn and both Jupiter and Saturn swing around to move back out into their current positions
            - It explains not only the size and distribution of the terrestrial planets (Mars grows at the outer edge of the mini-disk and gets pushed out into the space cleared by Jupiter’s track), but also how the asteroid belt came to have more rock rich material closer in and more water rich material farther out
            - Also explains how we end up with water on Earth, and sets up conditions for forming our moon
    - The Late Heavy Bombardment
        - The “Nice” and “Grand Tack” models end with the gas giants being pushed out into their current position and as Uranus and Neptune were ejected outward, small orbiting bodies would have their orbits disturbed and they would fall toward the sun and leave bombardment
        - We know that a large proportion of the craters on the moon were made between 4.1 and 3.8 billion years ago - end of planetary reshuffle
        - The surface of Earth has been geologically reworked since the heavy bombardment period so evidence of a late heavy bombardment of Earth is sparse
- Obliquity of the planets
    - The obliquity of any planet is the angle between its equatorial plane and its orbital/ecliptic plane
    - We expect that all planets should have the same sense of rotation and essentially a zero obliquity
        - Is wrong!
    - Toward the end of the planet formation period (planet shuffle stage), the final few large collisions of large protoplanets/planetesimals knocked the planets askew a bit

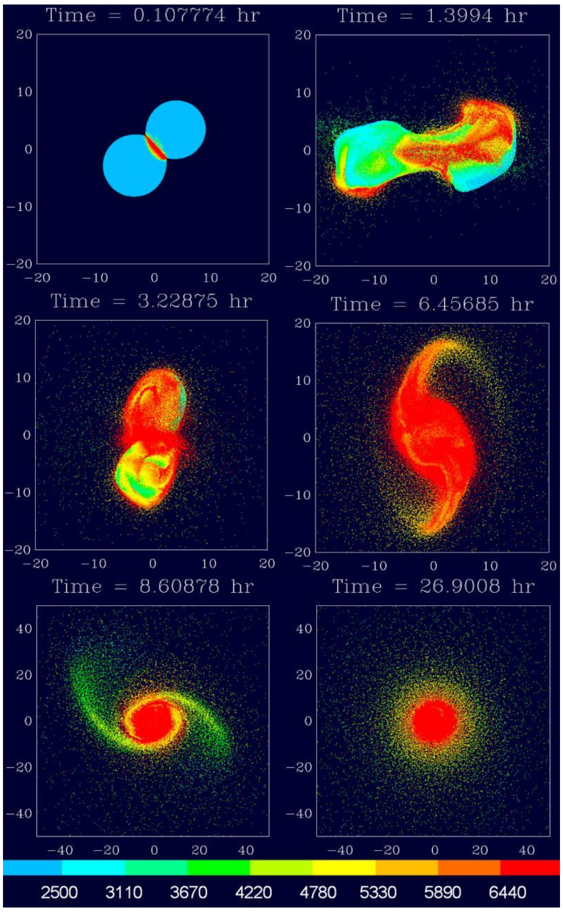
Unit 3

Chapter 6: when two planets collide

- The moon is weird
    - It’s very large relative to Earth
    - Abnormally low density for an object associated with a terrestrial planet
    - A core that amounts to 2-4% of its total mass, compared to 30% for Earth’s core
    - An abnormally high angular momentum
    - The fission hypothesis

        - Proposed by a British astronomer named George Darwin
        - The idea that Earth spun so fast in the early days of its formation that a bulge developed somewhere, and soon a chunk just broke off and was thrown into orbit
        - Rejected because it would require Earth to rotate once every 2.5 h
    - The condensation hypothesis
        - Both bodies formed at about the same time from exactly the same parental “cloud” of dust and gas
        - Rejected because they don’t have the same chemical composition (moon is a tiny metallic core) and the moon doesn’t orbit Earth exactly on an equatorial plane
    - The capture hypothesis
        - Rejected due to big problems
        - The probability for the exact gravitation and dynamic conditions needed for an object the size of the moon to fall into orbit about Earth is unlikely
        - Some chemicals (oxygen isotopes) were so similar between Earth and Moon that there had to be some close “genetic” relationship
        - Every single attempt to model a capture via computer program failed
- The giant impact hypothesis
    - A planet that was somewhat smaller than Earth (Theia), in an unstable orbit about the sun, gave Earth a blow sometime about 4.5 billion years ago
    - Kinetic energy is the energy that a body has by virtue of its motion
        - Exponentially increases with velocity
        - A glancing blow by a planet-sized body would likely result in so much kinetic energy being transformed to heat that both the impactor and Earth would melt in almost an instant
    - Computer simulations best modeled two mild collisions resulting from a glancing blow from a Mars-sized planet
    - What happened
        - Collisions and melting of both bodies
        - The glancing blows gave an increased angular momentum to Earth
        - The metal core of the impactor separated and dropped into Earth, thus giving Earth a large metal core and its remarkably high density
        - The molten mantle material of both bodies mixed, and formed debris in space just above Earth
        - Over a relatively short period of time, some of the debris fell back to Earth, but most of it collected into a single mass to become the moon
    - A challenge is that the mood has similar composition to the Earth rather than Theia
    - With precise measurements, some strong constraints emerged
        - Tungsten (W) isotopes tell us that the moon started life at least 30 million years after the start of the Solar System, which is a long time after a moon-sized body would have formed by accretion
        - The oldest moon rocks were formed when a “magma ocean” cooled, so the moon must have started out with a large enough input of energy to the largely melted
        - The isotopes of oxygen in lunar samples have almost exactly the same proportions as Earth rocks so Earth and Theia compositions must have been well mixed
    - Other research presented new computer simulations of a much larger impact that had been previously thought possible

