Solar System Astronomy Notes

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Chapter 1

The Sky and Time Keeping

Constellations

- Constellations are areas on the sky, usually defined by distinctive groupings of stars (Modern astronomers define 88, if you are interested a complete list is given in appendix 11 of the textbook). Constellations have boundaries in the same way that countries on the earth do.

- Prominent groupings of stars that do not comprise an entire constellation are called asterisms (for example, the Big Dipper is just part of the constellation Ursa Majoris).

Star Names

- Most bright stars have names (usually Arabic).

- Stars are also named using the Greek alphabet along with the name of the constellation of which the star is a member. The first five lower case letters of the Greek alphabet are: α (alpha), β (beta), γ (gamma), δ (delta), and ϵ (epsilon). The normal convention is for the brightest star in a constellation to be designated as the α star of that constellation, the next brightest the β star, and so on (although there are one or two counter examples.) For example, the Brightest star in Scorpius is named Antares, but is also called α Scorpii.

Coordinate Systems

Terrestrial Coordinates

- In order to locate points on the surface of the earth, we can divide Earth up using lines of longitude and latitude.
- Lines of longitude are great circles[1] running north-south on the globe.
- Lines of latitude run east-west on the globe, most of them aren't great circles.
- We define the equator as 0 degrees latitude, and define the longitude line through Greenwich, England as 0 degrees longitude. This line of longitude is known as the Prime Meridian.
- Measurements of both longitude and latitude are given by angles measured form the center of the earth, normally specified in degrees ($^\circ$), arc-minutes ($'$), and arc-seconds ($''$). Longitude is measured along Earth's equator, and latitude is measured north or south from the equator. For example Houston is at latitude $+29^\circ\ 45'\ 47''$, and longitude $96^\circ\ 21'\ 47''$. (If you don't know what a degree, arc-minute or arc-second are, read the supplement *Angles in Astronomy* from the website.) Note that latitudes vary between -90° and $+90^\circ$, while longitudes vary between 0° and 360°.

Celestial Coordinates

- Think of the sky as single spherical surface, centered on the earth. This is called the celestial sphere. The celestial sphere is an imaginary surface on which we can keep track of the positions of all celestial objects.
- Imagine projecting lines of longitude and latitude upward from the surface of the earth onto the celestial sphere. Astronomers call the coordinate analogous to the longitude the Right Ascension (RA) and

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[1] You are going to encounter a number of new terms in studying astronomy. When you do, it is important for you to learn what they mean, by looking for a definition in the textbooks glossary, or in a dictionary. A great circle is any circle you can draw on the surface of a sphere that cuts the sphere in half.

and that analogous to the latitude the Declination (Dec). Any object's position on the sky can now be given in terms of these two coordinates.

Time Systems

- The earth rotates around an axis through its north and south poles. This means that celestial objects seem to move across the sky with time. In fact, many of our basic time divisions (days, months, and years for example) are based on this apparent motion of celestial objects as seen from a fixed point on the earth.
- Notice that this means that we can define at least two different time systems using the apparent position of different types of objects on the sky. If we use the sun as our reference object, the time system is called solar time. If we use stars as our references, we call the time sidereal time.
- The length of time between two successive meridian crossings for the sun is called an apparent solar day (the meridian is the north-south great circle on the sky that runs through the point directly over your head.) The length of an apparent solar day varies from one day to the next throughout the year, mainly because Earth's orbit is elliptical in shape.
- For everyday use we define a mean solar day as average length of all the apparent solar days over the entire year.
- The time for a star to make two successive meridian crossings takes only about 23 hours 56 minutes (as measured on a clock keeping mean solar time); the orbital motion of the earth around the sun means that the earth most rotate about 361° to return the sun to the meridian, while the earth must rotate only 360° in order to have a star return to the meridian.

Units for Right Ascension and Declination

- Astronomers normally use units of sidereal time for Right Ascension. 24 hours of sidereal time is defined to be the time separating two successive meridian crossings as seen from a fixed location on the surface of the earth for any star.

- Zero hours Right Ascension is defined by the position of the vernal equinox. The local sidereal time of zero hours thus occurs at any position on the surface of the earth when the vernal equinox is on the meridian at that location.
- A star's Right Ascension is then defined to be the amount of sidereal time between when the vernal equinox crosses the meridian and time the star crosses meridian. (Example: A star with a RA of 21 hours will cross meridian 21 (sidereal) hours after the vernal equinox. The vernal equinox will then cross the meridian again 3 (sidereal) hours after this star.) Notice that the local sidereal time at any location is just the right ascension of the stars on the meridian at that location at that instant.
- A star's declination is measured as the number of degrees away from the equator (just like latitude on the surface of the earth), with declinations north of the equator having positive values and those south of the equator having negative values.

The Horizon Coordinate System

The RA-Dec coordinate system (also known as the equatorial system) is very useful for locating objects on the sky, but it has one drawback. If I give you the RA and Dec of a star and send you outside to look for it, where on the sky would you look? The rotation of the earth means that the RA's visible to you are constantly changing. In addition, the RA and Dec directly over your head at any instant is certainly *not* the same as that for someone elsewhere on the earth at that instant. Therefore, besides the equatorial system, it will also be useful to define a second coordinate system, one that tells us where to look on the sky guided by local landmarks, such as the point over head, due north, etc. This system is known as the Horizon (or Altitude–Azimuth) coordinate system. The essential parts of the Horizon coordinate system are:

- The **zenith**, which is the point on celestial sphere directly overhead at you location. Notice that your zenith will always have a declination equal to your latitude.

- The **meridian**, which is the great circle on the sky that runs through the zenith and the North and South celestial poles.
- The **celestial horizon**, which is the great circle on the sky 90° from the zenith. Note that this is a hypothetical horizon, and is almost always different than the geographical horizon where you are, which is defined by local land forms, such as buildings, trees, etc.
- With the above definitions, an objects position from a particular location is then given by its altitude and azimuth:
  - **Altitude**, angle above or below the celestial horizon.
  - **Azimuth**, angle around the horizon measured eastward from north.

The Motions of Celestial Objects on the Sky

- Stars make a circle on the sky from east to west once each sidereal day, due to the rotation of the earth.
- The sun travels across the sky once each solar day, due to Earth's rotation. It also makes a circle with respect to the background stars once every year (approx. 365.25 days), due to the revolution[2] of the earth around the sun.
- The sun's path with respect to the background stars is called the ecliptic. The ecliptic is titled by 23.5° with respect to the celestial equator, because the axis around which the earth rotates makes a 23.5° angle with the axis around which the earth orbits the sun. The tilt of the ecliptic causes seasons on the earth.
- Four special points on the ecliptic are the equinoxes and the solstices. The equinoxes are the two points where the ecliptic crosses the celestial equator. The solstices are the two points where the sun reaches is farthest northern or southern point on the celestial sphere.
- The moon travels across the sky roughly once each day, due to the rotation of the earth. The moon travels on a circular path across the

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[2] The terms rotation and revolution have very specific and different meanings in astronomy. Make you sure you know which is which.

sky once each month, due to the revolution of the moon around the earth.

Phases of the Moon

- The phases of the moon are caused by the relative orientation of the sun, Earth, and Moon, because the sun illuminates the Sun facing half of the moon. How much of the illuminated face of the moon we can see from the earth determines the phase of the moon.
- The time for the moon to return to the same position with respect to the background stars is called the sidereal period of the moon, and is about 27.3 days long.
- The time for the moon to return to the same position with respect to the sun is call the synodic period of the moon, and is about 29.5 days long (the orbital motion of the earth means that the Moon must go through more than 360° for this to occur.) This amount of time is also known as a lunar month.

Lunar Eclipses

An eclipse occurs anytime one object passes into the shadow of another, so a lunar eclipse occurs when the moon passes into Earth's shadow.

- Earth's shadow has two parts:
  - the **Umbra**, or zone of full shadow.
  - the **Penumbra**, or zone of partial shadow.
- There are three different types of lunar eclipse:
  - A total lunar eclipse, which occurs when the moon is totally within the umbra of the earth.
  - A partial lunar eclipse, where the moon is partially within the umbra and partially within the penumbra.
  - A penumbral eclipse, where the moon passes within the penumbra only.

Solar Eclipses

During a solar eclipse, the earth passes into the moon's shadow. Because the moon's shadow is much smaller than that of the earth, a solar eclipse will be visible from only a portion of the earth's surface. There are 3 types of solar eclipse:

- A total solar eclipse, where the entire disk of the Sun is blocked from view.
- A partial solar eclipse.
- An annular eclipse, in which a ring of Sun is visible around the outer edge of the Moon during the peak of the eclipse. An annular eclipse occurs when the moon is on the part of its orbit furthest from the earth. Because the moon is further away from the earth, it has a smaller angular size as seen from earth, and thus can't block out the entire sun.

The Motion of the Planets

- Because the earth and other planets orbit the sun, all the planets seem to move with respect to the background stars as seen from the earth.
- Planets are always seen on the sky near the ecliptic. Because the ecliptic traces out the plane of Earth's orbit on the sky, this means that the orbits of all the planets lie in similar (but not exactly the same) planes.
- Because both the planets and the earth are moving at the same time, the planets appear to perform peculiar motions on the sky as seen from the earth.

The Inner Planets: Mercury and Venus

- Mercury and Venus orbit closer to the sun than the earth does, and so never appear very far from the Sun on the sky as seen from the earth.
  - At most, Mercury gets 28° from the sun on the sky.
  - At most, Venus gets 53° from the sun on the sky.

- Because Mercury and Venus are always close to the sun on the sky, they only appear in the early evening or pre-dawn sky as seen from the earth.

The Outer Planets: Mars through Pluto

- The outer planets are further from the sun than the earth, therefore they can appear far from the sun on the sky.
- The further a planet is from the sun, the slower it moves on its orbit. Because of this, the earth periodically catches up to and passes the outer planets. During the time when Earth is passing an outer planet, the planet will appear to move backward with respect to the background stars as seen from the earth. This apparent backward motion is known as retrograde motion[3] (e.g. see figure 2.9 in the textbook).

Precession of the Equinoxes

- A torque (a torque occurs when a force is applied to an object in such a way as to cause the object to twist around some axis) causes a spinning objects axis to precess.
- The earth experiences torques due to the gravity of other objects in the solar system, primarily the moon and the sun.
- Earth's polar axis precesses over a 26,000 year period. This means that:
  - The RA and Dec of all celestial objects will constantly be changing due to precession, because these coordinates are based on the projection of the earth's equator on the sky.
  - The seasons during which particular constellations are visible in the nighttime sky will also change due to precession.
  - Because our civil calendar (the Gregorian calendar) is based on the tropical year (the time for the sun to return to the vernal equinox), the effects of precession are accounted for in the calendar. Thus, the months corresponding to a particular season will not change due to precession.

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[3] Retrograde motion also occurs for the inner planets, but occurs when the planets are passing near the Sun, making this motion difficult to observe.

Chapter 2

The Historical Development of Astronomy

The majority of the historical astronomical ideas were incorrect–their importance lies in examining the process of how we learn about the natural world[1]. Do we seek our inspiration from religious, philosophical or aesthetic considerations? What is the role that observation and experiment play in shaping our ideas?

Mesopotamian Astronomy

Mesopotamia was the region between the Tigris and Euphrates rivers, in what is today Iraq. The ancient civilizations in Mesopotamia including the Sumerian's, the Babylonian's, and the Assyrian's, who all shared a common astronomical tradition. These civilizations left considerable written records from which we know something of their beliefs and accomplishments. The most important thing to know about Mesopotamian astronomy is that the Mesopotamians believed that all the motions of objects in the skies where due to the actions of the gods. Therefore, the Mesopotamians never sought any natural or mechanical explanations for what they saw.

Among the accomplishments of the Mesopotamians where:

- Used base 60 number system.
- Divided the circle into 360°.

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[1] In fact the very use of the word natural has certain implications.

- Knew the length of the year and of the lunar month. Because there is not a whole number of lunar months in a solar year, they used a calendar that interspersed 12 month and 13 month years.
- Divided the day into 24 hours.
- Used a 7 day week. They chose 7 because they could see 7 objects on the sky that moved with respect to the stars.
- Invented fractions and algebra.
- Established the 12 zodiacal constellations, in more or less the form that we still use them today.
- Identified cycles on the sky for the planets and the moon, but never developed a physical model to explain the cycles.

The Ancient Greeks

- Thales of Miletus believed that the universe is rational (that is, that the universe obeyed a set of logically consistent laws), and that humans can understand those laws. He was the first recorded person to put forth a picture of the formation of the universe that did not contain any mystical elements. Note the difference in this viewpoint from the purely mystical picture of the Mesopotamians.
- Anaximander, who lived at the same time and in the same city as Thales put forth the first mechanical picture to account for the motion of celestial objects.
- Anaximenes was a contemporary of Thales and Anaximander, and also developed his own model to explain the motions of the heavens.

The Pythagoreans

Pythagoras founded a school (might also be described as a cult or monastic order, although none of these completely captures the nature of the Pythagoreans.) The members of the Pythagorean school lived communally, and women were allowed to join (a rarity for the time!) Pythagoras himself left no writings, so what we know of him and his teachings is based on the writings of others, some of whom lived well after Pythagoras had died. The Pythagoreans believed (among other things), that:

- Mathematics is divine.
- The perfect mathematical shapes were circles and spheres.

These beliefs lead them to look for a mathematical explanation for the motions of heavenly bodies, and for them to assert that the heavenly bodies followed paths that were among the perfect shapes in nature. Based on this philosophy, the Pythagoreans developed an extensive model for the universe:

- All objects in the universe revolve around a "central fire" (not to be confused with the sun, which was a separate object in this picture), including the earth. In the Pythagorean picture, the central fire could never be seen. Notice that the "central fire" thus represents a mystical element in the Pythagorean model.
- they believed that there where ten moving objects in the universe (probably motivated by the fact that they considered 10 to be a divine number). These objects were:
  - The stars (counted as one because they were all attached to the celestial sphere, and thus comprised "one moving part")
  - The 5 known planets (Mercury, Venus, Mars, Jupiter, and Saturn).
  - The earth, sun and moon.
  - In order to get the number of objects up to 10, the Pythagoreans invented a tenth object that they called the "counter earth", that had the special property of never being visible from the earth.

The Pythagoreans believed that the motion of all the objects in this picture produce sound, sometimes referred to as the "music of the spheres". Why couldn't you hear this music? Because the music is always present, we "tune out" the sound! They also believed that all of the 10 moving objects in the universe were spherical, although they offered no proof of this.

Socrates

Socrates was the first of the three great Athenian philosophers. He left no writings, so what we know of him is through the writings of others. Although Socrates contributed nothing to astronomy directly–being chiefly concerned with ethics–Plato was his student, and was very influenced by Socrates teachings.

