7.1.3 THE SOLAR SYSTEM[M54]

The story of the solar system is by no means completely known or understood. As with other fields of science, progress in astronomy seems to raise more questions than it answers. There are many theories that attempt to describe how our solar system formed, and we may never really know how it came about. The currently popular scientific belief[1] is that our solar system was formed when a cloud of gas and dust in space was disturbed, maybe by the explosion of a nearby star, causing the cloud to begin rotating and subsequently collapsing into its centre. Our Sun ultimately formed in the centre of this rotating mass. By studying meteorites, which are thought to be left over from this early phase of the formation of the solar system, scientists believe that our solar system is about 4.6 billion years old.

Current evidence also suggests that stars do not always remain the same. The Sun is now a middle-aged star. In another 5 billion years, it is thought that the Sun will become much larger as energy from within makes its outer layers expand, eventually becoming what is known as a red giant. As this happens, most of the inner planets (including Earth) will be destroyed. Eventually, after another 100 million years, the Sun will no longer be able to generate energy, and will become a white dwarf, the size of a small planet.

Today, our solar system consists of the Sun, the nine planets and their 137 (as of April 2005[2]) known moons, a large number of asteroids (particularly in the region lying between the orbits of Mars and Jupiter[3], but also elsewhere) and comets, dust and gas. These bodies revolve around the Sun, the centre of our solar system. Most travel along near circular, elliptical orbits, in an anti-clockwise direction (when viewed from above), with the Sun at one focus. The orbits of the planets are more or less aligned with the ecliptic, a geometric plane defined by the plane of the Earth's orbit, which is in turn inclined at 7° from the plane of the Sun's equator. The orbits of the comets and other bodies are often inclined at angles greater than 20° to the ecliptic.

The Kuiper Belt[4] is an area of the Solar System extending from the orbit of Neptune (at 30 AU) to 50 AU from the Sun. The objects within the Kuiper Belt together with the members of the Scattered Disk extending beyond, are collectively referred to as Trans-Neptunian Objects (TNOs). This band of icy debris is considered to be the source of 'short-period' comets—those, like Halley, with orbital periods of up to 200 years.

In January 2005, a Trans-Neptunian Object (TNO) believed to be larger than Pluto and named $2003UB_{313}$ was identified[5] (in images recorded in 2003) in the Scattered Disk region, beyond the Kuiper Belt, and dubbed (by some astronomers) the tenth planet. The International Astronomical Union (IAU) is scheduled to publish the definition of a planet[6] in early September 2006, which should determine whether or not $2003UB_{313}$ is classified as such. This definition might also result in the reclassification of Pluto, since some astronomers have argued that Pluto is not really a planet, but simply a large TNO in the Kuiper Belt.

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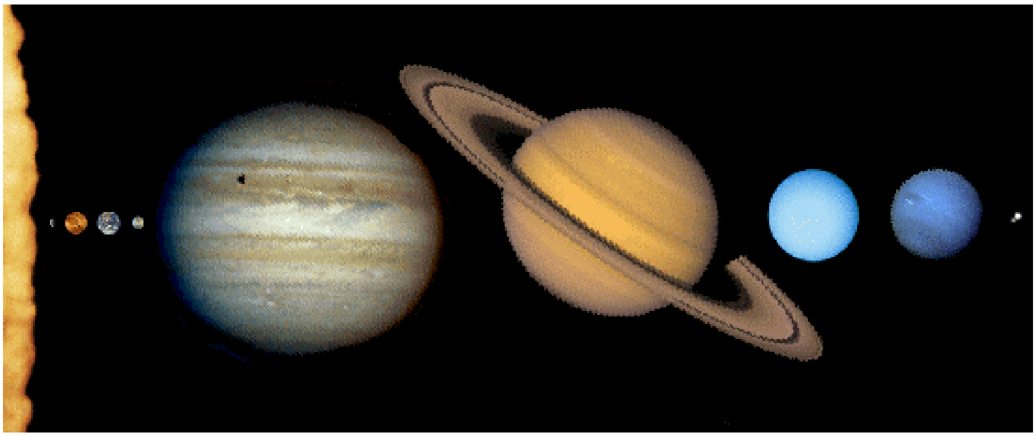
1 http://www.windows.ucar.edu/tour/link=/our_solar_system/solar_system.html
2 http://www.windows.ucar.edu/tour/link=/our_solar_system/moons_table.html
http://www.ifa/hawaii.edu/%7Esheppard/satellites/
3 http://en.wikipedia.org/wiki/Asteroid_belt
4 http://en.wikipedia.org/wiki/Kuiper_belt
5 http://en.wikipedia.org/wiki/2003_UB313#Moons
6 http://en.wikipedia.org/wiki/Definition_of_planet