- The only way to get a match for Earth and moon compositions is to make Theia nearly as massive as Earth
- Low-velocity collisions and subsequent mixing of Theia and Earth over about 26 h
- The halo of material surrounding Earth in the final panel presents the disc of material that would form the moon



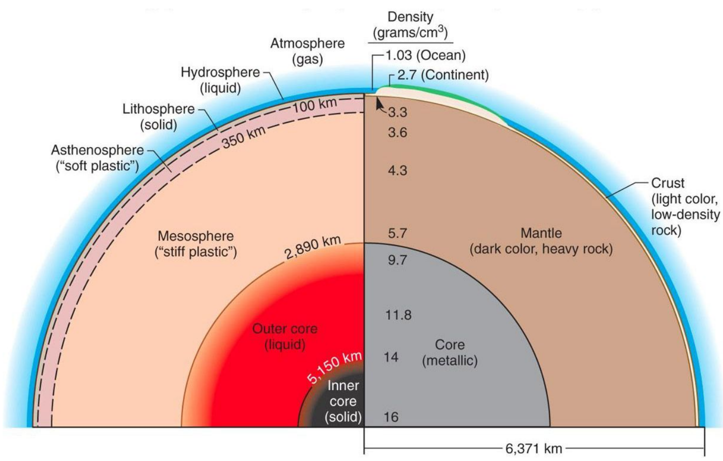
- More research came up with a different conclusion
  - Instead of a low velocity impact, they go for the opposite extreme
    - High velocity impact of a much smaller body
  - In order to spit out enough material to form the moon, Earth has to be spinning really fast (2 h)
  - Combination of the Fission hypothesis and the Giant Impact hypothesis
  - There is a mechanism for slowing down the rapidly spinning Earth (tidal interactions with the sun)

Chapter 7: Earth

- Earth facts
  - Third planet from the sun (1 AU/150 million km)
  - Fifth largest planet
  - Densest major body in the solar system (5.5 g/cm^3)
  - One permanent natural satellite (moon) - the first planet out from the sun to have any natural satellite
  - Plane of orbit (ecliptic) is only 7 degrees from the sun's equatorial plane
  - Orbital path is very nearly circular, the tilt of the rotational axis (23 degrees from vertical now aka obliquity/tilt angle) is primarily responsible for seasons
  - When earth rotates, its rotational axis moves, making a cone-like pattern (process called "precession")
  - Earth has a strong magnetic field generated by electrical currents in the iron-rich core
  - Unique to all planets found in this star system is Earth's atmosphere (78% nitrogen, 21% oxygen, and 1% other)
- Earth's earliest history
  - The iron catastrophe
    - Earth's composition: iron, oxygen, magnesium, silicon, and sulphur
      - Makes up 95% of Earth and iron is 30% of that
    - Since iron is heavy, as the upper 500 km of Earth melted, hot liquid iron from the upper layer would begin to pool and sink under its own weight
    - As iron sank, it released more energy and caused the whole planet to melt
    - Resulted in the removal of iron from the Earth's outer layers to form a liquid core that is nearly 100% iron
    - As Earth continued to grow, the pressure on the innermost core became so great that it became a solid

        - The lighter elements (silicon, aluminum, oxygen) ended up in the outer layers

- A differentiated earth
    - Differentiation
        - There was a general zonation of elements from heaviest at the core to lightest at the top
    - The subdivisions on the left are based primarily on physical properties
        - From surface to core - pressure, temperature, and density increase
    - Lithosphere - a solid, strong, rocky layer in the outer 100 km encompassing both Earth's crust and the uppermost portion of the mantle



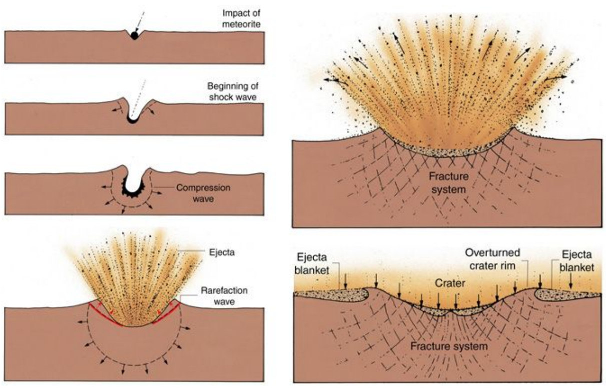
    - Asthenosphere - soft, weak, plastic like rock layer that is 100 - 350 km beneath Earth's surface that is within the lithosphere and asthenosphere
    - Mesosphere - below the asthenosphere where the confining pressure is so great that the rock has to be solid but the temperature is high enough that the material acts like a plastic
    - The core - divided into a liquid outer core and a solid inner core that is nearly pure iron and the temperature is thought to be between 5000 - 7000 C
- Magnets and magnetism
    - Mechanism to generate a magnetic field is a dynamo
        - Mechanical device that converts physical energy to electrical energy
        - Turbulence in the hot liquid of the outer core periodically disrupts the process to the point that the dynamo gets thoroughly confused
            - Magnetic field reversals
- Plate tectonics
    - The lithosphere is divided into segments called plates that move due to processes that occur beneath them
    - The hypothesis of continental drift
        - Leonardo Da Vinci (1508) - recognized that some fossils he had collected were the remains of seashells and seafloor uplift must have taken place
        - Charles Darwin (1830) - recorded important evidence in favour of uplift when he observed that part of the coastline of Chile had been raised up as a result of an earthquake (vertical movement)
        - Alfred Wegener - introduced the idea of continental drift
    - The rock magnetic pattern
        - Paleomagnetism - the study of magnetic properties of rocks
        - Magnetite is a mineral that can become permanently magnetized in basalt rocks
            - As basalt lava spills out on the ocean floor, it cools down (curie temperature) and the magnetic grains in the rock lock in to the magnetic field of the Earth at that time
    - Plate margins
        - Divergent margins - plates move apart, aka spreading centres