Plato

Plato wrote extensively on a number of diverse topics. Some of Plato's ideas relevant to astronomy are:

- Reality is distorted shadow of an ideal (perfect) world. Because of this, in order to discover the causes for things in nature, we must seek underlying perfect forms.

- the Perfect shapes in nature are circles and spheres (influenced no doubt by the Pythogoreans), and the perfect motion is uniform motion (i.e. motion that neither speeds up or slows down with time.)

Aristotle

Aristotle was Plato's student, and like Plato wrote on a number of diverse subjects. The most important of Aristotle's ideas for astronomy was the idea that the Universe was divided into two parts: the earth, which is made up of ponderous, corrupt, changeable materials, and the heavens, composed of materials that are perfect and immutable (i.e. unchanging.) In Aristotle's view, the study of the motions of objects on the earth and in the heavens must be separated, since the objects in these two realms are made of fundamentally different materials that must obey fundamentally different laws.

Aristotle and the Shape of the Earth

Aristotle argued for a spherical Earth, based upon (among other things):

- The observation that the shadow of Earth during a lunar eclipse appears circular.

- The observation that no matter where you are on the earth, a dropped object falls straight down. If the world were some other shape, *and* all objects "seek the center", then in most places objects would in general fall at some angle to the vertical.

- Aristotle's final argument was a philosophical one. If all Terrestrial material seeks the center, after some time that material will naturally end up in spherical distribution, since a spherical distribution gets all material as close as possible to the center. Note that both this and the previous argument are built on the idea that all terrestrial material is naturally attracted to the center of the universe; if this is not true then the results of both of these arguments are invalid.

Greek Cosmology

Cosmology is the study of the whole universe and its behavior. In their cosmology, the Greeks wanted to explain the motions of each type of object they could see in the universe, namely:

- The stars.

- The sun and moon.

- The planets = "wandering stars".

The Greeks believed that any successful cosmology should not only be able to explain the observed motions of the heavens, but also incorporate philosophical ideas, such as Plato's and the Pythagoreans' idea of spheres and circles being perfect shapes, etc. The ideas that formed the basis for the Greek picture (that survived until the 16th century) where put forth by Aristotle:

- Earth is at the center of the universe, and all celestial objects revolve around that center.

- The celestial objects are attached to crystalline spheres (or combinations of spheres), centered on the earth, that rotate at constant speed.

Other Important Greek Ideas and Discoveries

- Plato's student Eudoxus created a model of the universe that accounted for retrograde motion by attaching each planet to a set of spheres that turned independently of one another, around different axes.
- Aristharchus advocated a heliocentric (i.e. sun centered, not earth centered) cosmology, although view was largely rejected by other philosophers of his time.
- The size of the earth was measured by Eratosthenes using "the well trick."
- Hipparchus, who was probably the greatest astronomer of antiquity. Among other things, he is credited with:
  - creating a star catalog containing the positions and brightnesses of almost 1,000 stars, no printed version of which has survived to modern day.
  - Discovering the precession of Earth's axis.
- Ptolemy was the last great astronomer of antiquity. He:
  - Tried to fix up the geocentric model, in order to get an accurate description of both the retrograde and non-uniform motion of the planets.
    - Used epicycles to get retrograde motion.
    - Placed some of the spheres such that Earth was not at the center of that sphere in order to produce non-uniform motion.
    - Made motion uniform with respect to point called equant (i.e. not with respect to either the earth or the center of the sphere.)
  - Wrote a book describing all this, which is today referred to as *Almagest.* This name was given to the work sometime during the middle ages by Islamic scholars, and is Arabic for "The Greatest." *Almagest* became the standard astronomy book for next 1500 years!
- Some of the advantages of Ptolemy's system were:

  - Did manage to reproduce the retrograde and non-uniform motions of planets.
  - Initially was fairly accurate.
- Some of the disadvantages of Ptolemy's system were:
  - There was no justification of epicycles, off center spheres for the planets, or the equant in Aristotle's picture.
  - Over 100's of years, the predictions of the model became less and less accurate. It is important to note that this defect was not inherent to the model, but was simply due to the limited accuracy of the data used to set up the model initially.

Islamic Astronomy

The main concern of the Islamic astronomers had to do with religious observances. These requirements demanded the ability to perform fairly accurate calculations based on the positions of celestial objects, and led Islamic astronomers to develop significant improvements in spherical astronomy. The Islamic astronomers:

- Islamic scholars preserved Greek texts that would otherwise been lost.
- Use the lunar month, because the Koran says that a month is a lunar month. Also in the Koran, a year is specified to be 12 months long. Because of these restrictions, the months of the Islamic calendar shift slowly through the seasons, year after year. This is why Ramadan passes through a 30 year cycle of when it occurs during the year.
- Had to make accurate predictions of the phases of the Moon, since Islamic months start with the appearance of the thin crescent moon in west, not with the new moon (again as set forth in the Koran.) This makes determining the start of the month much more challenging.
- Needed to align Mosques with Mecca, requiring accurate determination of the position of the Mosque on the surface of the earth relative to Mecca, using accurate astronomical observations and calculations.
- Needed accurate time keeping in order to determine prayer times.

Nicholas Copernicus

Copernicus was born in the late 1400's, in what is today part of Poland. By this time, errors in astronomical tables calculated using Ptolemy's model had accumulated, so Copernicus wanted to compute more accurate tables, but he didn't like Ptolemy's model on philosophical grounds (Copernicus was very much an Aristotelian, and as such wanted uniform circular motion back!) In order to rescue uniform circular motion (at the price of the earth being the central body in the universe), Copernicus proposed a sun-centered (heliocentric) model:

- The Sun lay at the center of the universe.
- Planets were on uniform circular orbits around the Sun (the earth too!)
- the Moon orbited the earth.

From Copernicus' perspective, the advantages of this heliocentric model were:

- That it restored uniform circular motion.
- Naturally explains retrograde motion (although epicycles still needed to get non-uniform motion and exact shapes of retrograde loops.)

And the disadvantages of the model were:

- The earth was no longer at the center.
- There was more than one center for motion in the universe (the earth and the sun.)
- Still couldn't get rid of epicycles.

Some important things to note are::

- Copernicus was not the first to consider a heliocentric model.
- The model not widely accepted at time.
- The predictions no more accurate than Ptolemy's model.

So: why talk about Copernicus?

- Printing press = mass distribution.
- Renaissance, people started looking at new ideas.
- Improved technology = better observation. As we will see, this allowed astronomers to make much more stringent tests of astronomical models.

Galileo Galilei

Galileo Galilei was born in 1564 in Italy. Galileo made many important contributions to physics and astronomy, and can quite rightly be described as the first true modern scientist. This is because Galileo rejected the notion that philosophical or religious arguments could give us meaningful information about how the natural world worked. Instead, Galileo believed that the only criteria for telling whether a scientific hypothesis was correct or not was observation and experiment. Galileo was a Copernican, but unlike Copernicus, he favored this model of the universe based solely on observational, and not philosophical grounds. Galileo was the first to use a telescope to make systematic observations of the heavens. With his telescope Galileo saw:

- Many faint stars (showing Galileo that there was more in the universe than accounted for by Aristotle.)
- Mountains and craters on the Moon (which to Galileo meant that the moon was another world, just like the earth, violating Aristotle's assumption that the earth and heavens where fundamentally different.)
- Sunspots, which appeared and disappeared with time (showing Galileo that celestial objects were neither perfect nor immutable.)
- The Phases of Venus. Galileo observed that the apparent size of Venus depended on its phase, with Venus appearing largest during its crescent phase and smallest when it was close to full. This could naturally be explained if Venus orbited the Sun, but was difficult to explain if Venus orbited the earth. but were naturally explained if both the earth and Venus were revolving around the sun.)
- The four largest moons of Jupiter (showing Galileo that other centers of motion existed in the universe besides the earth, violating Aristotle's

assertion that the earth lay at the one center of motion for all objects in the universe.)

Galileo published all this in *The Sidereal Messenger,* which caused the Catholic church to prohibited him from publicly discussing or holding Copernican ideas. After the death of the pope, Galileo approached the new pope, and convinced him to let him to publish a "fair and balanced"–and hypothetical–look at the geocentric and heliocentric theories. This discussion was published in the *Dialog Concerning the Two Chief World Systems.* Three characters appeared in the dialogs, the important two being:

- Simplicio, who espoused the viewpoint of the pope, and
- Salviati (The hero) who demolished the viewpoints put forth by Simplicio, and instead argued persuasively for a Copernican explanation for the motions of the heavenly bodies.

Because of this, Galileo was tried by the inquisition, and forced to recant his Copernican beliefs.

Tycho Brahe

Tycho (a latinization of his given name Tyge) Brahe was born in Denmark three years after the death of Copernicus. From a young age, Tycho was interested in astronomy, and published works on several topics, including observations of the Nova of 1571. Tycho–like Copernicus– was troubled by the errors in Ptolemy's tables, and resolved to produce new, more accurate tables. Because of this, Tycho convinced the Danish king to give him money to build and run an observatory. At this observatory, Tycho:

- Made better instruments, which allowed him and his assistants to make more accurate and systematic observations.
- Measured the positions of stars and planets over a time of 20 years.

Before he could complete the new tables based upon his observations, the old king died, and his son cut off the funding for the observatory. Forced to search for a new benefactor to continue his work, Tycho found one in Prague, and finally settled down to begin work on the new tables. Tycho intended to compute the new tables using neither the model of Ptolemy or Copernicus, but instead using a new geocentric model of his own devising.

Johannes Kepler

Johannes Kepler was born in southern Germany 25 years after Tycho, and was a mathematician, astronomer, numerologist (i.e. someone who believes in the mystical properties of numbers), and a Copernican. As a young man, Kepler wrote a book on the spacing of the planets (based upon a numerological idea concerning the 5 regular polyhedrons), and sent copies to several people, including Tycho and Galileo. Although the underlying premise of the book was questionable, the book showed that Kepler possessed significant mathematical skill. Because of this, Tycho invited Kepler to come to Prague and help him with the calculation of the new tables. Soon after Kepler had joined him, Tycho died. Before Tycho's death however, he had named Kepler as his successor. Being a Copernican, Kepler began work on the new tables using a Copernican model, not Tycho's. It took 5 years for Kepler to analyze the data for Mars. When he had finished, he had found 2 laws of planetary motion:

1. The orbits of the planets are ellipses, with the Sun at one focus.

2. The line connecting each planet to the sun will sweep out equal areas in equal times.

   It took Kepler 8 more years to analyze the data for the other planets and discover the 3rd law of planetary motion:

3. The square of a planets orbital period is proportional to the cube of the semi-major axis of its orbit ($P^2 = a^3$.)

Chapter 3

Modern Science

> The practice of science is many things, but bloodless and coldly rational it is not. Nor, being an activity practiced by humans, can it be. –William Keel in *The Sky at Einstein's Feet*

> Science is built of facts the way a house is built of bricks, but an accumulation of facts is no more science than a pile of bricks is a house. –Henri Poincare

First, some definitions:

- **Science:** A systematic method for discovering the basic laws of nature.
- **Hypothesis:** A tentative assumption made on order to draw out its logical or empirical consequences. –Meriam Webster Dictionary

Premises of Modern Science

Modern Scientists Believe

- Universe obeys a set of fixed laws
- Humans can understand these laws
- Laws may be determined by observation and experimentation

In order to test a science of hypothesis, in science we require are hypotheses:

- To be falsifiable.
- To successfully predict phenomena outside the scope of the data that motivated it.
- Be the simplest explanation to explain the observed phenomena (this requirement is known as **Occam's Razor.**)

Some Misconceptions About Science

- **The purpose of science is to find "The Truth".** Science is designed to study the natural world. If any of the assumptions we make as scientists are false, the inferences we make using the machinery of science will be unreliable.
- **Science must involve competing hypotheses (and any proposed hypothesis must be considered by scientists.)** As long as a hypothesis is falsifiable, science can function by considering only that hypothesis.
- **Science is atheistic; all scientists are atheists.** Science tries to answer questions about the natural (and not supernatural) questions, so science has nothing to say either way about the existence of God.

Chapter 4

The Laws of Motion and Gravitation

Physics Terms

If you haven't figured it out by now, scientists are picky about how we use terminology. We give specific definitions to terms, and then try to be careful to only use those terms in a way consistent with the definitions (i.e. we try not to be "sloppy" with our use of terminology.) Physicists are no different than other scientists in this regard; terms in physics have specific meanings, and in many cases where students get confused about things, the confusion is due to them not being careful when they read or use specific terms. To make matters worse, some terms that are interchangeable in every day language are not when you are using them in "physics speak". For example, the terms velocity and speed have very specific, somewhat different meanings in physics, so changing speed to velocity in a particular statement can change the meaning of that statement, possibly even changing the statement from a true statement to a false statement. The bottom line is, be careful with your terminology when talking to a physicist or astronomer (or taking one of their exams!)

To start off our discussion of physics, here are two terms that it is important to understand:

- **Vector:** a vector is a quantity that has both magnitude (size) and direction (note: don't confuse direction and position; they're different.) Examples of quantities that are vectors include velocity, force, acceleration, and momentum. When we write down formulas that include vectors, we denote all the vectors in the formula in bold face, in order to distinguish them from quantities that are just numbers (e.g. we write $\mathbf{F}$ for a force instead of F.)

- **Scalar:** A scalar is just a number. Examples of quantities that are scalars include mass, speed, and the amount of money in your bank account.

Quantities Related to Motion

In order to predict the motion of an object, we must start by defining quantities that help us keep track of an object's motion.

- **Velocity:** In physics, we define an object's velocity to be the change in position, divided by the time it takes for the position to change. We denote velocity as $\mathbf{v}$. Notice that the change in position tells us a direction, so that velocity is a vector.

- **Speed:** The size (i.e. the length) of the velocity vector is referred to as speed. We denote the speed as v. Notice that an object's speed is therefore a scalar, not a vector, since it doesn't include any direction information. When you are driving in a car, the speedometer tells you your speed, but not your velocity (because it doesn't give you information about the direction of travel.)

- **Acceleration:** Notice, if an object's velocity never changed, predicting its position in the future would be easy; just take the object's starting position, and use its velocity to project its new position after the amount of time you are interested in. In most cases, however, an object's velocity will change with time. We define the change in velocity divided by the time it took for the velocity to change the acceleration. We denote acceleration as $\mathbf{a}$.

Notice that there are two things that we can change about a vector, its length or its direction. This means that when something is accelerating, that either its speed, or its direction (or both) are changing.

Isaac Newton

Isaac Newton was born in England in 1642, and most certainly must be considered to be one of the few greatest physicists of all time. Newton had a large number of achievements in both mathematics and physics, including developing calculus, along with Leibniz. In addition, it is reasonable to consider him to be the father of "modern" physics, because of his statements of the laws motion and of gravity. Newton's Laws of Motion are:

- 1st Law (Law of inertia): Unless it is acted on by an unbalanced external force, an object in motion will stay in motion, traveling in a straight line at a constant speed, while an object at rest will stay at rest. (First stated by Galileo)
- 2nd Law (Law of force): $\mathbf{F} = m\mathbf{a}$.
- 3rd Law (Law of Action and Reaction): For every action there is an equal and opposite reaction.