7.1.3.1 The Planets[7]



Using information from the Planetary Data handout sheet, draw circles representing the relative sizes of the planets, and (on a separate diagram) show their relative distances from the Sun.

The nine bodies currently identified as planets are often further classified in several ways:

By Composition

- Terrestrial or rocky planets: Mercury, Venus, Earth and Mars
  - The terrestrial planets are composed primarily of rock and metal, and have relatively high densities, slow rotation, solid surfaces, no rings and few satellites.
- Jovian or gas planets: Jupiter, Saturn, Uranus and Neptune
  - The gas planets are composed primarily of hydrogen and helium, and generally have low densities, rapid rotation, deep atmospheres, rings and many satellites.
- Pluto

By Size

- Small planets: Mercury, Venus, Earth, Mars and Pluto
  - The small planets have diameters less than 13000 km.
  - Mercury and Pluto are sometimes referred to as lesser planets (not to be confused with minor planets, which is the official term for asteroids)
- Giant planets: Jupiter, Saturn, Uranus and Neptune
  - The giant planets have diameters greater than 48000 km.
  - The giant planets are sometimes also referred to as gas giants

By Position Relative to the Sun

- Inner planets: Mercury, Venus, Earth and Mars
- Outer planets: Jupiter, Saturn, Uranus, Neptune and Pluto
- The asteroid belt between Mars and Jupiter forms the boundary between the inner solar system and the outer solar system

[7] http://pds.jpl.nasa.gov/planets/
http://www.nineplanets.org/overview.html
http://www2.jpl.nasa.gov/galileo/sepo/education/nav/ss2.gif

By Position Relative to Earth

- Inferior planets: Mercury and Venus
    - Closer to the Sun than Earth
    - The inferior planets show phases, like the Moon's, when viewed from Earth
- Earth
- Superior planets: Mars through Pluto
    - Farther from the Sun than Earth
    - The superior planets always appear full or nearly so

By History

- Earth.
- Classical planets: Mercury, Venus, Mars, Jupiter and Saturn
    - Known since prehistorical times
    - Visible to the unaided eye
- Modern planets: Uranus, Neptune and Pluto
    - Discovered in modern times
    - Visible only with optical aid

7.1.3.2 Kepler's Laws of Planetary Motion

Aristotle (384 BC – 322 BC), a student of Plato (427 BC – 347 BC), is credited with first describing the geocentric (earth-centred) model of planetary motion that had the sun and the planets revolving around the Earth. Several hundred years later, Ptolemy (85 AD – 165 AD) developed a mathematical model, in support of the system described by Aristotle, which prevailed for the next 1400 years. Around 1514, Polish astronomer Nicolaus Copernicus (1473 – 1543) first proposed an heliocentric (sun-centred) model of planetary motion, where planets revolved around the Sun in circular orbits. It was left to Johannes Kepler (1571 – 1630), using the extensive astronomical observations of the planet Mars made by Danish astronomer Tycho Brahe (1546 – 1601), to develop the heliocentric model into its present form, where planets orbit the sun in elliptical orbits.

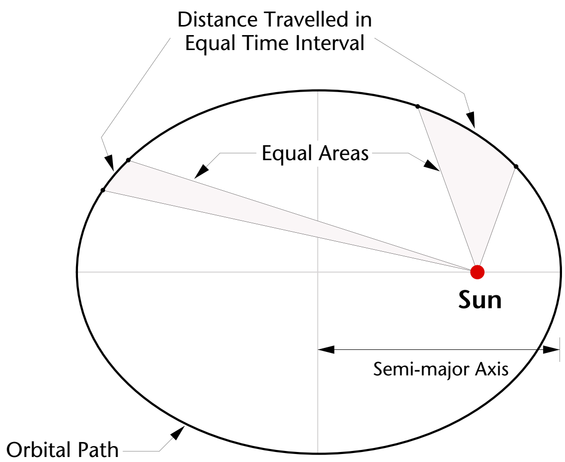
Kepler ultimately proposed three Laws that define the motions of the planets (and comets) around the Sun.