        - Convergent margins - plates move together where one plate subducts on another, aka subduction zones
        - Transform fault margins - two plates slide past each other, aka strike-slip faults
    - Convection and subduction
        - Plates move because of heat transfer (radioactive decay)
        - Heat transfer provides the force to move material around, aka convection
        - Seismic tomography - detects lithospheric plates dropping into the asthenosphere and beyond into the mesosphere
    - Mantle plumes
        - The core produces large pockets of hot, less dense, material that starts to rise through the more stable mesosphere above it
        - It continues and gives rise to a plume of hot material that may rise to the base of the lithosphere
        - Once the plume arrives to the base of the lithosphere, it can break through the brittle, cold layer forming volcanoes
- Dating rocks; earth's geological time scale
    - Relative age dating
        - Having arranged rock sequences, you can match them with others around the world, and put together a geological time scale
        - You can divide the time into recognized blocks
            - Proterozoic - big block of time just before 545 million years ago (simple soft bodied cells)
            - Phanerozoic - all of time from the Cambrian period until present day (abundant complex life)
                - Paleozoic (early life)
                - Mesozoic (middle life)
                - Cenozoic (recent life)
    - Absolute age dates
        - Radioactivity provides a "clock" that begins running when radioactive elements are sealed into minerals
        - The rates at which radioactive elements decay have been measured and duplicated in many laboratories
        - What we need to determine the age of most rocks
            - The rate of radioactive decay (half life)
            - The amount of the isotope that is in the process of breaking down (parent)
            - The amount of the isotope produced by the breakdown (daughter)
        - Most common radioactive elements used are uranium and thorium
        - If you want to date something organic you use an isotope of carbon that's radioactive
- Earth's atmosphere, hydrosphere, and the beginning of life
    - The ancient atmosphere
        - The primordial atmosphere consisted of the gasses contained in the solar nebula from which Earth formed (mostly hydrogen and helium)
        - Today on earth, nitrogen makes up 78% of the atmosphere and oxygen is 21% and traces of argon, carbon dioxide, and water
        - Venus and Mars are composed of approximately 96% carbon dioxide, 2-3% nitrogen, and lesser amounts of various other elements

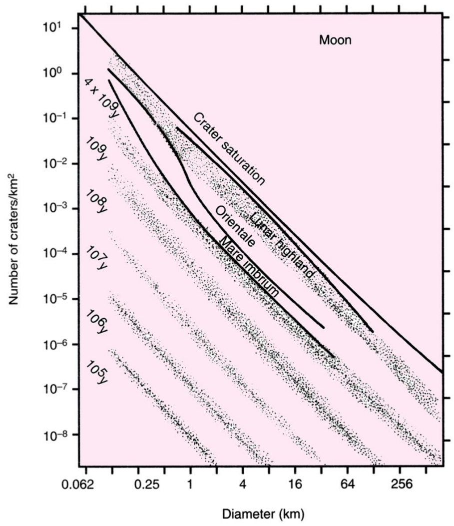
        - Mars' weak gravity cannot hold its atmosphere explaining why it's so thin
        - Venus' atmosphere is extremely high in pressure which is explained by liquid water dissolving into carbon dioxide lessening the amount of gas in the air increasing pressure
    - Hydrosphere and biosphere
        - When the surface of earth had cooled sufficiently, water vapour in the atmosphere started to condense and rain began which created the hydrosphere
            - Closed system - neither lose or gain water
        - Primitive microscopic life eventually appeared on earth in the ocean (biosphere)
        - The biosphere slowly started to change the atmosphere - photosynthesis
    - The rise of oxygen and fall of carbon dioxide
        - Carbon dioxide in the atmosphere is dissolved in water (rain)
        - Primitive life was mainly anaerobics (prokaryotes) that were capable of photosynthesis
        - Paradox: oxygen is poisonous to anaerobic organisms but they are producing oxygen themselves
            - Possible because ancient oceans were rich in dissolved iron that absorbs oxygen
        - The iron would have been consumed and free oxygen began to appear and eukaryotes began to appear
        - Carbon dioxide is adjusted by volcanic deposits, tectonic processes, and biological processes

Chapter 8: the moon

- Tidal coupling - synchronized pattern of the Moon's rotational period and orbital period with the Earth
- Earth has at least one Trojan satellite (an object that has the same orbit as another body, but doesn't collide because it's located in a particular point on the orbit, called the Legrangian point, where it can remain stable)
- The view from earth
    - Gravity tells us that the moon must have a low escape velocity
        - Escape velocity is the initial velocity any object needs to escape gravity
    - Lunar highlands are composed of anorthosite
    - Lunar maria is composed of dark, solidified basalt lava
    - Highlands are old regions where the craters were from the early history of the solar system and maria were formed later
        - Called relative ages because we can tell which features formed first
    - The lava flows that created the maria were too fluid to build peaks so they're just small domes pushed up by lava below the surface where you can see long, winding channels called sinuous rilles
- Craters
    - Asteroids (>100 m - 1000 km) or meteoroids (100 m) makes impact craters that accumulate with time so more craters = older surface
    - Crater making
        - Combination if orbital speed and planetary gravity, meteoroids and asteroids strike planets at 10 or more km/s
        - If the planet has an atmosphere, smaller meteoroids may be destroyed or slowed
        - The moon has no atmosphere so there are craters of all sizes