If you know the forces acting on any body, you can use Newton's laws of motion to analyze the motion of that body.

Conservation Laws

- In physics when we say something is conserved, we mean that the total amount of that something doesn't change with time. This makes conservation laws particularly useful in physics, since we can analyze many problems simply by keeping track of how much stuff is there before and after something happens.
- An objects momentum is defined to be $\textbf{Momentum} = m\mathbf{v}$.
- Newton's 3rd law means that momentum is conserved for an object or group of objects any time there is no unbalanced external force acting the object(s). For example, two billiard balls will have the same amount of momentum right before and right after a collision. So, to analyze what happened as the result of the collision of the two balls, we add up how much momentum they had right before the collision, and set that equal to the total amount they must have right after the collision.

- Energy is also conserved, although it can be converted from one type of energy to another. Some types of energy are:
  - Kinetic energy, "energy of motion". If an object has a speed v and a mass m, then its kinetic energy will be given by $\frac{1}{2}mv^2$[1].
  - Potential energy, which you can think of as the energy "stored in a force". For example, when an apple falls from a tree, it gains speed as it falls and thus kinetic energy. This energy is available because at the same time the apple is losing potential energy, in this case gravitational potential energy.
  - Heat, which is microscopic kinetic and potential energy.
  - Rest mass energy ($E = mc^2$.)

Angular Momentum

- Any body that is rotating or revolving has angular momentum. A body's angular momentum depends on two things, the speed with which the body is rotating or revolving, and how the mass of the body is distributed with respect to the axis of rotation or revolution. The further the mass is from the axis, the greater the angular momentum will be. Notice that angular momentum is *not the same as momentum!*

- As a consequence of Newton's second and third laws, angular momentum is a conserved quantity.

- Angular momentum is a vector, with the angular momentum vector pointing along the rotation axis. Notice because angular momentum is conserved, that both the size of a body's angular momentum and its direction will not change.

- A torque, is a "twisting force, and relates to angular momentum in the same way force relates to momentum. So, in order to change a body's angular momentum, you must apply a torque to that body.

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[1] This formula is correct as long as the object's speed is well below the speed of light.

Mass vs. Weight

In physics, mass and weight are not the same thing!

- Mass is an intrinsic property of a body that depends on how much inertia a body has (i.e. it is defined by how it shows up in $\mathbf{F} = m\mathbf{a}$.)
- Weight is the force of gravity acting on a body. On the moon, your weight would be less than it is on the earth (because the gravitational force at the surface of the moon due to the moon is less than the gravitational force at the surface of the earth due to the earth), but your mass would be the same (because your mass is an intrinsic property of you.)

Newton's Law of Universal Gravitation

Any object that has mass can produce a gravitational force, that can act on other masses. Newton realized that the law describing gravitation is a universal law (i.e. it applies no matter whether you are on Earth, or in the depths of space.) This was the final nail in the coffin for Aristotle's idea that you *must* have separate rules for the earth and the heavens.

For 2 masses, gravity:

- is attractive, directed from one mass to the other along the line separating the two masses.
- diminishes in strength as the square of the separation of the two masses.
- is proportional to the product of the two masses.

As a formula we can write the strength of the force between masses m_1 and m_2, that are separated by a distance r as:

$$F = \frac{Gm_1 m_2}{r^2}$$

G in this formula is called the gravitational constant.

Newton's Laws and Orbits

By using data about the positions of planets over time, Kepler was able to determine the laws that governed the orbits of planets around the sun. However, Kepler couldn't explain why the orbital laws were what they were. In addition, Kepler's laws applied only to things orbiting the sun, but couldn't be applied to things like the orbit of the moon around the earth, or Jupiter's moons around Jupiter. With his laws of motion and gravitation, Newton could determine the general laws for orbits, and show that Kepler's laws arose as a natural consequence of those laws.

1. **Orbits are ellipses** When he solved the equations arising from the laws of motion and the law of gravity, Newton discovered that any closed orbit of one object around another is an ellipse.

2. **Equal areas in equal times** The conservation of angular momentum means that things move faster on their orbits when close to the object they are orbiting, and slowly when they are further away. When worked out mathematically, this leads to equal areas in equal times.

3. $\mathbf{P^2 = a^3}$ To see how this law arises, we'll solve the problem of an object in a circular orbit around another object (remember, all circles are ellipses, but most ellipses aren't circles; the answer we will get for the circle turns out to be the same as the one we would get if we worked the answer out for *any* ellipse, but it is much easier to work out the answer for a circle.) We must start with the laws of motion and the law of gravity.

   First, we have to figure out the direction of the force acting on the orbiting body. When we do that we will know the direction of the acceleration, since $\mathbf{F} = m\mathbf{a}$. The law of gravity says that the force between two objects always points from one to another, so the force on the orbiting body will always point to what it is orbiting. Since the orbit is circular, the object being orbited must be at the center of the orbit[2], so, the gravitational force and thus the acceleration must point toward the center.

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[2] Actually, both the planet and the Sun orbit the center of mass of the combination; because the Sun's mass is much greater than any of the planets in the solar system, the center of mass lies very close to the center of the Sun.

Now that we know the direction of the acceleration, we can look at $F = ma$ to see how the size of F and a relate. In this case, the force is the force of gravity, so

$$F = \frac{Gm_1m_2}{r^2} = ma.$$

Now, lets go ahead and assign the object orbiting the mass m_1 (i.e. set $m = m_1$), and assign the thing being orbited m_2, which we'll rename as a capital M (so $m_2 = M$.) The formula above can then be written

$$\frac{GmM}{r^2} = ma.$$

Notice that there is an m on each side, so they will cancel out:

$$\frac{GM}{r^2} = a.$$

Next, we need to take care of the acceleration term. When an acceleration is pointed toward the center of a curved path, that acceleration is referred to as a centripetal (i.e. a "center seeking") acceleration. The size of a centripetal acceleration is $a = v^2/r$, so making the replacement for a in our formula makes it look like:

$$\frac{GM}{r^2} = \frac{v^2}{r}.$$

In order to make this look like Kepler's third law we need to do one more thing: get rid of the speed v and replace it with something to do with the orbital period P. This is actually pretty easy, since the period is the time to complete one orbit, a distance of $2\pi r$ (i.e. the circumference of a circle), so the speed–which is just distance divided by time–is $v = 2\pi r/P$. Replacing v with that in our formula turns it into:

$$\frac{GM}{r^2} = \frac{(\frac{2\pi r}{P})^2}{r} = \frac{4\pi^2 r}{P^2}.$$

OK, now we just solve for P^2, and the formula looks like:

$$P^2 = (\frac{4\pi^2}{GM})r^3.$$

Now for a circle, its semi-major axis a is just its radius, so that

$$P^2 = (\frac{4\pi^2}{GM})a^3.$$

Now, let's compare this to the way Kepler wrote the third law:

$$P^2 = (1\tfrac{AU^3}{yr^2})a^3$$

$$P^2 = (\tfrac{4\pi^2}{GM})a^3.$$

Apparently, $1AU^3/yr^2 = (4\pi^2/GM)$, (remember that here M is the mass of the sun.)

Chapter 5

Overview of the Solar System

The solar syatem is comprised of a single star, orbited by several major bodies (planets) and many minor bodies. The planes of the orbits of the planets are closely aligned with one another (recall that the orbits of the planets lay close to the ecliptic), meaning that it is not unreasonable to think of the solar system as a flat structure. Radioactive dating of rocks and meteorites suggest that the solar system formed approximately 4.6 billion years ago.

The Sun

The Sun is a main sequence star of spectral type G2. In the universe, stars range in mass from roughly 1/10 the mass of the sun to about 100 times its mass. Although it seems like this we make the Sun un-spectacular in its properties, it turns out that the majority of stars formed are of relatively low mass, so that the Sun is more massive and more luminous than roughly 90 % of the stars in our galaxy. Over 99 % of the mass in the solar system is in the sun, making it the dominant gravitational influence in the solar system.

The Sun is composed largely of hydrogen and helium (the two lightest elements in the universe), with only 1-2 % of heavier elements. This composition is typical for stars, and in fact for our galaxy as a whole.

The Sun also blows a steady wind of particles outward into space. The solar wind has pushed out the interstellar gas in its vicinity making a bubble of radius 100-200 AU, that is referred to as the heliosphere.

2 AU and In: The Rocky Planets

The largest bodies in the inner solar system beside the sun are Mercury, Venus, Mars, Earth, and Earth's moon. All are composed largely of heavy elements–a consequence of their formation in the inner part of the gas cloud from which the solar system formed where temperatures were fairly high.

Body	Distance from Sun (AU)	Radius (Earth = 1)	Atmosphere	Distinguishing Characteristics
Mercury	0.39	0.38	Trace (sodium)	High density, heavily cratered
Venus	0.72	0.95	Very dense (CO_2) (carbon dioxide)	Higher average surface temperature than Mercury
Earth	1	1	Moderate density (nitrogen/oxygen)	Liquid water, plate tectonics
Moon	1	0.27	Essentially none	Heavily cratered surface
Mars	1.52	0.53	Low density (carbon dioxide)	North-south asymmetry

Asteroids

There are a large number of small rocky bodies in the inner solar system; those with sizes smaller than 1000 kilometers but larger than about 50 meters in size are referred to as asteroids. The majority of known asteroids orbit the Sun in the area between the orbits of Mars and Jupiter. This collection of asteroids is collectively known as the asteroid belt.

5-30 AU: The Gas Giants

The area beyond the asteroid belt is dominated by four large planets–Jupiter, Saturn, Uranus, and Neptune–that are characterized by their extensive atmospheres composed primarily of hydrogen and helium, and are thus sometimes referred to as gas giant planets[1]. The most massive of these planets is

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[1] They are also sometimes referred to as Jovian (i.e. Jupiter-like) planets.

Jupiter, that has a mass roughly 0.0001 that of the sun, or roughly 320 times the mass of the earth. Each of these planets is accompanied by an extensive set of satellites as well as a ring system.

Body	Distance from Sun (AU)	Mass (Jupiter = 1)	Distinguishing Characteristics
Jupiter	5.2	1	Great red spot, Strong magnetic field
Saturn	9.5	0.30	Low density, bright rings
Uranus	19.2	0.046	Rotation axis parallel to plane of orbit
Neptune	30.1	0.054	Largest moon in retrograde orbit

Satellites of the Gas Giants

Each of the gas giant planets has a large number satellites, ranging in size from larger than the earth's moon, down to objects a few miles across or smaller. The source of the satellites is mixed; some formed along with the planet they orbit, while others seem to have been captured by the planets at later times.

Beyond 30 AU: Small Icy Bodies

For nearly seventy years, it was difficult to know what to make of Pluto. Was it a one-of-a-kind oddball in the solar system, or only one of a number of icy bodies orbiting the Sun in the outer solar system? In the last 10-15 years many icy bodies similar in size to Pluto have been discovered in the outer solar system, indicating that it is not an oddball. The properties of these newly discovered bodies have been a great surprise, and have sparked new interest in studying how the early outer solar system evolved.

Comets

In the same way that the inner solar system contains many small rocky bodies (asteroids), the outer solar system is home to many small icy/rocky bodies–

comets. On occasion–due to gravitational interactions with larger bodies in the outer solar system–some comets end up on orbits that bring them into the inner solar system. This ultimately spells the destruction of these comets, since on each passage through the inner solar system the material making of the comet is vaporized and blown away by the Sun.

Chapter 6

The Terrestrial Planets

When studying the planets and large moons in the solar system, it makes sense to divide the planets up into 4 categories:

1. the rocky inner planets and moons,
2. the gas giant planets,
3. the icy/rocky outer moons of the gas giants, and
4. Pluto and the other outer solar system objects.

The key is then to study each group, trying to understand the overall properties of the group as a whole. We will first study the inner, rocky planets and moons (i.e. the terrestrial planets).

6.1 The Earth

The most important rocky planet we will study is the earth. This is because we know much more about the earth than any other planet. When planetary geologists study other planets, they use our understanding of the structure and properties of the earth, and of the processes that lead to the earth being as it is to interpret what they see on other worlds.

The Earth's Interior

The earth has a radius of a little under 6400 km. The deepest hole that has yet been drilled in the crust of the earth has a depth of just over 12 km. Clearly, if we want to learn about the interior of the earth or other terrestrial planets, we must use indirect means to get the information.

Average Density

An object's density is defined to be its mass divided by its volume. Different materials have different densities, so one way to tell the difference between objects is compare their densities. For terrestrial planets, we actually need to distinguish between two different types of density:

- **Compressed Density** This is the actual density we measure for a planet or moon. Because the interior parts of the body must support the weight of all the material above the interior, the central material tends to compress making the average density higher than it would be without compression. The compressed density of the earth is 5.5 times the density of liquid water.

- **Uncompressed Density** With an estimate of the composition of a planet, it is possible to use its compressed density to make an estimate of its uncompressed density. In general, the larger the mass of a planet, the greater the difference between its compressed and uncompressed density. The uncompressed density of the earth is estimated to be 4.3 times that of liquid water.

The average density of the rocks on the surface of the earth is in the range 2.5-3.3 times that of liquid water. Therefore, the density of the materials making up the earth's outer parts is lower than that of the planet as a whole, and so the interior of the planet must be composed of more dense materials.

Waves

A wave is a traveling disturbance that transports energy, without transporting material. Waves have the following general properties:

- **Amplitude** A measure of the "height" of a wave. For a wave of a particular frequency, the amount of energy carried by the wave increases as the amplitude squared.
- **Wavelength** The distance separating two successive peaks or troughs in a wave. We usually denote the wavelength of a wave with the Greek letter lambda (λ).
- **Period** The time for two successive peaks or troughs (i.e. one whole wavelength) to pass a fixed position, usually denoted as T.
- **Frequency** The total number of waves to pass a fixed location per second, denoted as f. Notice that $f = 1/T$.
- **Speed** The speed of anything that travels is simply the distance traveled divided by the time it takes to travel that distance. Thus: for a wave $v = \lambda/T$, or, in terms of the frequency, $v = \lambda f$.

Seismic Waves

Waves that pass through the earth are known as seismic waves. There are two types of seismic waves that pass through the body of the earth:

- **Primary (P) waves** In a P wave, the oscillations occur in the same direction as the wave is traveling. P waves are the fastest seismic waves, and so arrive at the seismograph first, which is why they are called primary waves.
- **Secondary (S) waves** In an S wave, the direction of oscillation is perpendicular to the direction of wave travel. S waves arrive at the seismograph after the P waves, and thus are called secondary waves.