7.1.3.2.1 Kepler's First Law

The orbit of a planet about the sun is an ellipse with the Sun's centre of mass at one focus.

7.1.3.2.2 Kepler's Second Law

A line joining a planet and the Sun sweeps out equal areas in equal intervals of time. The practical consequence of this Law is that the speed of revolution of a planet around the Sun is not uniform, but changes throughout a planet's "year". It is fastest at the point (the *perihelion*) when the planet is nearest the Sun and slowest at the point (the *aphelion*) when the planet is farthest away.



7.1.3.2.3 Kepler's Third Law

The squares of the periods (T) of the planets are proportional to the cubes of their semi-major axes (R):

$$\frac{T_a^2}{T_b^2} = \frac{R_a^3}{R_b^3}$$

This relationship can be reduced to $T = kR^{3/2}$, where T is the sidereal period and R is the length of the semi-major axis of the orbit.

Thus, if T is measured in years (Earth's sidereal period) and R in Astronomical Units (the semi-major axis of Earth's orbit is 1 AU), then the constant *k* in the above equation is 1 and the mathematical relation becomes $T^2 = R^3$.

7.1.3.3 The Four Seasons

We've seen that the rotation of a planet on its axis generally leads to the change from day to night and back again—most planets rotate around their axis much more quickly than they orbit the Sun. Most also rotate on axes which are inclined at between 20° and 30° to the perpendicular of the plane of their orbit. It is this latter characteristic, together with the eccentricity of their orbits, that gives rise to what we observe on Earth as the seasons—spring, summer, autumn and winter.

The cycle of the seasons on Earth, as it orbits the Sun, is illustrated below[8].

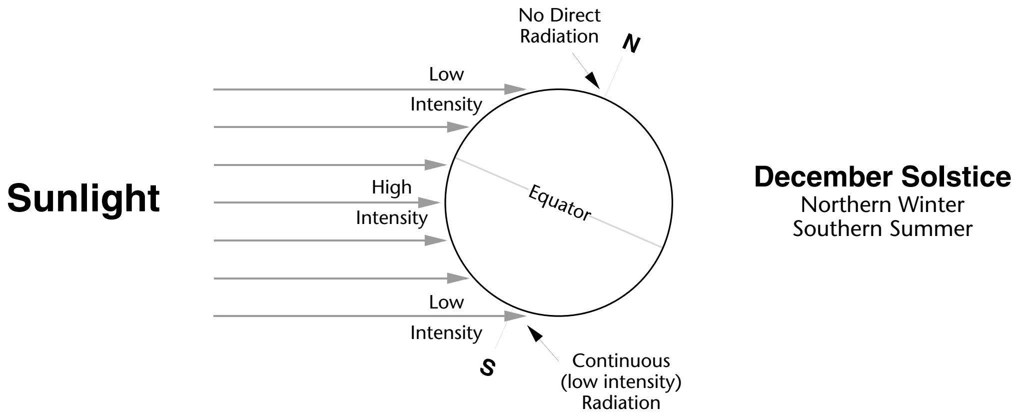
7.1.3.3.1 The Reason for the Season

The seasons on Earth are primarily the result of its axis being tilted, at an angle of approximately 23.5° from the vertical, with respect to its orbital plane[9]. As a consequence of this tilt, at certain times of the year some parts of the planet are exposed to more of the Sun's radiation than are others. There are two factors involved here. The more directly overhead is the Sun the more intense is the sunlight—at noon on the summer solstice the Sun will be 47° higher above the horizon than it will be at noon on the winter solstice for locations outside the Tropics, where season variations are most obvious. The second factor is simply that the higher the Sun rises above the horizon, the longer is the day and the more hours of sunlight there are. Furthermore, apart from generally lower light intensity at higher latitudes, the dissipation of light in the atmosphere is also greater when it falls at a shallow angle. Lower light energy levels, resulting from lower intensity sunlight and fewer sunlight hours, lead to lower heat energy levels and lower temperatures.