        - Kinetic energy is converted into thermal, acoustic and mechanical energy upon impact
        - A shockwave compresses the rock and makes it deform around the impact site
    - Cratering curves
        - Impact bombardments can be dated by counting craters and using a plot called cumulative crater size frequency distribution
        - There are more small impactors than large ones looking at the surface
        - Plotting the number of craters of different sizes, they fall on a straight line
        - As exposure time of the surface increases, the total number of craters increases, and the straight line shifts from the bottom left outward toward the top right
        - Crater saturation is the point of saturation when every new crater obliterates an old one
        - Counting craters on the surface you can build up a geological timescale



- Lunar exploration
    - 1959 - Luna 1 was the first lunar exploration (USSR)
    - Pioneer 4 carried lunar photography experiment (USA)
    - Ranger series (Ranger 3, 4, 6, 7, 8, 9) took photos and scientific instrument readings (USA)
    - 1966 - Luna 6 was the first ever to soft land on another planetary body, landing in the Ocean of Storms (USSR)
    - Surveyor also did a soft landing (USA)
    - 1968 - Zond 5 orbited the moon with payload of organisms and then brought it back (USSR)
    - 1968 - Apollo 8 sent humans around the moon and brought them back, Apollo 10 did a dry run without the landing and orbited the moon (USA)
    - July 20, 1969 - Neil Armstrong and Edwin Aldrinlanded on the moon with Apollo 11 and set up experiments, took photographs, and collected lunar samples (USA)
- Moon rocks
    - Every solid rock on the moon's surface is igneous in origin
        - Formed by the cooling and solidification of molten rock
    - Igneous rocks are the most commonly identified rock type in planetary surface studies
    - Rocks from the lunar maria are dark-coloured, dense basalts that are rich in iron, manganese, and titanium
    - Some basalts are vesicular, meaning that they contain holes caused by bubbles of gas in the molten rock
    - The highlands are composed of anorthosite: low density rock containing calcium, aluminum, and oxygen rich materials
    - Large fraction of the lunar rocks are breccias, rocks that are made up of fragments of earlier rocks cemented together by heat and pressure
    - Meteoroid/asteroid impacts have broken up rocks and fused them together making regolith that covers the entire surface
- Surface heat flow
    - The rate at which heat escapes from a body and the rate at which temperature increases as you go into the interior is a small fraction of what's measured on earth

- Seismic activity
    - The moon is seismically much quieter than earth, only having some deep quakes in the interior and surface quakes from impacts
    - Scientists say the moon has a core that is hot and perhaps still partially molten but is small
- Geologic history of the moon
    - The surface of the moon has been completely mapped by US probe, Clementine
    - The four-stage history of the moon is dominated by the fact that the moon is small
    - Stage 1: the moon must have formed in a molten state
        - As the moon cooled, denser materials sank to form a small core, and low density minerals floated to the top to form a low density crust
        - There is no evidence for any lunar magnetic field so there's no core dynamo
        - The radioactive ages of moon rock tells us that the surface solidified from 4.6 - 4.1 billion years ago
    - Stage 2: period that cratering began as soon as the crust solidified
        - Cratering was intense during the Late Heavy Bombardment
        - The largest impacts formed giant multi-ringed crater basins hundreds of km in diameter
    - Stage 3: intense cratering led to lava flooding
        - Some process (probably radioactive decay) heated material deep in the crust and part of the material melted
        - Molten rock flooded the giant basins with lava flows of dark basalts from 3.8 - 3.2 billion years ago
        - The lava flows formed the maria (eg. mare imbrium)
        - Opposite of the Imbrium Basin is now a disturbed landscape called jumbled terrain
        - The largest impact basin in the solar system is the south-pole Aitken Basin on the moon
        - Studies show that the crust is thinner on the near side due to tidal effects, whereas the far side was thicker due to lava flooding it
    - Stage 4: the final period of slow evolution
        - The overall terrain on the moon is almost fixed
        - Impacts will have formed only a few more large craters, and nearly all of the lunar scenery will be unchanged
        - Micro-meteorites will have blasted the soil, erasing everything from previous lunar missions

Chapter 9: mercury

- The only spacecraft to have made a close approach to mercury was Mariner 10
- Much of our current understanding of mercury is based on data from the MESSENGER mission
    - Took 7 years for it to reach the destination
    - Main objective was to determine surface material composition, investigate reflective materials at poles, analyze magnetic fields, and determine if there is a liquid outer core
    - MESSENGER successfully entered orbit around mercury on March 18, 2011 and spent 4 years collecting data
- Mercury looks similar to the moon
    - Rotation has been altered by tidal attraction
    - Their surfaces are heavily cratered

- Their large craters are flooded by ancient lava flows
- Both are small, airless, and have ancient inactive surfaces

- Planet facts
  - Diameter: 4878 km (this is roughly about one and one-half that of Moon).
  - Density: 5.4 grams per cubic centimetre, or g/cc (Earth is 5.5 g/cc).
  - Mean surface temperature: 350°C day; -170°C night.
  - Rotation period: 58.65 days (compared to 24 hours for Earth)
  - Orbital period: 88 days (compared to 365 days for Earth).
  - Orbital speed: 47.87 km/s (that would be 172,332 km/h – which is really moving!)
  - Orbital eccentricity: most eccentric of all terrestrial planets.
  - Orbital inclination: 7 degrees to the plane of Earth's orbit (the ecliptic)
  - Axial tilt: almost too small to measure
  - Magnetic field: present (at about 1.1% the strength of Earth's field)
- Orbital chaos
  - An italian astronomer hypothesized mercury was tidally coupled to the sun just as the moon is tidally coupled to earth (AKA resonance)
    - Wrong
  - The orbital pattern of mercury is the most eccentric of all the planets in our solar system
  - The tidal relationship has imposed a 3:2 spin-orbit effect
- Mercury's surface
  - Surface temperature
    - At perihelion (the point in its orbit when it is closest to the sun), mercury is only 46 million km away from the sun
    - At aphelium (the point in its orbit when it is furthest from the sun), it's 70 million km away
    - Temperature variations on mercury are the most extreme ranging from 427C to -173C
  - Atmosphere
    - Very thin atmosphere consisting of atoms blasted off its surface by the solar wind
    - In addition to hydrogen, helium, and oxygen, mercury's atmosphere contains tiny traces of sodium, potassium, calcium, and magnesium
    - This atmosphere is called an exosphere
  - Craters and plains, cliffs and hollows
    - Mercury has enormous cliffs that are hundreds of km long and are thought to be fault systems
    - Smooth plain (volcanic deposits) cover ~40% of the surface, appearing to be a result of explosive eruptions
    - The largest basin on mercury is called the Caloris Basin
    - Much of the surface is old, cratered terrain, but other areas called intercrater plains are less heavily cratered produced by lava flows that partially buried older crater-pitted terrain
    - Smaller regions called smooth plains appear to be even younger than the intercrater plains that appear to be ancient lava flows
    - Mercury's surface is a uniform gray
    - Albedo is used to describe the proportion of light that gets reflected by a planetary body and mercury has a low albedo
    - There's no evidence of plate tectonics despite the escarpments that appear in some places
    - As mercury cooled, its diameter has decreased by at least 10 km