The Earth's Internal Structure

By analyzing the seismic waves that arrive at different positions from around the earth relative to where an earthquake has occurred, we gain information about the regions in the earth that the waves must have traveled through. An important difference between P and S waves that helps us understand the interior of the earth is that S waves can't pass through liquids, while P waves can. Seismologists have discovered that the for a region surrounding the the point on the earth opposite the position where an earthquake occurs, no S waves are ever observed, but P waves are. This "S wave shadow" shows that at least some of the central regions of the earth must be liquid.

We can divide up the interior of the earth based upon either the physical properties of the materials, or using their composition (i.e. their chemical makeup). If we divide by properties, the earth has the following internal structure (from outside to in):

- **Lithosphere:** the outer 100 km or so of the earth's surface is composed of rocks that are rigid and strong, and thus not easily deformed.
- **Asthenosphere:** in the region from about 100 km down to 350 km, the temperature and pressure the rocks are experiencing make them easily deformable (but not liquid.)
- **Mesosphere:** as we move inward the pressure increases, causing the rocks at depths between 350 and 2900 km to become strong and rigid a gain.
- **Outer Core:** in the outer core (at depths of 2900 km to 5140 km), the temperature becomes high enough for the material there to become molten (i.e. liquid). The "S wave shadow" is created by the outer, liquid core.
- **Inner Core:** deeper in the core, the pressure continues to rise, increasing the melting point of the materials there until they exceed the temperature in that part of the core. The inner core of the earth is therefore solid, even though the outer core, that is at a lower temperature, is liquid.

If we instead look at the makeup of the earth's interior, we divide it somewhat differently:

- **Crust:** The outer parts of the earth can be divided into two types of crustal material: continental crust and oceanic crust. The continental crust can range from 20 to 70 km thick, and is composed largely of rocks with relatively high silica content. The oceanic crust is thinner (typically around 10 km thick), and is composed of rock with lower silica content.

- **Mantle:** We know little about the composition of the earth's mantle, which extends from the crust to the outer core. Analysis of the speeds of seismic waves traveling through the mantle, along with the few samples geologists think represent mantle material, suggest that it is made up of rocks that are more dense than those of the crust.
- **Core:** The high density of the core, combined with the fact that iron is by far the most common heavy element in the universe suggests that the core of the earth is composed largely of iron.

Sources of Earth's Internal Heat

The core of the earth is at a temperature of over 5000°. A major source of the heat that maintains this high temperature is the decay of radioactive materials such as uranium in the earth's core.

Magnetic Fields

Magnets have at least two poles, with two possible magnetic polarities, North and South seeking. Magnetic fields are created by moving electric charges (i.e. an electric current.) Electric charges that are stationary in a magnetic field experience no force due to that magnetic field. Moving charges may experience a force due to a magnetic field. Whether they do or don't depends on the direction of the particle's velocity vector relative to the direction of the magnetic field lines. If the velocity vector of the charged particle is parallel to the field lines, no force is experienced. If, on the other hand, the velocity vector cuts across the field lines, the particle will experience a force due to the field. The direction of the force that the particle experiences is perpendicular both to the direction of the magnetic field line and the velocity vector of the particle.

Therefore the magnetic force allows charged particles to move freely along magnetic field lines. Motion perpendicular to the field lines causes the particle to circle the field line instead. The combination of these two motions in general causes charged particles to spiral around magnetic field lines. Because of this, magnetic fields can serve as "traps" for charged particles, in which the particles spiral around the field lines, but cannot easily exit the region where the magnetic field is.

Earth's Magnetic Field

Because planetary magnetic fields are generated deep in the core of planets, they also give us information about the central regions of a planet. The earth's magnetic field has the following characteristics:

- The Earth's magnetic field currently has a structure similar to that of a bar magnet. Such a field is sometimes referred to as a dipole magnetic field.

- The earth's field is created by convection in the outer core. The circulation gives rise to electric currents that produce the field. In turn, the field that is produced tends to reinforce the current flow. A field that is produced in this manner is sometimes referred to as a dynamo magnetic field. This dynamo action is capable of maintaining an existing magnetic field, but is not able to produce a field where non existed. Therefore Earth's initial field must have been created by some other mechanism.

- The region around the earth where its magnetic field dominates the solar magnetic field is called the **magnetosphere**.
  - The solar wind (speed = 400-800 km/s, about 1,000,000 mph) forms a bow shock where it encounters the magnetosphere, and blows out a long magneto-tail on the side of the earth opposite the Sun.
  - The Van Allen Belts are belts where energetic charged particles are trapped in the earth's magnetic field.

- Analysis of magnetic grains in volcanic rocks shows that there have been a number of magnetic field reversals, typically occurring every 100,000 years or so. Geophysicists still don't completely understand what causes this to happen.

Plate Tectonics

The earth's crust is not a single piece, but instead is made up of 7 major, and many minor tectonic plates. These plates are in constant motion; the arrangement of continents on the surface of the earth is changing over geologic time. This motion is possible because the easily deformable asthenosphere is fairly close to the surface in the earth, and because the sources of internal heat in the planet are sufficient to drive plate motion due to convection in Earth's mantle.

The boundaries of the plates are places of particular importance, since they are locations where the greatest change in the surface of the earth due to plate motion that is occurring. In fact, plate boundaries are the most frequent sites for both active volcanism and earthquakes.

Types of plate boundaries:

- **Convergent:** at a convergent boundary, the plates are moving toward one another. At a convergent boundary, one plate will be forced below the other, and driven down into the mantle; this process is called subduction. If a continental plate is subducting another continental plate, the over riding plate will be forced upward, creating folded mountain belts. Current examples where this is happening include the Himalayas and the Alps.

- **Divergent:** at a divergent boundary, the plates are moving away from one another, which creates a rift between the plates. If both the plates are oceanic plates, new material will rise from lower levels to fill in the rift. A current example of this is the mid-Atlantic ridge.

- **Transform:** at a transform boundary, the plates are sliding past one another. Transform boundaries are often sites of intense earthquakes. A current example of a transform boundary is the San Andreas fault in California.

Volcanism

Volcanism is a process where molten rock is extruded from below Earth's surface. The nature of a volcanic region depends on the viscosity of lava erupted there. Lava's of low viscosity will easily flow away from the site of the eruption, while high viscosity will pile up near the eruption site. Because the viscosity depends on the silica content of the lava being erupted, and because the lava is nothing more than melted rock, the structure of a volcano can immediately tell a trained geologist something about the composition of the crust in the area where the volcano occurs.

Viscosity vs. Silica Content

Magma Type	Silica Content	Viscosity
Felsic	$> 65\%$	High
Intermediate	52-65 %	Moderate
Mafic	45-52 %	Low
Ultra-Mafic	$< 45\%$	Very Low

Types of Volcanoes

- **Shield:** result from the eruption of fairly low viscosity lava. This leads to a fairly broad, slowly sloping volcano. (Example: Mauna Kea and other volcanoes in the Hawaiian islands)

- **Strato-volcanoes:** result from eruptions of lava that is largely of intermediate viscosity. This leads to a volcano that is conical in shape, with fairly steep sides (examples include Mount St. Helens and Mt. Fuji.) Strato-volcanoes are also called composite volcanoes.

- **Cinder cones:** are due to eruptions of high viscosity lava, making them very steep sided. Cinder cones are small, and their activity short lived. The viscosity of the lava is so high that the eruptions are explosive; the erupted materials take the form of pyroclasts ("pieces of hot rock".) The cinder cone is formed by the accumulation of these pyroclasts around the vent from which they are erupted.

- **Fissure Eruptions:** Sometimes lava will reach this surface via long fissures (up to tens of miles long or more.) The lava extruded from these fissures tends to be of extremely low viscosity, that tends to spread out over large areas around the fissure, forming what are known as **basaltic plains**.

Earth's Atmosphere

Earth's atmosphere is composed of nitrogen (78%), oxygen (21%), argon (1%) (percents by number), as well as various trace gases, such as carbon dioxide and water vapor. This is a strange composition for a planetary atmosphere, since oxygen will easily combine with other chemicals. The presence of an oxygen rich atmosphere is a due to the action of plant-life on the earth.

Layers in the Atmosphere

- **Troposphere:** the lowest 10 km or so of the earth's atmosphere. The temperature drops steadily as you move upward in the troposphere, because convection is fairly strong in this layer.
- **Stratosphere:** from approximately 10 to 30 km above the surface. The temperature changes very little with height, due to little convection occurring in this layer.
- **Mesosphere**[1]**:** from 30 to 80 km above the surface, the temperature actually rises, due to absorption of UV light by the ozone layer.
- **Ionosphere:** Above about 100 km, some fraction of the atmosphere is ionized (i.e. electrons are stripped from atoms or molecules), meaning that there are free positively and negatively charged particles in the atmosphere. The ions are produced by the atoms and molecules absorbing short wavelength UV and x-rays from the sun.

The Greenhouse Effect

If Earth had no atmosphere, its surface temperature would be determined by the balance of the rate at which its surface absorbed solar radiation, and the rate it emitted radiation (remember, any object with a temperature above absolute zero will radiate). It turns out that the average surface temperature for the earth in this case would be below $0^\circ\ C$. Earth's surface actual average surface temperature is above the freezing point of water because of the effect of its atmosphere, and is known as the greenhouse effect:

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[1] You may have noticed that both Earth's interior and atmosphere have a layer known as the mesosphere. The prefix meso just means middle, so both layers are the result of some particularly un-inspired naming on the part of Earth scientists.

- Certain gases (notably water vapor and carbon dioxide, although there are others) are transparent to electromagnetic radiation in the visible part of the spectrum, but strongly absorb electromagnetic radiation in the infrared part of the spectrum.
- Visible light can penetrate to the earth's surface and be absorbed, heating the surface. Earth radiates some of the absorbed energy. At the temperature of the earth's surface, most of its energy is radiated in the infrared part of the spectrum.
- This radiated energy is absorbed in the atmosphere by carbon dioxide and water vapor (as well as other gases), heating the atmosphere.
- The heated atmosphere radiates energy, some of which travels downward to be absorbed by the ground, raising its temperature above what it would be due to heating by direct sunlight alone.
- The net effect of this process is that the surface and troposphere of the earth will contain more energy than they would in the absence of any atmosphere. This increased energy can take different forms, including higher temperatures, increased amounts of water vapor in the atmosphere, etc. This is what people mean when they refer to the greenhouse effect, and is not synonymous with global warming, which is a change of average surface temperatures presumably induced by an increased efficiency of the green house effect produced by increased concentrations of carbon dioxide in Earth's atmosphere due to the burning of fossil fuels.

Water on Earth

One feature that distinguishes Earth from the other terrestrial planets in the solar system is the abundance of liquid water on its surface. This is important in the evolution of the earth in several ways:

1. Water is an important agent in altering the surface of the earth by weathering, by such processes as erosion and glaciation.
2. The presence of liquid water throughout Earth's past has significantly changed the earth's atmosphere. Water acts to remove carbon dioxide

from the atmosphere. In addition it is important for the production of life on the earth.

3. Simple aquatic plants (mostly algaes) are important for producing atmospheric oxygen via photosynthesis.

The History of the Earth

The evolutionary history of the earth can be divided into several distinct stages (note: byrs = billions of years):

- **Accretion** (4.6-3.8 byrs ago) During this phase, the earth was being built up by collisions with smaller solar system bodies and was largely molten. The sinking of the more dense materials to form Earth's core (differentiation) occurred during this period.

- **Continent growth** (3.8-2.5 byrs ago) During this phase, the continents and ocean basins are formed, and the first life appears.

- **Continents Stabilize** (2.5-0.6 byrs ago) Oxygen is released into earth's atmosphere by early plants (remember, these plants were largely algae!)

- **Modern Tectonics** (0.6 byrs-present) Evolution of the surface is largely controlled by global tectonics, as well as the weathering influence of the atmosphere and liquid water.

6.2 The Moon

The surface of the moon shows two distinctive types of terrain: lighter colored regions that are known as the lunar highlands, and darker regions that are known as maria (singular mare.) The highlands are the oldest exposed regions on the surface of the moon, while the maria are large flows of low viscosity lava, which occurred somewhat after the highlands had formed. The near side of the moon to the earth shows large areas of both highlands and maria, while the side facing away is composed almost exclusively of highlands.

Tides and the Moon's Rotation

The moon always shows the same face to the earth. This is due to the effects of tides produced by the earth on the moon. Tides occur because of the form of Newton's Law of Universal Gravitation, in particular because of the fact that the gravitational force drops off as $1/r^2$. Because of this, the gravitational force due to the earth on the moon is largest on the near side, and decreases continually as you move toward the far side. The earth thus distorts the shape of the moon slightly, so that the moon is elongated along the line separating the centers of the earth and moon. The earth can then produce a torque on this tidal bulge that act to keep the bulge aligned with the earth. Therefore, if the moon initially had a faster rotation period than orbital period the torque would slow the rotation until the two periods matched, while if the rotation started out slower than the orbital period, the torque would act to speed the rotation until the periods matched. This effect, where the rotation and orbital period of a body match due to the tides and torques produced by the body they orbit is known as a tidal lock, and occurs many places within the solar system.

Impact Craters

Besides the maria and highlands, the next most obvious surface feature on the moon are lunar craters. Craters are formed by the impact of meteorites with the lunar surface. A typical meteoroid will be traveling at speeds from a few to a few tens of kilometers per second when they impact, so they have a large amount of kinetic energy when they strike. The collision drives seismic shock waves down into the moon, and can melt a significant amount of the surface around the impact site. In addition, a large amount of debris will be blasted outward from the impact site, forming an ejecta blanket around the crater.

One use of craters in studying planetary surfaces is that their surface density (i.e. number of craters per square kilometer) can be used to determine relative ages of different regions on that body.

Relative vs. Absolute Age

A relative age scale is one where you can place things in the correct sequence of age, but are not able to assign exact ages (i.e. you can say that A is older than B, but can't say what the age of either A and B are.) An absolute age scale is one that allows you to attach exact ages (e.g. A is 74 years old, while B is 36.) Crater surface densities allow us to get relative ages; when comparing two regions, that with the higher crater density will be older. Crater densities don't allow us to determine absolute ages by themselves, because we don't know how the rate that craters are produced has changed throughout the history of the solar system. In order to get absolute ages, we must instead use radioactive decay dating of rocks.

Ages of Lunar Surface Features

Using samples returned by the Apollo missions, the lunar highlands date from 4.2-4.4 byrs, while the mare regions date from 3.2-3.9 byrs ago. The two important points to be noted here are that:

1. Though younger than the highlands, the mare are still as old as the *oldest* geologic features on the earth, indicating that geologic activity ceased on the moon long ago.