        - Hollows are puts in the surface, thought to be formed when material beneath was vapourized away after asteroid impacts
- The interior of mercury
    - Mercury is denser than any other planet except earth
    - Its interior contains a large core of dense metals
        - Inner iron core is surrounded by a solid shell of iron and sulphur
    - Magnetic field around mercury was found to have 0.5 - 1% the strength of earth's so part of the core is molten
    - MESSENGER found many tilted craters on mercury meaning that it remained geologically active long after its formation
    - Hypothesis proposed that there was a giant impact when mercury was young that blaster the lower density material into space
- History of mercury
    - Stage 1: mercury formed in the innermost part of the solar nebula, a giant impact may have robbed it of some lower density rock and left it small, dense, and metallic
    - Stage 2: mercury suffered heavy cratering by debris in the young solar system
        - Occurred over the same period as the moon (heavy bombardment period)
        - Because of mercury's stronger gravity, the ejecta from a crater on mercury would be thrown only ~65% as far as on the moon so it doesn't blanket as much of the surface
        - The intercrater plains appear to have formed when lava flows occurred during the early bombardment
        - At the end of cratering, a planetesimal >100km smashed into the planet (Carolis Basin)
        - Cratering rapidly declined, the cooling interior contracted, and the crust broke to form the curved scarps
    - Stage 3: flooding began with lava flows filling some lowlands
        - The Carolis impact may have been so big it fractured the crust and triggered more outpourings of molten lava
        - The lava flows formed the smooth plains
        - The shrinkage of the planet squeezed off the lava channels to the surface
    - Stage 4: slow surface evolution
        - Limited to micrometeorites, which grind the surface to dust
        - Rare, larger meteorites, which leave bright-rayed craters
        - The slow by intense cycle of heat and cold, which weakens the rock at the surface
        - Heat flowing outward is unable to drive plate tectonics that would erase craters and build folded mountain ranges
- Surface composition
    - Mercury has much more sulphur than the other terrestrial planets
    - The minerals that make up the surface rocks are high in magnesium, which is a characteristic of igneous rock
    - The surface rocks are thought to have a high abundance of the minerals pyroxene, feldspar, and sulfide minerals
- Ice??
    - Radar imaging of mercury indicated that in the constant shadows of dozens of high-walled craters at both north and south poles water ice was thought to be seen
    - Spectrometers on MESSENGER measured high levels of hydrogen at mercury's north pole that suggests water ice

  - Mercury's rotational axis is less than 1 degree from the ecliptic which means that there are areas that are never exposed to sunlight

Chapter 10: venus

- Venus is often called the evening star or morning star because you see it for only about 3 hours after sunset and before sunrise
  - Brighter than any other object in the sky except the moon during those times
- Venus is 0.95 times the diameter of earth with very similar density
- USSR finished 15 successful missions to venus, including 10 landings
  - The soviet spacecrafts Venera 9, 19, 13, and 14 transmitted images of the surface
- Best data of venus came from Magellan, the first space probe to be launched from a space shuttle in 1989
- Planet facts
  - Diameter: 12,104 km
  - Density: 5.24 g/cc
  - Mean surface temperature: 462°C
  - Rotation period: 243.01 Earth days (apparent retrograde)
  - Rotational speed: 6.52 km/h (you could easily run faster!)
  - Orbital period: 224.68 days (so 1 day is longer than 1 year!)
  - Orbital speed: 35 km/s
  - Orbital eccentricity: 0.0068 (most nearly circular of all the planets)
  - Orbital inclination: 3.23° to Earth ecliptic
  - Axial tilt: 177.36° (zero or 180 would be vertical)
  - Satellites: none
- Orbit and rotation
  - Venus revolves around the sun in a very slightly elliptical orbit
  - It rotates in a clockwise direction (retrograde) very slowly which is different than the counterclockwise direction most planets have
  - The slow retrograde rotation of 243 earth days and the direct revolution around the sun of 225 days combines to give a venusian day of 117 earth days
  - The clouds rotate in the same sense as the surface of venus but more rapidly
- Atmosphere and greenhouse
  - Venus is completely covered with a thick blanket of clouds consisting primarily of droplets of liquid/solid sulfur and droplets of sulfuric acid
  - Below the sulfuric acid layer, the thick atmosphere is composed of 96.5% carbon dioxide, 3.5% nitrogen, 0.1% - 0.4% water vapour, 130 ppm sulfur dioxide, and 60 ppm free oxygen
  - Large volumes of the atmosphere is escaping into space
  - Venus has a greenhouse effect
    - Carbon dioxide is transparent to in-coming light energy, but opaque to out-going infrared energy
    - Any greenhouse effect begins with incoming short wavelength light energy from the sun warming a planet's surface, but ends up with a surface growth of heat because the inability of the long wavelength infrared energy to escape
  - The surface temperature of venus is about 462C
  - There is evidence of liquid water on early venus meaning that it was cooler in the distant past than now and it took a while for the greenhouse atmosphere to build to full strength