2. The much lower density of craters on the mare than the highlands indicates that the rate of cratering must have been extremely high initially, but by 3.9 byrs ago must have dropped significantly. In fact, the rate from 3.9 byrs ago until today has not changed much.

Volcanic Features

The major volcanic features on the surface of the moon are somewhat different than those on the earth. The major volcanic feature on the moon are the Maria, which are fissure eruptions that created extremely large flows of very low viscosity lava.

Other volcanic features observable on the surface of the moon include:

- **Sinuous Rilles** Sinuous rilles are channels observed in the maria. The current best guess is that they represent old lava tubes where the roof of the tube has collapsed.
- **Cinder Cones** There are a few cinder cones observed on the lunar surface. Like on the earth, they are small in size.

Note that the majority of the volcanic features indicate very low viscosity lavas, suggesting that the rocks on the moon are low in silica content, and thus similar to the oceanic crust or mantle on the earth. The samples of maria brought back by Apollo astronauts, along with the crater densities on the maria suggest that all volcanic activity on the lunar surface stopped over 3 billion years ago.

Tectonic Features

Unlike the earth, the moon has no large scale tectonic features akin to plate boundaries. All the tectonic features that are observed are small scale features, and the signs are that tectonic activity stopped 2-3 byrs ago. Some of the observed tectonic features are:

- **Linear Rilles** Linear structures a few hundred kilometers long, they appear to be places where the crust has pulled apart. Possible mechanisms that caused them to form are:
  - Expansion during cooling of the moon.
  - Local stress due to the added mass on the surface by mare flows.
  - Fracturing caused by large nearby impacts.
- **Wrinkle Ridges** Normally found in the maria. Possibly formed by surface adjustment due to the mass of the over-lying lava flow.

Internal Structure

- The average (i.e. compressed) density of the moon is 3.3 g/cc, and uncompressed density is 3.2 g/cc. This suggests that the moon has a much lower proportion of iron than the earth does.
- Seismographs left by some of the Apollo missions show that the moon suffers relatively few moon-quakes, that are much weaker than typical earthquakes. In addition, the epicenters of the moon-quakes are deep in the interior of the moon.
- The moon has no global magnetic field.

Based on this evidence, the best current model for the interior of the moon is:

- **Crust:** Varies from 50-150 km thick, and is thinner on the Earth facing side, which probably explains the fact that most maria are found there. This difference in thickness from near to far side is most likely due to the tides produced by the earth.
- **Mantle:** appears to be rigid, and about 1000 km thick. Notice that unlike the earth, the lithosphere comprises both the crust and the mantle.
- **Asthenosphere:** Has a thickness of a few 100 km, and lies below the mantle, deep in the interior of the moon, as inferred from the epicenters of moon quakes.
- **Core:** Most planetary scientists expect that the moon has a small iron core, possibly a few 100 km in radius. The core is probably solid.

Theories of Formation for the Moon

Any acceptable theory of the formation of the moon must at the least be able to explain the following facts about the moon:

1. The difference in iron content between the earth and the moon.
2. The composition of the lunar surface rocks seems similar to the composition of the rocks in Earth's mantle.

3. The ratios of different isotopes of oxygen and other elements is the same in lunar and earth rocks, suggesting that they formed from the same “batch” of material.

4. The overall lack of volatile elements such as water on the moon.

5. The combined angular momentum of Earth/Moon system is very large compared to the other terrestrial planets.

Over time, four popular models for the formation of the moon have been proposed.

- **Fission** The earth and Moon formed as a single object, but later split into two unequal sized objects due to the rapid rotation of the parent body. This model can explain the mantle-like composition, iron deficiency, and isotope ratios, but not the lack of volatiles. This model requires–but does not explain–the large angular momentum of the Earth/Moon system, but it predicts that the Moon should orbit the earth above the equator, while instead the Moon’s orbit is inclined by about 5° to the equator.

- **Co-accretion** The earth and the moon formed as a “twin planet”. This model can explain the isotope ratios, but not the other items.

- **Capture** The earth and the moon formed at different places in the solar system, and the moon was later captured by the earth. This model can’t explain the isotope ratios.

- **Collision** Early in Earth’s history, it was struck by a roughly Mars sized body, knocking free the material that later coalesced to become the moon. This model explains the isotope ratios (since the material from both bodies comes from the same source), mantle-like composition of the surface (computer simulations of such a collision show that most of material that ends up forming the moon started out in the mantle of the precollision Earth plus colliding body), iron deficiency (the simulations indicate that the collision wasn’t able to dredge out much of the core, so the earth retains most of the iron while the moon gets little), lack of volatiles (vaporized during collision, so none incorporated in moon), and large angular momentum, most of which comes from the orbital angular momentum of the Mars size impactor. The collision model is currently the most popular theory of lunar formation, because it can explain all of the known features of the Earth-Moon system.

History of Moon

- **Formation** (4.6-4.5 byrs ago) The material that will form the moon is knocked free from the earth by the collision of a Mars sized body, and coalesces in orbit. The lunar crust forms.
- **Heavy Bombardment** (3.8-4.5 byrs ago) Lunar highlands heavily cratered during this time.
- **Mare Flooding** (3.9-3.2 byrs ago) Most of the volcanic activity on the moon seemed to happen during this time.
- **Slow cratering** (3.2 byrs-present) No significant geological activity, probably due to the rapid cooling of the lunar interior due to the moon's small size.

6.3 Mercury

We know relatively little about the planet Mercury. About 50% of its surface has been mapped by Mariner 10, revealing a heavily cratered surface, not dissimilar in appearance to the surface of the Moon, although with a somewhat lower crater density. Possible explanations for this lower crater density include a re-melting of the surface early in Mercury's history, an intense period of early volcanism that obscured craters, or major impacts that removed signs of early craters.

Mercury's Rotation

Early on, astronomers expected that Mercury would rotate once for every revolution around the sun, due to tidal locking with the sun. It turns out though that Mercury rotates 3 times for every 2 revolutions. This is because Mercury has a somewhat eccentric orbit ($e \approx 0.2$) which means that its orbital speed at closest approach to the sun (when tidal forces are by far the strongest) is the same as it would be for a circular orbit with period 2/3 times that of Mercury.

Internal Structure

The average (i.e. compressed) density of Mercury is 5.4 g/cc, and uncompressed density is 5.2 g/cc, suggesting that Mercury must have a fairly large iron core. Because of Mercury's small size, it was expected that Mercury's core should be solid. This, together with its slow rotation suggested that Mercury should have no magnetic field, however Mariner 10 discovered a global magnetic field approximately 1% as strong as that of the earth! Perhaps Mercury's core is partially molten today, or some form of permanent magnetism is active in its solid core.

From the above observations, we infer that the internal structure of Mercury is:

- **Crust + Mantle** Only 500-600 km thick. Little is known about the relative thickness of the crust and mantle.
- **Core** $\sim$ 3600 km in radius.

Volcanism

Relatively few volcanic features were visible in the Mariner 10 images. The most significant features are known as smooth plains, areas that appear similar to Lunar maria.

Tectonic Features

The major tectonic feature on Mercury are the scarps; cliff-like structures that are a kilometer or more high, and run 100's of kilometers along the surface, generally in a north-south direction. Possible mechanisms that formed the scarps include:

- Tidal stresses due to the nearness of Mercury to the sun and the eccentricity of its orbit.
- Stresses due to the contraction of the planet as it cooled (the currently popular hypothesis.)

The Caloris Basin

The Caloris Basin is a large impact structure (approximately 1300 km across, only about half of the basin is in the area Mariner 10 imaged). On the opposite side of the planet from the basin is an area of "Chaotic Terrain", presumably formed by the focusing of shock-waves produced when the Caloris Basin was formed.

History

Note that relative and not absolute ages are used here. For everything in the solar system other than the earth and the moon, we don't have enough information to establish an absolute scale.

- **Accretion and Differentiation** It may be that at the end of this period, heat released during the formation of Mercury's core re-melted the surface.
- **Heavy Bombardment**
- **Caloris Basin Formed**

- **Smooth Plains Formed**
- **Light Cratering** Like the moon, we believe that all major geological activity on Mercury ceased long ago.

6.4 Venus

Venus may be loosely thought of as “Earth’s Twin”, in that it is closest to Earth among the other planets in the solar system in its size and distance from the sun. The most obvious feature of Venus observed from afar is that it has a thick, cloud dominated atmosphere. Information about its surface must thus be obtained through either radar mapping or landing probes upon its surface.

Venus has relatively few impact craters on its surface. Two factors probably contribute to this. First, the thick atmosphere keeps smaller meteoroids from reaching the surface. Second, we expect that Venus is geologically active today (remember the size part of the earth’s twin business?) and so is constantly removing older craters through various geological processes. One curious fact about the crater density on Venus is that it is very uniform over the entire surface, suggesting that a global event occurred about 500 million years ago that removed craters over the entire surface. Suggestions for what that event might have been include a period of strong global volcanism, or a re-melting of the entire surface of the planet due to a large internal release of heat.

The Rotation of Venus

One curious feature of Venus is that it rotates in a retrograde sense, with a period of 243.01 days. It isn’t clear what gives rise to this; it is possible that it is a tidal lock with the earth, although the period isn’t exactly correct (243.16 days would be.) The most popular (although difficult to corroborate) theory is that this may be due to a giant impact sometime early in Venus’ history.

Atmosphere

The atmosphere of Venus is 50 times as dense as Earth’s, with a pressure at the surface of about 90 atmospheres. It is composed largely of carbon dioxide (96%) and nitrogen (3.5%), with traces of water, sulfuric acid, hydrochloric acid, and hydrofluoric acid. The clouds that enshroud the planet are composed largely of small particles of sulfur and droplets of sulfuric acid.

High atmospheric pressures greatly enhance the effectiveness of carbon dioxide as a greenhouse gas. Because of this fact, Venus exhibits an extremely strong green house effect. In fact, the average surface temperature on Venus is higher than any other planet in the solar system, even Mercury.

Geology

What we know about the surface of Venus comes from the surface maps created from radar measurements by the US Magellan probe, and from a few Soviet probes that actually landed on the surface. The picture they give us of the surface is:

- 60% of the surface is rolling plains, with elevation changes less than 500 meters.
- 24% is highlands, with elevations about 4.5 km above that of the rolling plains.
- An amazing 16% of the surface is covered with large shield volcanoes.

Tectonic Features

Given its other similarities to the earth, we might expect Venus to have large scale plate tectonics similar to those on Earth. However, no evidence of large scale rifts can be found on the surface, although there are some folded mountain belts. The speculation is that the high surface temperature causes the crust of Venus to be softer and less rigid than that of Earth, so that it doesn't form the same type of plate system as the earth does.

Volcanic Features

As noted earlier, the most impressive volcanic features on the surface of Venus are the many large shield volcanoes. It is guessed that at least some of these are active, although we have no direct evidence of this.

Another volcanic feature are the Coronae, which are large circular bulges surrounded by fracture systems. It is speculated that these are due to upwelling over hot spots in Venus' mantle, that lift and fracture the crust.

Internal Structure

Not much is known about the internal structure of Venus. It's size and density are similar to that of the earth–compressed density of 5.24, uncompressed density of 4.2–suggesting a significant iron core. Venus has no global magnetic field, probably due to its slow rotation.

History

Other than it appears that there was a global resurfacing of the planet about 500 million years ago, we do not currently know enough about Venus to say anything meaningful about its history.

6.5 Mars

Mars may also be loosely thought of as "Earth's twin", although for different reasons than Venus. Mars has a ~ 25 solar hour day and a $\sim 25^\circ$ axial tilt, both close to the values for Earth. In addition, the surface conditions on Mars are the closest to those on Earth of any solar system body (although the conditions aren't *that* close, as you will see!) The red or orange color of Mars is due to Iron Oxides in its soil. On occasion the surface will experience large dust storms, sometimes obscuring the entire surface of the planet for weeks at a time.

One interesting feature of Mars that we don't currently understand is the fact that the two hemispheres of the planet are considerably different in their properties. The elevation of the southern hemisphere is roughly 4 km higher than in the northern hemisphere, and the crater density is significantly higher in the south than the north. A large scarp (i.e. cliff) divides the two hemispheres. It has been variously suggested that perhaps a global flooding event or large impact may have created the asymmetry, but these are currently little more than speculations.

Atmosphere

The Martian atmosphere is composed largely of carbon dioxide (95%), with a bit of nitrogen (3%). The final 2% of the atmosphere is composed of Argon and other trace gases. The density of the atmosphere at the surface of Mars is only about $\sim 1\%$ that on Earth. Although its atmosphere is composed largely of carbon dioxide, Mars does not exhibit a significant greenhouse effect because of the very low density of its atmosphere.

Internal Structure

Both of the Viking landers in the 1970's carried seismographs, however one of them did not work. We must therefore rely on our other techniques to tell us about the interior of Mars.

- The average density of Mars is 3.9 g/cm^3. Because of the planets relatively low mass, the uncompressed density of Mars is about 3.8 g/cm^3, somewhere between that of the earth and the Moon.

- Mars currently has no global magnetic field. Mars Global Surveyor has detected local fields, which show a pattern of stripes of reversed polarity, similar to that at divergent plate boundaries on the earth.

From this rather meager evidence, the inferred internal structure of Mars is:

- **Lithosphere (crust + mantle)** ∼ 2000 km thick.
- **Iron Core** ∼ 1500 km in radius.

Tectonics

There are no signs of large scale plate tectonics on the surface of Mars today, although the "magnetic striping" suggests that there might have been some in Mars' past. There are many examples of local tectonics, the most impressive of which are associated with the the Tharsis bulge. Chief among these is the Valles Marineris, a 5000 km long canyon system that radiates away from the bulge. The Valles was not formed by erosive processes, as are many large canyons on the earth such as the Grand Canyon, but instead is due to fracturing of the crust by the bulge.

Volcanism

Besides creating the Valles Marineris, the Tharsis bulge is also the site of several large shield volcanoes, the largest of which, Olympus Mons, is $\sim 27\ km$ (19 miles) high. The immense size of Olympus Mons and the other shield volcanoes on Mars is probably due to 2 factors:

1. The area of the crust over the bulge has stayed relatively motionless over the upwelling in Mars' mantle that created the bulge, so that the volcanoes are the result of a number of eruptions over a long period of time.

2. The relatively low acceleration of gravity on the Martian surface allows larger volcanoes to be formed than would be possible on the earth or Venus.

In addition to the shield volcanoes, Mars also shows examples of volcanic plains, probably similar to lunar maria, but on a smaller scale.