- There is about 150 times more deuterium (heavier hydrogen isotope) per atom of light hydrogen in the venus atmosphere than in earth's
- OH was also detected in the atmosphere meaning that it had an abundance of liquid water
- Without an ozone layer to protect it from ultraviolet radiation, the atmospheric water was broken up and hydrogen was lost in space and the released oxygen formed oxides in the soil
- The runaway greenhouse effect made the surface so hot that even sulfur, chlorine, and fluorine have baked out of the rock and formed sulfuric, hydrochloric, and hydrochloric acid vapours
- The clouds of venus prevent much sunlight from ever reaching the surface, Soviet Vanera spacecraft equipped with searchlights for illuminating the surface, found no need for it
    - Rocks near the spacecraft cast sharp shadows, indicating the lower atmosphere is clear
- Winds at the surface are gentle whereas faster winds are higher up
- Atmospheric circulation on venus is organized as a single, planet-wide pattern

- Geology
    - Impact craters
        - Relatively few and small impact craters (most are medium to huge) because of the dense atmosphere
        - The craters seen appear to be young, rarely filled with lava, indicating they formed after a recent major volcanic activity
        - Suggests the surface of venus is young, about 500 million years old, but the planet is the same age as earth
    - Volcanic features
        - Surface varies from clusters of very small volcanic domes sitting on a fairly level lava field, immense volcanoes, to immense blocky ridges and valleys bounded by faults
        - Coronae - huge dome surrounded by concentric fractures thought to be formed by mantle plumes
        - Many volcanoes appear as flattened domes, called pancake volcanoes, and these are thought to be formed by viscous magma, flattened by the high atmospheric pressure
    - Global volcanic event
        - Venus lacks signs of plate tectonics but it could build up tremendous heat and, like a gigantic pressure cooker, periodically boil over into volcanic eruptions that resurface the whole planet
        - Theory that 300-500 million years ago, the whole planet was resurfaced by basaltic lava flows
    - Weathering/erosion features
        - There are unexpectedly sharp geological features, like knife sharp mountain ridges and cliffs, that show no suggestion of erosion
        - Rocks may be stronger on venus because they have 0 water content
        - Erosion is done by wind but surface winds are relatively gentle
- The interior of venus
    - The interior must be a mix of rock and metal and is hot
    - Missions found no evidence of a magnetic field so there's no magnetosphere
        - The core could be completely liquid metal
        - The core could also be completely solid
- History of venus
    - Venus may have had small ocean when it was young but being closer to the sun, it was warmer, and the carbon dioxide in the atmosphere created a greenhouse effect

  - Venus lacks tensional crustal rifts, and its numerous volcanoes cannot carry must of the heat out of the interior so it gets rid of the heat through large currents of hot magma that rise beneath the crust (coronae, lava flows, volcanism)
  - The low density crust is more buoyant than earths and resist being pushed/pulled into the interior
  - The crust is so hot that it's halfway to the melting point of rock
  - The small number of craters on the surface hints that the entire crust has been replaced within the last half-billion years

Chapter 11: mars

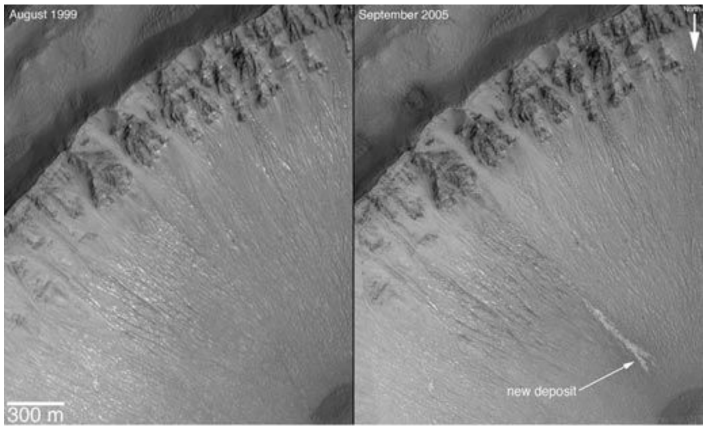
- First effort of producing a map of mars was by German/Italian astronomer G. V. Schiaparelli in 1877
  - In addition to the large scale features, he drew artificial lines across the desert regions, calling them canali (channels) but was misunderstood as canals
- Astronomer Percival Lowell built an observatory in Arizona to study mars and mapped and named hundreds of canals
  - He thought the canals were planet wide irrigation system built to pump water from the ice caps at the poles to the equatorial regions
- By 1907 the public was so sure that life existed on Mars that the Wall Street Journal could suggest that the most extraordinary event of the previous year had been "the proof by astronomical observations that conscious, intelligent human life exists upon the planet mars"
- Planet facts
  - Distance from Sun: 1.52 AU
  - Diameter: 6792 km (about 0.53 of Earth)
  - Density: 3.934 g/cc (Earth = 5.515)
  - Surface temperature: -87°C to -5°C
  - Rotational period: 1.026 days
  - Equatorial rotational speed: 868.22 km/h (Earth's is 1670 km/h)
  - Orbital period: 686.97 days
  - Orbital speed: 24 km/s
  - Orbital eccentricity: 0.0933
  - Orbital inclination: 1.850°
  - Axial tilt: 25.19°
  - Satellites: two (Phobos and Deimos)
- Orbit and rotation
  - A day on Mars is nearly the same length as an earth day - 24 h 40 min
  - A martian year lasts 1.88 earth years
  - Mars' axis is tipped 25 degrees meaning it has seasons
- Missions to mars
  - Functioning spacecraft currently orbiting Mars
    - Mars Reconnaissance Orbiter (2005, USA)
    - Mars Express (2003, European Space Agency)
    - Mars Odyssey (2001, USA)
    - MAVEN (2013, USA)
    - Mars Orbiter Mission (MOM), also called Mangalyaan (2013, India)
  - Functioning spacecraft currently on Mars' surface
    - Mars Curiosity (2011 - present, USA)
    - Mars Opportunity (2003-2018, USA)