Evidence for Water

One of the most evocative questions about Mars is whether Mars had liquid water on its surface in the past, and if so, how much water there was and where that water might be today. Evidence for liquid water in the past on Mars includes:

- "Teardrop"craters, presumably formed by the flow of large amounts of water around the craters.
- "Splat" craters, whose ejecta look similar to a mud-flow on Earth, suggesting that the impact melted subsurface ice, which mixed with the Martian soil to form the ejecta.
- Runoff channels, similar to those created by rainfall on Earth. Unlike the channels on the earth, however, the systems of channels are much more widely spaced. This suggests that if they were formed by rainfall that areas where rain did fall were fairly localized. Another possibility is that the channels were formed not by rainfall, but instead by the melting of localized areas of surface water.
- Outflow channels, similar to channels created by large, catastrophic floods on the earth.

Polar Caps

The polar caps on Mars are also places that may harbor water ice. The caps actually grow and shrink with the Martian seasons. The seasonal caps are believed to be carbon dioxide ice (i.e. dry ice), that freezes out of the atmosphere during the winter, and sublimates back into the atmosphere in the summer. The residual caps that are left during the summer are different in the southern and northern hemisphere. In the south the residual cap is approximately 350 km across and stays at the sublimation temperature of carbon dioxide ice, suggesting that this cap has significant amounts of carbon dioxide, although large amounts of water ice cannot be ruled out. In the northern hemisphere, the residual cap is about 1000 km across, and reaches temperatures well above the sublimation point for carbon dioxide, suggesting that the cap is largely composed of water ice.

Where's the Water Now?

At least some of the evidence above suggests large amounts of liquid water in the past. If the inferences are correct, the question then becomes, where is this water today? The amount in the present day polar caps and atmosphere isn't nearly enough. Some possibilities include:

- The water is locked up in a layer of permafrost. Mars Odyssey has detected what appear to be large deposits of sub-surface ice. The instruments cannot probe very deeply, so we are currently unsure how thick these deposits might be.
- Lost into space. Mars low surface gravity means that it has difficulty holding onto light atmospheric gases, so if the water ended up as water vapor in the air, it could have been lost to space.
- It may simply be that the estimates of the amount of water in the past are too high.

Chapter 7

The Gas Giant Planets and Their Ring Systems

The Gas Giant Planets

The predominant feature of Jupiter, Saturn, Uranus, and Neptune is their extensive atmospheres, which are composed largely of hydrogen and helium. The gas giant planets are sometimes also referred to as the Jovian (i.e. Jupiter-like) planets.

Jupiter

The basic properties of Jupiter are:

- Mass 318 times the earth (1/1000th that of Sun)
- Diameter 11 times the earth
- Density 1.33 grams/cc
- Rotation period 9.9 hours

Atmosphere

The atmosphere of Jupiter is composed 99.9% of hydrogen and helium, with 75% hydrogen and 25% helium present by mass. There are two obvious features in the atmosphere; the banded structure (known as belts and zones), and the great red spot.

- **Belts and Zones** There is strong convection in the outer atmosphere of Jupiter. This, combined with the rapid rotation of the planet produce the banded structures observed in Jupiter's atmosphere. The Belts (darker colored bands) are areas where the atmosphere is descending, while the Zones (lighter colored bands) are places where the atmosphere is rising. The Belts are at somewhat higher temperatures than the Zones.

- **The Great Red Spot** Is a large rotating disturbance that has persisted for at least 300 years. Its direction of rotation shows that the spot is a high pressure system (remember the Coriolis effect?) A second, smaller red spot has formed recently, out of the merger of two somewhat smaller disturbances known as white ovals.

Interior

Compared to terrestrial planets, the interiors of the gas giants are more difficult to get information about (since the fact that any solid surface lies deep within the planet makes seismographs impractical.) Extracting structure information from a gas giant's density is also more difficult, since gases are highly compressible ,and if compressed sufficiently can change state from a gas to a liquid. Some information about the distribution of mass in the interior of the planet can be gained by analyzing the trajectories of spacecraft orbiting in Jupiter's gravitational field. In order to use this data to gain information about the interior of the planet, calculations of the behavior of the gases in the planets atmosphere as they respond to the temperature and pressure as we work our way into the interior of the planet are necessary. Observations of the magnetic fields of the planets also give useful information. Jupiter has a fairly strong magnetic field, suggesting that it must have a fairly large conducting and convective core.

- **Atmosphere** The outer parts of Jupiter are gaseous. Calculations suggest that the atmosphere stays gaseous well below the layers we can directly observe.

- **Liquid Hydrogen** The pressure increases as we move inward into Jupiter. Eventually, the pressure becomes high enough that the hydrogen goes from being a gas to a liquid. The change from gas to liquid is not abrupt, but instead takes place slowly as you move inward.

- **Liquid Metallic Hydrogen** When liquid hydrogen gets to high enough pressures, it becomes a good conductor of electricity. Calculations show that the pressures are high enough that a fairly extensive region in Jupiter's interior is in this state. The liquid metallic hydrogen, along with the rapid rotation of the planet account for Jupiter's strong magnetic field.

- **Rocky Core** The structure calculations indicate that there must be a solid core to Jupiter (about 15 times mass of the earth or so.)

Jupiter's Internal Heat Source

Jupiter radiates roughly twice as much electromagnetic radiation as it absorbs from the Sun, indicating there must be a substantial interior heat source in the planet. In Jupiter's case, the source is probably residual heat from its formation. Jupiter formed from the gravitational collapse of a portion of the gas cloud that collapsed to form the solar system. Recall that objects that fall in a gravitational field will convert gravitational potential energy to kinetic energy; in the case of Jupiter, gas that comes far from the center of the collapsing cloud will initially have large amounts of gravitational potential energy. When the collapse occurs, this gas will accelerate inward, and by the time it reaches a collapsed state, will have a large kinetic energy. When the density in the forming planet is sufficiently high, the collapse will be halted, during which the kinetic energy will be converted to heat.

Soon after its collapse, Jupiter was very hot, and since then has slowly cooled by radiating this heat. It is this reservoir of heat from its formation that produces the excess radiation we observe today.

Saturn

The basic properties of Saturn are:

- Mass 95 times Earth's mass

- Diameter 9.5 times Earth's diameter

- Density 0.69 grams/cc (less than water)!

- Rotation period 10.7 hours

Atmosphere

Like Jupiter, the atmosphere of Saturn is composed 99.9% of hydrogen and helium. Unlike Jupiter, however, there is about 7 times as much hydrogen as helium by mass. This is most likely due to condensation of liquid helium in the lower levels of the planet. Saturn has a lower temperature than Jupiter, so it possible for helium–which condenses at a lower temperature than hydrogen–to condense in Saturn but not in Jupiter.. Unlike Jupiter, the banding structure in Saturn's atmosphere is much weaker (again, due to Saturn's lower temperature), and there are no signs of strong, persistent cloud features akin to Jupiter's great red spot.

Interior

Because of its lower mass, the interior of Saturn suffers less compression than that of Jupiter. Saturn has a magnetic field, but it is much less strong than that of Jupiter.

- **Atmosphere**
- **Liquid Hydrogen**
- **Liquid Metallic Hydrogen** Because of Saturn's lower mass, it has a much less extensive zone of liquid metallic hydrogen than Jupiter does.
- **Core** Calculations indicate a core similar to that of Jupiter, somewhere in the range of 10-15 Earth masses.

Saturn's Internal Heat Source

Saturn radiates approximately 3 times as much electromagnetic radiation as it absorbs from the Sun. Because it is only 1/3 the mass of Jupiter, Saturn released significantly less gravitational potential energy during its collapse than Jupiter did, so its internal heat today must come from a different source than Jupiter's. The answer lies in the precipitation of liquid helium in Saturn's interior. Going from a gas to a liquid releases a significant amount of heat (just as the reverse process of converting a liquid to a gas requires a significant input of heat.) This, along with the loss of gravitational potential energy of the helium rain falls inward is the source of Saturn's internal excess of heat.

Uranus and Neptune

Compared to Jupiter and Saturn, relatively little is known about Uranus and Neptune. The Basic properties of Uranus are:

- Diameter 4.1 times that of Earth
- Mass 14 times Earth
- Density 1.3 grams/cc
- Rotation axis is approximately parallel to the plane of the planets orbit.

The basic properties of Neptune are:

- Diameter 3.9 times that of Earth
- Mass 17 times Earth
- Density 1.5 grams/cc
- Rotation axis at an angle approximately 30° to plane of orbit

The Discovery of Uranus

In 1781, an English musician and amateur astronomer named William Herschel was at work using a small telescope to compile a catalog of stars. Herschel noted one star that appeared fuzzy and not point like (as stars typically do.) Observations on subsequent nights showed that the fuzzy star moved with respect to the other stars, and was in fact a planet orbiting the sun. Herschel originally named the planet "Georgium Sidus" (i.e. "George's Star") after King George III of Great Britain. Fortunately, this name didn't stick, and the planet was given the name Uranus (who was Saturn's father in Roman mythology.)

The Discovery of Neptune

With repeated observations of Uranus, it became possible to quite accurately determine its orbit, and predict its future positions using Kepler's laws. By 1830 it was known that there were small but significant deviations in Uranus' actual position compared to its calculated position. Several scientists realized that these deviations could be due to the gravitational pull of another undiscovered planet further out in the solar system. Two people successfully undertook the task of calculating the position of this planet based upon the observed deviations of Uranus' orbit; Englishman John Adams, and Frenchman Urbain Leverrier. Adams completed his computations first, but had difficulty getting English astronomers to search for the planet. When they did finally search, they lacked good star charts of that region of the sky and were unable to locate the planet. On the other hand, Leverrier sent the results of his calculations to a German astronomer, who did have good charts; with these charts he quickly identified the planet Neptune, at very near the position predicted by both Adams and Leverrier.

Atmospheres

Like Jupiter and Saturn, Neptune and Uranus have atmospheres that are 99.9% Hydrogen and Helium.

Interiors

Because of their relatively low masses, calculations of the interior structure of Uranus and Neptune indicate that there should be no zone of liquid metallic hydrogen, but that there should still be substantial solid cores to the planets (around 10 times the mass of the earth or so.) Quite surprisingly given this expected lack of liquid metallic hydrogen, both planets do have global magnetic fields. Furthermore, the field axes in both planets are tipped substantially with respect to their rotation axes, and the center of the field axes are substantially offset with respect to the centers of the planets. All of this taken together suggests that a mechanism different from that producing Jupiter and Saturn's fields–one that is not currently well understood–generates the magnetic fields of Uranus and Neptune..

Internal Heat Sources in Uranus and Neptune

Uranus radiates approximately the same amount of energy as it receives from the sun. On the other hand, Neptune radiates about twice as much as it receives. The reason for this difference is currently not well understood. People have suggested everything from differences in the insulation of the two planets interiors, to heating due to radioactive decay, to gravitational potential energy, to a giant impact (so you *know* that they have to be desperate!) The number of unexpected features of these two planets suggests we have much to learn about them!

Ring Systems

Each of the gas giant planets has a system of rings, but the character of the rings varies significantly from planet to planet.

Saturn's Rings

The rings of Saturn are very extensive, extending from 1.2 to 2.3 times the radius of Saturn. Although they extend very far radially, the rings are very thin, being no more than about 20 meters (60 feet) in thickness! The rings appear bright because of the reflection of sunlight by icy and/or ice covered particles in the rings. The particles making up the rings range in size from grains of sand to house size. Data from the Voyager probes in the early 1980's showed that the actual structure of the rings on the small scale is very complicated, with many small ringlets, gaps, and braided and kinky rings.

Jupiter's Rings

The rings of Jupiter were discovered by the Voyager probes. Jupiter has a primary ring that orbits from about 1.5 to 1.8 Jupiter radii. The ring is made up of darkly colored particles no larger than grains of dust. Because of this, Jupiter's ring appears brighter from the far side of the planet from the sun than the near side, due to forward scattering of the sunlight by the small grains.

Rings of Uranus

The rings of Uranus where discovered in 1977 by astronomers observing the occultation of a bright star by Uranus. They found that before and after the occultation there where brief dips in the brightness of the star, due to the star passing behind the rings. the originally discovered ring system consists of 12 rings, which are all very narrow. The particles in the rings are dark, and all are above a few centimeters in size.

New observations with the Hubble Space Telescope have discovered 2 new rings, orbiting at roughly twice the radius of the rings that were first discovered. These rings seem to be composed of very small dust particles, unlike the original ring system.

Rings of Neptune

After the discovery of the rings of Uranus, people also tried to search for rings around Neptune using the occultation technique. Sometimes no occultations were seen, while at other times a dip in brightness was seen on one side of the planet but not the other, suggesting that if Neptune did have a ring system, that the rings were only partial arcs, or at least that the material was distributed in a clumpy way along the rings. Voyager 2 showed that there are 4 rings of Neptune, 3 of which are too insubstantial to have been detected by occultation, and that the earlier occultation results where the result of clumpy regions in the fourth ring. The rings are much brighter in forward scattered than back scattered light, indicating that the rings are made up of small particles.

Ring Dynamics

In order to understand how the structures seen in different planetary rings arise, their dynamics must be analyzed using Newton's laws of motion and gravity. In fact, there are certain features in the ring systems that we don't completely understand, because no one has yet been smart enough to completely write down and solve the correct equations describing some features. Several ideas that are important for shaping the rings that we do understand well are:

- **The Roche Limit** Imagine being able to take a large moon of the outer planets, and move it around so that it is orbiting at different distances from the planet. The closer you put the moon to the planet, the higher the tidal stresses are on the moon. In fact, there is a distance within which the stresses are so strong that the moon would be torn apart. This distance is known as the Roche Limit. Almost all the planetary rings lie within this limit, suggesting that a major source of ring material may be the remnants of planetary satellites that got within the Roche limit on their orbits, or possibly material that was never able to accrete itself into a larger satellite, due to being within the Roche limit.

- **Resonances** Imagine pushing someone on a swing. The most effective way to get them to swing higher is to give them a push in the same direction once every period of the swing. This is an example of a resonance; you are matching the period (or frequency) of the applied force to the natural period (or frequency) of the body. The same thing can happen to any orbiting object. If a force is applied that matches the period (or if the periods are whole multiples of one another), the orbit will eventually be changed by the resonance. Some of the gaps in planetary rings are caused by just this mechanism. For example, the Cassini division in Saturn's rings is caused by a 2 to 1 resonance with the moon Mimas. Resonances can also produce sharp outer edges in a ring. For example, the sharp outer edge edge of the A ring of Saturn is due to a 6 to 7 resonance with two of Saturn's moons, Janus and Epimetheus.

- **Shepherd Moons** Some narrow rings can be formed by the actions of a pair of small moons, orbiting slightly inside and outside the position of the ring. The combined action of these satellites will be to "herd" the ring particles into a narrow ring, due to the gravitational effects of the two moons.

- **Embedded Satellites** The gravitational action of a small satellite embedded with in a ring can act to clear gaps, and even more surprisingly if the conditions are right, create a narrow ring.

Chapter 8

The Large Moons of the Gas Giants

The Large Satellites of Jupiter

The four large satellites of Jupiter, ordered from furthest to nearest to Jupiter are Callisto, Ganymede, Europa, and Io. It was these 4 satellites that Galileo saw through his telescope, so they are sometimes referred to as the Galilean satellites.

Callisto

The basic properties of Callisto are:

- A diameter 1.3 times that of Earth's Moon.
- A density of 1.8 g/cc (remember, the Moon is 3.3 g/cc, liquid water is 1 g/cc.)

The density of Callisto suggests that there are roughly equal amounts of water ice and rock making up Callisto. The surface of Callisto is about as heavily cratered as the lunar highlands, suggesting that the surfaces of the Moon and Callisto are of similar age. Callisto lacks large craters and impact basins, probably because its icy surface is not rigid enough to retain such features.

Ganymede

The basic properties of Ganymede are:

- A diameter 1.5 times that of the Moon.
- A density of 1.9 g/cc.
- Ganymede has a global magnetic field, which was detected by the Galileo probe.

The similarity of Ganymede's density to that of Callisto suggests a similar mix of materials. Half of Ganymede's surface is as heavily cratered as Callisto's, while the other half is somewhat less heavily cratered, although the inferred ages in the least heavily cratered areas are still billions of years old. The younger areas show a system of parallel grooves, suggesting an early era of depression and uplift for some areas of Ganymede's surface.

Europa

The basic properties of Europa are:

- A diameter 0.9 times that of the Moon.
- A density of 3.0 g/cc.

The surface of Europa is coated with ice, but its relatively high density suggests that it is composed largely of rocky material. The surface of Europa has a crater density about the same as the surface of Venus, suggesting a relatively young age. Images of "ice rafts" on the surface of Europa by the Galileo probe, along with measurements of how the magnetic field of Jupiter is modified in the area of Europa, suggest that a salty, liquid ocean underlies the solid ice on Europa's surface.

Io

The basic properties of Io are:

- A diameter of 1.1 times the Moon.
- A density of 3.3 g/cc.

The high density of Io suggests that there is little or no ice on Io. There are no craters observable on its surface, suggesting that Io actually resurfaces itself at a rate higher than the earth does! This resurfacing is due to extensive volcanic activity on Io. In fact, a number of active volcanoes have been observed on the surface of Io.

The volcanic activity of Io came as a great surprise to planetary scientists, because other bodies the size of Io (such as Earth's moon) ended their activity long ago, due to the speed at which their interiors cooled. In Io's case, its interior maintains a high amount of heat due to tidal squeezing by Jupiter.

The Moons of Saturn

Titan

The basic properties of Titan are:

- A diameter of 1.5 times that of the Moon.
- A density of 1.9 g/cc.

Titan's density implies a mixture of ice and rock, similar to Callisto and Ganymede. Titan has a substantial atmosphere, composed largely of nitrogen, with small percentages of argon and methane. Up until recently, little was known about the surface of Titan, because it is obscured by haze in its atmosphere. Images of a small portion of Titan's surface have been returned by the Huygen's probe in late 2004 as it descended through Titan's atmosphere. These images showed a region of ridged terrain, cut by river channels. These channels were not produced by running water (since the surface temperature of Titan is well below the freezing point of water), but instead are most likely caused by liquid ethane and methane. Radar mapping by Cassini has revealed large regions dominated by sand dunes.

Medium Sized Moons

Moon	Diameter (Moon=1)	Density (g/cm^3)
Mimas	0.11	1.2
Enceladus	0.14	1.2
Tethys	0.30	1.3
Dione	0.32	1.4
Rhea	0.44	1.3
Iapetus	0.41	1.2

Moons of Uranus

Uranus has no large satellites comparable to those of Jupiter and Saturn. It does have 5 medium sized satellites:

Moon	Diameter (Moon=1)	Density (g/cm^3)
Miranda	0.14	1.3
Ariel	0.33	1.6
Umbriel	0.34	1.4
Titania	0.46	1.6
Oberon	0.45	1.5

These moons all orbit in the equatorial plane of Uranus, which is essentially perpendicular to Uranus' orbital plane around the Sun. The only one of these moons to be imaged up close is Miranda; given its small size it was expected that it would show a heavily cratered surface. Instead, its surface shows some of the most bizarre terrain seen on any planet or moon in the solar system.

Moons of Neptune

Triton

The basic properties of Triton are:

- A diameter of 0.78 times that of the Moon.
- A density of 2.1 g/cc.

- Is in a retrograde orbit around Neptune.

This last fact about Triton suggests that it did not form along with Neptune and its other medium sized satellites, but instead must have formed elsewhere in the solar nebula, and was later captured by Neptune. This suggests that Triton might well be grouped with Pluto for further study, rather than with the other moons of the gas giants.

Chapter 9

Minor Solar System Bodies

Besides the larger bodies we have already discussed, the solar system is also filled with a large number of smaller bodies, including meteroids, asteroids, comets, as well as the smaller satellites of the planets.. These are of particular interest because some of them may hold clues to what the early material in the solar system was like.

Meteoroids, Meteors, and Meteorites

Small pieces of rocky debris in space that have not yet fallen to Earth are known as meteoroids. The same bodies that fall to Earth but are burned up in Earth's atmosphere are known as meteors, while those that survive to reach the ground are called meteorites. Radioactive dating of meteorites show that most solidified from 4.4 to 4.5 billion years ago. Meteorites are found to have a number of distinct compositions:

- **Iron Meteorites** are almost purely a mixture of Iron and Nickel.
- **Stony-Iron Meteorites** have some Iron-Nickel material, mixed with some rocky material.
- **Stony Meteorites** Can be divided into two categories.
    - **Primitive Stones,** which show little modification since their initial cooling.
    - **Differentiated Stones,** which show signs of significant re-melting after their initial cooling.

The irons, stony-irons, and differentiated stones thus represent material that underwent major chemical changes after their formation, while the primitive stones have not. Primitive stones thus represent relatively pristine samples of the material in the early solar system.

Fractions

The most reliable percentages of the different types of meteorites comes from meteorites that are found because their fall through the earth's atmosphere was actually observed. These meteorites reveal the following percentages:

- Primitive Stones: 87 %
- Differentiated stones: 9 %
- Iron: 3 %
- Stony-Irons: 1 %

The Differentiated Meteorites

As their names imply, the differentiated meteorites appear to have come from smaller solar system bodies that had differentiated into a core/mantle structure, and were later fragmented. The iron meteorites thus represent material from the cores of these bodies; the differentiated stones, which are similar to basalts in their properties, are from the mantles; and the stony-irons are from the interface of the core and mantle. Analysis of isotope ratios in different differentiated meteorites suggests that there are at least several dozen parent bodies from which the differentiated meteorites come. The times for these bodies to cool and solidify can be inferred from the crystal patterns in iron meteorites (in essence, the larger the crystals, the slower the cooling). These patterns give typical cooling times of a few million years, suggesting that the original parent bodies were around 100 km in diameter.

Primitive Meteorites

The lack of significant melting since the formation of the primitive meteorites suggests that their parent bodies are also relatively small. The least processed of the primitive meteorites, which represent a few percent of all primitive meteorites are the **carbonaceous meteorites**, so called because they contain relatively large amounts of carbon (a few percent by weight.) Carbonaceous meteorites usually contain some water and other volatile compounds, chemically bound up in clays. In addition, many carbonaceous meteorite contain complex organic compounds such as amino acids (remember that organic compounds can be created by non-organic processes, so that that the presence of organic molecules doesn't necessarily imply that they are produced by living organisms.)

Asteroids

Rocky bodies somewhat larger than meteoroids are referred to as asteroids. Most known asteroids in the solar system orbit the sun in the asteroid belt, which lays between the orbits of Mars and Jupiter. The largest known asteroid is Ceres, which has a diameter of 0.3 times that of the Moon, although most asteroids are much smaller. The total mass in asteroid belt asteroids is only about 1/2000 that of the earth. Asteroids can be classified into different families, based upon their orbits and compositions. Asteroids appear to be the most likely parent bodies for meteorites.

Orbits

As already mentioned, most known asteroids orbit in the asteroid belt, but their distribution in the belt itself is not uniform. In fact, there exist gaps in the asteroid belt (known as Kirkwood gaps after their discoverer) where relatively few asteroids orbit. These gaps are created by orbital resonances with Jupiter, in much the same way as the Cassini division is created in the rings of Saturn by orbital resonances with the moons of Saturn.

Besides the main belt asteroids, there are two other orbit families of asteroids worth mentioning; Trojan point asteroids and Earth orbit crossing asteroids.

- **Trojan point asteroids** The Trojan points of Jupiter occur at the two points on Jupiter's orbit leading and trailing Jupiter by 60°. At the Trojan points, the perturbing effects of Jupiter's and the Sun's gravity essentially cancel, so that small bodies such as asteroids can orbit stably there.[1]

- **Near Earth asteroids** Also known as Apollo or Aten asteroids, named after the prototypes of two different classes of Earth crossing asteroids. These types of asteroids have been all the rage for newspaper reporters in the past 10 years or so (and we won't even mention Hollywood...) Because of the perturbing effects of the gravity of the inner planets, orbits in the inner solar system for asteroids over the long term aren't stable. This means that in the long term there are two possible fates for such asteroids; the gravitational ejection of the body from the solar system, or a collision with with one of the inner planets in the solar system.

Comets

Too many ancient civilizations (remember the Mesopotamians?), comets were harbingers of doom. In fact, up until the time of Tycho Brahe, it was a matter of scholarly debate as to whether comets were astronomical objects, or some sort of disturbance in the earth's upper atmosphere. Tycho attempted to measure the distance to a comet by looking for an angular shift in the comet's position as seen from different locations on the surface of the earth. Tycho's inability to detect any such shift meant that the comet must be at a considerable distance from the earth, and thus must be a celestial object.

A Comet's Structure

There are two easily discernible parts to a comet's structure:

- **The Coma** The bright, fuzzy head of a comet is known as the coma, and is made up of dust and gas boiled from the surface of the comet by the Sun as the comet moves into the inner solar system.

- **Tail** The tail of a comet is actually two tails:

  - **The Plasma Tail** The bluish, straight tail is made up of ionized gases from the comet. Because the gas molecules are very light,

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[1] You can also think of the presence of the Trojan Points in terms of resonances; they are the 1:1 resonances with Jupiter.

  they are easily blown away from the comet by the solar wind, forming a straight tail pointing directly away from the Sun.

  - **The Dust Tail** The yellowish tail of the comet is known as the dust tail, and is made up of (surprise!) small dust grains liberated from the comet. Because the dust grains are heavier than the molecules in the plasma tail, the dust tail tends to curve under the combined affect of the Sun's gravity and radiation pressure.

The Comet's Nucleus

The actual solid body that makes up the comet is known as the nucleus, which is typically somewhere around 5-20 kilometers in size. The nucleus may be thought of as a "dirty snowball", being a roughly equal mixture of small dust grains and different types of ices (largely water, carbon dioxide, and carbon monoxide.) At the rate material is lost from a comet as it passes the Sun, a typical comet contains enough material for a few hundred or at best few thousand passages through the inner solar system.

Comet Orbits

Based on the structure and periods of their orbits, we can break comets into two classes.

Short Period Comets

- Have orbital periods $<$ 200 years or so.
- Usually have orbital planes close to that of the planets.
- Orbit the Sun in same direction as the planets.

Notice that the short period plus number of possible orbits before their material is used up suggests that a typical short period comet will last for a few hundred thousand to a few million years. This means that there must be a reservoir of comets in the outer solar system from which the supply of short period comets is constantly replenished.

Long Period Comets

- Have orbital periods in the range 1,000-100,000 years.
- Have orbital planes that are randomly oriented.
- Have orbits that are close to unbound, suggesting that many may escape the Sun's gravity after one passage through the inner solar system.

This final point suggests a source for long period comets in the outer solar system, distinct from that supplying the short term comets.

Comet Origins

The two comet reservoirs in the outer solar system are thought to be:

- **The Kuiper Belt** Calculations show that the reservoir for the short period comets must:
    1. Be a flat structure with its plane aligned with the plane of the solar system, in order to account for the comets having similar orbital planes to the planets.
    2. Extend from the neighborhood of Pluto, outward.
- **The Oort Cloud** Analysis of the orbits of long period comets shows that:
    1. Most long period comets originated at distances about 50,000 AU from the Sun.
    2. Because of the random orientation of orbital planes, the reservoir most be roughly spherical.

Chapter 10

The Outer Solar System

The outer solar system is largely a mystery to us. the existence of comets suggests that there must be a large number of icy bodies orbiting the Sun beyond Neptune, but it has only been in the past fifteen years that objects (other than Pluto) have been detected.

Pluto

Because no spacecraft has ever visited Pluto, we know very little about the planet. The basic properties of Pluto are:

- Diameter 0.66 that of Moon.
- Density 2.1 grams/cc.

Pluto has a relatively eccentric orbit, and one that is tipped at an angle of about 17° to the ecliptic. In fact, Pluto's orbit is sufficiently eccentric that for a portion of its orbit, Pluto is actually closer to the Sun than Neptune. There is no chance of Pluto colliding with Neptune however, for two reasons. First, Pluto is in a 3 to 2 orbital resonance with Neptune; in this case the resonance is such that the two bodies never approach one another. Second, at the parts of its orbit where Pluto is at the same distance from the sun as Neptune, the large inclination of Pluto's orbit insures that it is well above or below the plane of Neptune's orbit.

Pluto has a moon, named Charon, that was discovered in 1978, due to periodic eclipses of the planet by the moon, and vice-versa. Charon has a mass approximately 1/6 that of Pluto, which is a large mass for a satellite relative to the body it is orbiting.

Kuiper Belt Objects

Starting in 1992, significant numbers of Kuiper belt objects in orbits larger than that of Neptune have been discovered, thanks to very sensitive surveys that became possible due to the advances in electronic detectors at telescopes. There seem to be at least three distinct classes of such objects:

1. **Classical Kuiper Belt Objects** are in orbits that stay sufficiently far from Neptune that the planet is unable to make significant changes in their orbits. Curiously, there are very few of these objects in orbits with semi-major axis larger than 50 AU or so.

2. **Scattered Kuiper Belt Objects** are on fairly eccentric and inclined orbits, probably due to weak gravitational interactions with Neptune over times of billions of years.

3. **Plutinos** are in orbits that put them in the same 3 to 2 resonance with Neptune that Pluto is in. (This means that it is probably reasonable to think of Pluto as simply the largest of this class of objects.)

A few larger objects in the outer solar system are worth mentioning:

- **Quaoar** (pronounced Kwah-o-wahr) is a classical Kuiper Belt Object discovered in 2002, that has a diameter approximately half that of Pluto.

- **Sedna** was discovered in 2003 and probably has a diameter of between 1/3 and 1/2 that of Pluto. Sedna is in a very eccentric orbit with a semi-major axis of about 500 AU, and a closest approach to the sun of 76 AU. It appears that Sedna might be neither a Kuiper Belt or an Oort Cloud object, but instead lies on an orbit between the two.