- Phoenix Mars lander (2008)
- Viking 1 and 2 (1975, USA)
- Pathfinder (1996, USA)
- The twin rovers Spirit and Opportunity were a success where they completed more than their expected 90 days lifetime
  - Spirit got stuck in a sand trap and all attempts to free it just dug in deeper and because of low power it shut off all systems
  - Opportunity was working in the other martian hemisphere and lasted 15 years from 2003 - 2018
- Mars curiosity
  - Launched by NASA on november 26, 2011 and landed on August 6, 2012
  - Its objectives were
    - To investigate whether mars could or has ever held microbial life
    - To explore the presence of water on mars
    - To explore martian climate
    - To explore martian geology
  - Results include new measurements of the composition of the atmosphere, a chemical analysis of an igneous rock, and soil analysis that showed an unexpectedly large concentration of water from hydrated material and the presence of organic molecules

- Atmosphere and greenhouse
  - Air on mars is 96% carbon dioxide, 2% nitrogen, 2% argon
  - It contains miniscule traces of water vapour and oxygen and its density at the surface of the planet doesn't provide enough pressure to prevent liquid water from boiling into vapour
  - It had a primitive atmosphere of hydrogen and helium, with a bit of argon, neon, methane, and some ammonia
  - Leakage of the primitive atmosphere would have been rapid and replaced by a secondary atmosphere of volcanic emitted gases
  - Volcanism on terrestrial planets releases carbon dioxide and water vapour plus other gases and since mars formed farther from the sun, you expect that it incorporated more volatiles than earth when it formed
    - Mars is smaller than earth so it has less internal heat to drive geological activity so it has not outgassed as much
    - Outgassing occurred early in the planet's history and mars cooled rapidly and now releases little gas
  - How much atmosphere a planet has depends on how rapidly it releases internal gas and how rapidly it loses gas from its atmosphere
    - Rate at which it loses gas depends on mass and temperature
    - More massive = stronger gravitational attracting so the higher the escape velocity
    - Mars is 11% less massive than earth and its escape velocity is 5 km/s
    - Gas atoms can escape from it much more easily than they can escape from earth
  - Mars has lost much of its lower mass gases
    - Water molecules are massive enough to keep but ultraviolet radiation breaks them up
    - Hydrogen escapes and oxygen forms iron oxides that make the planet red
  - Mars has no magnetic field and the atmosphere is thin so solar winds interacts directly with both the atmosphere and the surface
- Clouds and winds

- Areas warmed by the morning sunlight emit water vapour into the air
- Half an hour after darm, the vapour freezes to form clouds of ground fogs of water ice crystals in some regions
- Poleward of latitudes of about 65 degrees, winter conditions lead to freezing of even the CO2 at about 148 k
    - The freezing creates a polar good of CO2 clouds and haze
- The process of local heating causes winds and is a key to the summer onset of global dust storms
- The reddish soil is caused by iron oxides and the polar caps are frozen water and carbon dioxide
- Strong winds can pick up larger grains, enabling them to hop erratically over the surface in a process called caltation
    - Plays a role in erosion
- Dune fields, or large masses of wind-sculpted dunes, are common on mars and earth

- Water and ice
    - The current atmospheric pressure is too low to keep water from boiling away to vapour
    - Many geological features were formed by moving water
    - Evidence of water is still in existence just below the surface
        - The bright linear features were likely caused by water/sediment "slurry" moving down two gullies within the previous few years



    - Mars Reconnaissance Orbiter proved that liquid water commonly flows down gully walls during martian summers
        - The patterns are made by water that is salty, this liquid to a lower temperature than normal water and denser
    - Spectroscopic data from the orbiter revealed the existence of hydrated salts in the recurring deposits
        - The salts are perchlorates that lower the melting point of ice and allow water to flow at temperatures as low as -70C
    - Other evidence detected enough enrichment of deuterium to say that mars had abundant liquid water supplies
    - Mars has permanent polar ice caps
        - North seems to be nearly all water ice while the south appears to have a mix of carbon dioxide ice and water ice
    - The Mars Odyssey spacecraft found remains of ancient water
        - Water ice makes up a significant fraction of the crust from latitude 60 degrees north and -60 degrees south
    - Analysis of rock samples from meteorites that landed on earth found them to be basalts that contain small traces of water and minerals that are deposited by water (1.8% water)
    - A huge ocean apparently covered the northern lowlands 2.5 - 3.5 billion years ago
        - The atmosphere must have been thicker long ago
        - Volcanism was more active in the past

- Mars Express took the photo that shows a small section of Eberswalde crater which was filled with water
- If humans were to reach mars, the don’t have to dig deep to find water and they can use solar power to break it down to hydrogen for fuel and oxygen as a breath of life