- **Orcus** is a plutino discovered in 2004, which may have a diameter larger than either Quaoar or Sedna.

- **2003 UB 313** A scattered Kuiper belt object discovered in 2003, it is essentially the same radius as Pluto. It has a satellite, so eventually, a mass will be measured for it. The discovery of this object has added new fuel to the "is Pluto a planet or not?" controversy.

Chapter 11

The Sun and Its Influence in the Solar System

In this course, we are primarily interested in the properties of the Sun that can have significant effects on things elsewhere in the solar system. That is, we are largely interested in the external properties of the sun. In ph1306, we instead look more closely at the Sun as a star, and thus its internal properties. The Sun is the dominant object in the solar system in at least:

- It contains over 99% the solar system's mass, making it the dominant gravitational feature in the solar system.
- It produces the majority of the energy in the solar system, meaning that most energy intensive activities or processes on the earth or elsewhere in the solar system ultimately rely on the Sun as their energy source.

The basic properties of the Sun are:

- Composed largely of Hydrogen and Helium.
- Rotates once every 25.4 days at the equator (33 days at the poles).

The Sun's Energy Production

The Sun radiates a tremendous amount of energy from its surface every second, and has been doing so at roughly the same rate for the past 4.5 billion years. The source of this energy production remained mysterious for a very long time; it wasn't until the discovery of the nature of the atomic nucleus in the 1920's and 1930's that astrophysicists realized the the Sun's energy was being produced by the fusion of light nuclei to heavier nuclei in the core of the Sun.

Nuclear Fusion

The nuclei of all elements are made up of protons and neutrons, where the number of protons in a particular nucleus determines which element that nucleus is (e.g. hydrogen contains one proton, helium two protons, and so on.) Notice this means that there must be processes in nature that can stick together two nuclei to make a heavier nuclei (fusion), and to split a large nuclei into smaller nuclei (fission). Depending on the nucleus undergoing the fusion or fission process, energy may be released or absorbed during these processes.

Fundamental Forces

When boiled down to its essence, there are only 4 different mechanisms by which a particle in the universe can act on another. Physicists refer to these as the fundamental forces in nature:

- **Gravity** We've already talked a bit about gravitation. Any particle with mass can act by and be acted upon by the gravitational force. [1]

- **Electromagnetism** Any particle with an electric charge can act by and be acted upon through the electromagnetic force.

- **Strong Nuclear** This is the force that works between nuclear particles (i.e. protons and neutrons), and allows them to bind together to form nuclei.

- **Weak Nuclear** This force is responsible for certain types of radioactive decays.

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[1] Because mass is convertable to energy–and vice-versa–even massless particles such as photons produce and respond to gravitation. In the current day universe however, the mass in massive particles greatly exceeds that in massless particles, so we usually neglect the effect of massless particles.

These forces can be grouped together based upon the range of distances over which they act. Gravity and electromagnetism are examples of **long range forces**; although the strength of these forces gets weaker the further you get from the object producing them, they never drop to zero. On the other hand, the weak and strong nuclear forces are **short range forces**. They act over dimensions comparable to that of an atomic nucleus, and over larger distances quickly drop to zero.

The Proton-Proton Chain

In the core of the Sun, energy is produced through a multi-step process in which 4 hydrogen nuclei (i.e. 4 protons) are fused to form a single helium nucleus (which contains 2 protons and 2 neutrons). The mass of the neutron is slightly larger than that of the proton, so 4 free protons will have slightly less mass than 2 free protons and 2 free neutrons. Surprisingly then, the mass of a single helium nucleus is 0.7 % less than that of the 4 protons. This difference in mass is just the amount of energy it would take to break the helium nucleus back into free neutrons and protons (this conversion of mass to energy–or vice-versa–is possible because $E = mc^2$), and is referred to as the binding energy of the nucleus. That 0.7 % of mass is released as energy in the form of photons during the fusion reactions. This basic process is the ultimate power source for the Sun.

Energy Transport

Because the core of the Sun is hotter than its outer parts, the energy produced in the core will naturally flow outward. Remember that nature has 3 mechanisms for this heat flow:

- **Conduction**, where heat is transferred due to physical contact between bodies.
- **Radiation**, where warmer regions emit, and cooler regions absorb the energy in the form of electromagnetic radiation.[2]

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[2] Actually any object with a temperature above absolute zero will emit electromagnetic radiation; objects at lower temperature emit less than those at higher temperature. This means that if two regions are at a different temperature, the cooler will emit less than it absorbs from the warmer, and vice-versa.

- **Convection**, the mechanism that occurs when all else fails. Hot material rises, and mixes with cooler material, raising its temperature. At the same time, cooler material sinks and mixes with hotter material at the level, reducing its temperature.

Observable Layers of Sun

The outer, directly observable parts of the Sun may be divided into three distinct layers:

- **The Photosphere** The lowest observable layer, where the great majority of all the light emitted by the sun emanates from. The photosphere has a temperature of around 5800 K. Two obvious features are visible in the photosphere: sunspots (which are discussed a bit later) and granulation. Granulation is a "salt and pepper" appearance to the photosphere when seen at high resolution, and is caused by the tops of convective cells, from lower layers in the Sun.

- **The Chromosphere** The temperature in the photosphere slowly drops as you move outward in the Sun, but eventually reaches a minimum and begins to rise again. This temperature minimum is the boundary between the photosphere and the chromosphere. The chromosphere is much less dense than the photosphere, and has an average temperature of about 10,000 K. At high resolution the chromosphere can be seen to be made up of hundreds of thousands of spicules; small spiky structures that appear and disappear over times of 10 minutes or so.

- **The Corona** Above the chromosphere, the temperature of the solar atmosphere rapidly shoots up to a few million degrees (because the density is very low, however, the total amount of energy in the gas is fairly modest), this layer is known as the corona. The corona is visible during solar eclipses in white light as a hazy halo of light extending from 1 to 3 solar radii above the chromosphere, often showing several spiky features known as coronal streamers. Because of its high temperature, the solar corona is also observable from space due to its x-ray emission.

The Active Sun

The above features of the Sun are sometimes referred to as the “quiet” Sun, since they are always present. Other solar features appear and disappear over an eleven year cycle, and collectively are sometimes known as the “active” Sun.

Sunspots

Sunspots are darker appearing regions in the solar photosphere. Sunspots come and go, some lasting only days while others can persist for months. Sunspots aren’t actually dark, but are places in the photosphere where the temperature is cooler than that in surrounding areas. Sunspots thus emit somewhat less light than their surroundings and thus appear dark by comparison. The locations of sunspots are areas where the magnetic field is approximately 1000 times stronger than the average field in the photosphere. The magnetic field in these locations inhibits convection (remember, charged particles have a hard time crossing magnetic field lines), so that the sunspot is receiving less heat from below than surrounding areas and is thus cooler.

The average number of sunspots on the surface of the Sun rises and falls over an 11 year cycle, suggesting that the magnetic field on the Sun is varying over 11 years also. Actually, at the end of one sunspot cycle, the polarity of the Sun’s magnetic field ends up the reverse of what it was at the beginning of the cycle. This means that each 11 year sunspot cycle represents half of a 22 year cycle in the solar magnetic field.

Other Forms of Activity

Besides sunspots, there are a number of other features on the Sun that follow the magnetic activity cycle.

Prominences

Prominences are hot gas trapped in magnetic field lines that loop up out of the photosphere, and can easily be several times the diameter of the earth in size. Some prominences are structures that can last for days or weeks, while others can erupt rapidly from the solar surface.

Solar Flares

Solar flares are explosive releases of energy, that can be seen as bright flashes on the sun, and can last from minutes to hours. Large amounts of electromagnetic radiation can be given off during flares, at wavelengths from the radio through the x-ray. Flares are thought to be produced by the local restructuring of the solar magnetic field in the region where the flare is produced. The released magnetic energy during this process heats gas at the flare site to millions of degrees, creating the observed electromagnetic radiation.

Coronal Mass Ejections

Continuous observation of the corona in white light from satellites shows that the corona is constantly ejecting parts of itself, at speeds from a few hundred to a few thousand kilometers per second. These coronal mass ejections happen more often around the peak of the magnetic cycle. The fastest coronal mass ejections drive shocks into the solar wind, which can accelerate large bursts of energetic particles into the inner solar system. Like solar flares, coronal mass ejections seem to be a symptom of restructuring of the solar magnetic field.

Effects of Flares and Coronal Mass Ejections at Earth

Both flares and coronal mass ejections can have significant effects at Earth:

- The x-rays and ultraviolet radiation released during large flares can ionize Earth's upper atmosphere, affecting radio communications and possibly even increasing the chances of thunderstorms.
- The charged particles created by coronal mass ejections, and less frequently by flares can have a number of effects at Earth.
    - Aurora's are caused by fluorescence of atoms and molecules in Earth's atmosphere excited by collisions with energetic charged particles.
    - Strong bursts of energetic charged particles have the ability to knock out the electronics in orbiting satellites. In addition, the particles can pose a radiation risk for humans in space.

Effects on Earth’s Climate

One of the difficulties in determining how changes in the earth and its atmosphere affect Earth’s climate (for example, how do the observed increases in carbon dioxide levels affect temperatures?) is taking into account changes due to other sources, among them small variations in the energy output of the sun. At least two different mechanisms for changing the solar energy reaching the earth are known:

- During the late 1600’s, few sunspots were observed on the Sun over 3 solar cycles. This time is known as the Maunder minimum. At the same time, northern Europe experienced a “Little Ice Age”, during which cooler temperatures led to shorter growing seasons. In fact, during this time there were ponds and other bodies of water in northern Europe that never completely thawed, even in the middle of summer. While not conclusive by itself, this coincidence of lower sunspot number and lower temperatures on Earth suggests a possible link between solar energy output and the solar magnetic cycle.

- During the 1920’s, a Yugoslavian scientist named Milutin Milankovitch showed that small gravitational perturbations on the earth by Jupiter would create periodic changes in the orbital parameters of the earth, over periods of 10’s to 100’s of thousands of years. Milankovitch suggested that the changes in the amount of sunlight being received by the earth due to these changes might be enough to affect the climate on the earth.

Chapter 12

Life Elsewhere in the Solar System

The current wisdom among astro-biologists is, if you want to know where to look for life elsewhere in the universe, follow the water. This is because many of the chemical reactions necessary for life as we know it occur only when the reactants are dissolved in liquid water.

Evidence for Life on Mars

The evidence that Mars had liquid water on its surface in its past suggests it might have once (and maybe still does) harbors life. The whole question of life on Mars actually has a somewhat disreputable past. In the early 1900's for example, Percival Lowell reported with confidence the presence of an intricate network of canals on Mars; canals built by intelligent beings. Although these claims received much attention in the popular press at the time, it turns out the putative canals were actually due to a combination of the human brains pattern matching abilities (which are so good that it can discern patterns, even in random noise where no pattern exists), and a too willing to believe mind set on the part of Lowell.

More current measurements are ambiguous on the topic. They include:

- The Viking Landers
  - Looked for organic compounds in Martian soil, and found no signs of any.

  - The probes also had three experiments designed to stimulate microbial activity if any microbes were present in the soil. These experiments produced an observable signal, but further examination of the experiments showed that these signals were the result of inorganic chemical reactions in the soil, and not the result of biological action.

- ALH84001 (The famous Martian meteorite). The meteorite is an igneous rock, blasted free from the surface of Mars 16 million years ago by a meteoroid impact, that landed on the antarctic ice sheet around 13,000 years ago. The evidence put forth by the investigation team that lead them to conclude that there might be fossil remains of Martian life in the meteorite include:
  - Carbonate minerals in the rock that they believe must have been formed in the presence of liquid water.
  - Magnetite grains, which are formed by some bacteria on Earth, although magnetite is also formed by non-organic processes.
  - The presence of various organic and non-organic compounds near on another, which might have been formed by bacteria.
  - Bacteria shaped formations seen in electron microscope images of the rock. These formations are much smaller than any known terrestrial fossils of bacteria, however.

Europa

The evidence suggesting that the icy crust of Europa overlies a substantial ocean of liquid water has caused speculation that perhaps microbial life might exist there; perhaps near sea-floor volcanic vents similar to those where extromophiles have been found on Earth. In this case, the presumed heat source in Europa's interior would be due to tidal squeezing by Jupiter.

Callisto and Ganymede

There is some evidence of liquid water well below the surface of both of these moons.

Enceladus

New observations of Enceladus by the Cassini probe show areas that are geologically young, suggesting that like Europa, it may harbor liquid water below its ice covered surface.

Titan

One provocative suggestion is that methane based life may exist on Titan. However recent observations by the Cassini probe suggest that the expected oceans of methane on Titan's surface don't actually exist.

Chapter 13

The Formation of the Solar System

Initial Phases

The space between the stars contains clouds of cool and cold gas. These gas clouds are composed largely of hydrogen and helium, as well as some small grains of dust and soot, and small particles of different types of ices. If conditions are right, these clouds will be unstable and collapse under their own gravity.

- The most dense parts of the cloud will collapse most rapidly. Since the core of the cloud is usually the densest part, the clouds usually develop a large mass concentration at the center (in the case of the solar system, this concentration became the sun.)
- If the cloud is rotating (and virtually all of them are), conservation of angular momentum dictates that the cloud will collapse easily along its rotation axis, but much less easily inward toward the axis.

At the end of its initial collapse phase then, an interstellar gas cloud will be a flat, rotating cloud, with a large mass concentration at its center. In the case of the solar system, this gas cloud is referred to as the **solar nebula**.

The Accretion Process

In this flat, rotating gas cloud, the small dust and soot particles will occasionally collide and stick together to form larger particles; this process is known as **accretion**. The larger particles will tend to accrete other particles faster than smaller particles will. So, as the accretion process goes on there will be a build of of a few large objects from the many small particles that started out. These large objects will eventually become the planets and large moons in the solar system.

Growth of the Gas Giant Planets

Due to its rapid initial collapse, the inner part of the solar nebula will be at higher temperatures than the outer parts. This means that the small particles of ice in the initial gas cloud will only be able to survive in the outer part of the solar nebula. If the objects that are growing in the outer solar system get large enough, then their surface gravity will be high enough to hold onto the hydrogen and helium gas in the gas cloud (how large is large enough? around 10 times the mass of the earth or so.) We believe this is how the gas giant planets formed (notice that this accounts for the fact that all the gas giant planets have a solid core with a mass in the range 10-15 times that of the earth.)

Final Phases

Eventually the mass at the center (i.e. the proto-Sun) will get large enough to start nuclear fusion reactions in its core. As this happens, the intense electro-magnetic radiation produced, along with the intense winds that are produced by the young star will clear the solar system of any gas that has not already been incorporated in a large gravitating body, such as the sun or planets.