- Geology
  - Large-scale surface features
    - November 14, 1971, Mariner 9 orbited mars that mapped the whole planet and photographed volcanoes, sand dunes, and dry riverbeds
    - Viking 1 and 2 found a striking desert landscape devoid of life
    - Mars is a one-plate planet, and includes some of the largest volcanoes in the solar system
    - The atmosphere of mars grings micrometeorites to dust and dust storms sweep them away from some areas and leave larger rocks exposed
    - The southern highlands are heavily cratered meaning that they are 2-3 billion years old
    - Northern lowlands re smooth and free of craters that it must have been resurfaced roughly a billion years ago
      - Volcanic floods filled the craters
      - Also suggests that it was filled by an ocean of liquid water
    - The martian volcanoes are shield volcanoes - shaped like an inverted warrior shield; formed by low viscosity lava flows
    - The largest volcano in the solar system is Olympus Mons on mars
    - Other evidence shows that the martian crust was once thinner, and more active than the moon’s
      - Valles Marineris is a network of canyons that was produced by faults in the crust that allows great blocks to sink
    - It’s possible that some of the volcanoes are still active
      - Craters in the youngest lava flows show that the volcanoes may have been active as recently as a few million years ago
    - Evidence shows there’s supervolcanoes in a region called Arabia Terra that may have contributed to volcanic material to the ridged plains in the region and could have affected the early climate history of mars
  - Rocks and minerals
    - The silicon content of some of the rocks is much higher than that of the martian meteorites
    - The martian meteorites are mostly igneous and are relatively low in silicon and high in iron and magnesium
    - The igneous rocks analyzed were not basalts, which is what was expected to find, but andesites
    - Magma melts took slightly different crystallization trends on each planet (mars and earth)
    - Many of the rocks seen on the surface are not volcanic but sedimentary
      - Caused by standing and running water
    - Evidence of standing bodies of water has been found in martian soils rich in sulfates
      - Evaporative salts, sulfates, and carbonates tend to bond surface dust into crumbly or flaky layers
      - Duricrust is the flaky layers and was found to be 20-50% richer in sulfur than the loose dust

        - Fresh terrestrial sediments deposited in high humidity regions tend to be brownish and blackish and involve hydrated iron oxides in poorly crystallized states
            - Wetting and drying the sediments encourages the production of red beds
        - Martian “blueberries” are small spherules of iron oxide scattered over some areas of soil
- Interior of mars
    - Mars has an iron core with a radius of 1520-1840 km with at least the outer part molten
        - Core size and density implies it is rich in low density contaminants like iron sulfide and magnetite
        - The core is something like a thick “goopy” syrup meaning that the planet has not cooled as much as earlier thought
    - The ancient parts of the crust are magnetized while the younger parts are not, implying an early dipole magnetic field
        - Distribution of magnetized rock is not uniform and occurs in irregular strips
- Tectonics
    - The plains of the western hemisphere of mars are dominated by the Tharsis dome which is surrounded by the huge volcano, Olympus Mons, and other shield volcanoes
        - One or more mantle plumes have been active under that region
        - No plate tectonics so the lava kept accumulating in one area
- History of mars
    - The martian geological eras
        - Noachian era: earliest period of martian history
            - Characterized by a thicker early atmosphere
            - High rates of catering, heat flow, volcanism, fluvial activity, and glacial activity
            - Lasted from planet formation 4.5 billion years ago until 3.5 billion years ago
        - Hesperian era: transition from noachian conditions to modern amazonian conditions
            - Many of the major outflow channels, the last water flows and erosion episodes
            - Lasted from 3.5 billion years ago until 3.3 billion years ago
        - Amazonian era: modern, dry, dusty, mostly frozen era
            - Geologic activity declined
            - Lasted from 3.3-2.9 billion years ago to present
    - Developmental history - stages of planet formation
        - Stage 1: differentiation into core, mantle, and crust
            - No traces of plate tectonics like folded mountain ranges
            - Lacked a magnetic field so its core couldn't contain much molten iron
            - Mars once had a magnetic field and presumably a molten iron core
        - Stage 2: cratering, the crust of mars was battered during the heavy bombardment
            - Old southern hemisphere survives from this age
            - Largest impacts blasted out great basins
        - Stage 3: flooding by great lava flows that smoothed some regions
            - Not only magma but also water
            - Thicker atmosphere and water erosion
            - Water probably filled the northern hemisphere lowlands and formed flood features and valley networks
            - Surface temperature fell as gases leaked into space and water became trapped as permafrost

                - Mars may have rotated at a much steeper angle to its orbit (45 degrees) which made climate warmer and kept more CO_2 from freezing at the poles
                - Rise of Tharsis bulge tipped the axis to 25 degrees and cooled the climate
        - Stage 4: crust is too thick to be active
            - Planet lost much of its internal heat and lacks a molten core so no magnetic field
- Satellites of mars
    - Phobos, the closest natural satellite to any planet in the solar system, is shaped like a flattened loaf of bread and appear less than half as large as earth's fill moon
    - Deimos, smaller and 3 times farther from mars, would appear only 1/15 of the diameter of the moon
    - Both satellites are tidally locked to mars and revolve around mars in the same direction as mars rotates
        - Phobos has a smaller orbit and revolves faster than mars rotates so it rises in the west and sets in the east
        - Phobos is also not very stable and it will disintegrate and crash into the surface of mars in 50 million years
    - The satellites are small, rocky, dark gray, with albedos of only about 0.06, and they have low densities (2 g/cm^3)
    - Their properties hint that they are captured asteroids from the asteroid belt
        - The asteroid approached the planet along a hyperbolic orbit and the planet slowed it down by tidal forces from being swung back into space
    - Both satellites are heavily cratered that occured while the objects were either still in the belt or in orbit around mars
        - It broke the satellites into irregular chunks of rock that cannot pull themselves into smooth spheres because of weak gravity
    - These satellites demonstrate 3 principles
        - Some satellites are probably captured asteroids
        - Small satellites tend to be irregular in shape and heavily cratered
        - Tidal forces can affect small moons and gradually change their orbits