The figure below illustrates the situation during the southern summer solstice. Note also that, regardless of the time of day (*i.e.* the Earth's rotation on its axis), at this time of year the North Pole will be dark, and the South Pole will be illuminated.

[8] http://en.wikipedia.org/wiki/Seasons

[9] Seasons on Earth are not influenced significantly by the eccentricity of its orbit, which is nearly circular.



As the Earth orbits the Sun (*i.e.* at different times during the year), the region of higher exposure moves back and forth between the northern and southern hemispheres. Six months later, during the June solstice, the Earth will be on the opposite side of the Sun and the situation in the northern and southern hemispheres will be reversed.

7.1.3.3.2 The Geography of the Earth[10]

The tilt of the Earth, the cause of the apparent movement of the Sun between the seasons, defines a number of imaginary lines (latitudes) that circle the Earth, perpendicular to its axis:

- The Equator runs around the middle of the Earth splitting it equally north and south. The Sun is directly over the Equator twice a year—at the spring and autumn equinoxes;
- The Tropic of Cancer encircles the Earth 23.5° north of the Equator. At this latitude, the Sun is directly overhead at the northern summer solstice;
- The Tropic of Capricorn encircles the Earth 23.5° south of the Equator. At this latitude, the Sun is directly overhead at the southern summer solstice;
- The Arctic Circle is 23.5° from the North Pole, 66.5° north of the Equator. At the southern summer solstice, the Sun never appears above the horizon inside the Arctic Circle, and the North Pole is continually in darkness;
- The Antarctic Circle is 23.5° from the South Pole, 66.5° south of the Equator. At the northern summer solstice, the Sun never appears above the horizon inside the Antarctic Circle, and the South Pole is continually in darkness.

7.1.3.3.3 The Precession of the Equinox

The Earth's poles are not always pointing in the same direction—they wobble very slightly. The wobble is such that it takes over 25,000 years for a pole to trace a full circle. This phenomenon is known as the Precession of the Equinox.

In terms of the seasons it has no real effect. In fact, about the only effect is that Christmas Day (25 December) no longer falls on the Winter Solstice as it used to when it was first proclaimed.

7.1.3.3.4 Climatic Effects

Seasonal weather fluctuations also depend on factors such as proximity to oceans or other large bodies of water, currents in those oceans, El Niño/La Niña and other oceanic cycles, and prevailing winds.

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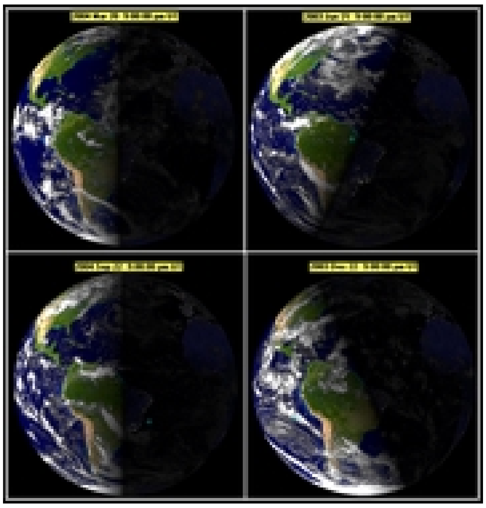
[10] http://www.bbc.co.uk/dna/h2g2/A526673

In the temperate and polar regions, seasons are marked by changes in the amount of sunlight, which in turn often cause cycles of dormancy in plants and hibernation in animals. These effects vary with latitude, and with proximity to bodies of water. For example, the South Pole is in the middle of the continent of Antarctica, and therefore a considerable distance from the moderating influence of the southern oceans. The North Pole is in the Arctic Ocean, and its temperature extremes are thus buffered by the surrounding ocean. The result is that the South Pole is consistently colder during the southern winter than the North Pole is during the northern winter.

7.1.3.3.5 Polar Day and Night



Illumination of the earth during various seasons

A common misconception is that, within the Arctic and Antarctic Circles, the sun rises once in the spring and sets once in the fall; thus, the day and night are erroneously thought to last uninterrupted for 183 calendar days each. This is true only in the immediate region of the poles themselves.

What does happen is that any point north of the Arctic Circle or south of the Antarctic Circle will have one period in the summer when the sun does not set, and one period in the winter when the sun does not rise. At progressively higher latitudes, the periods of "midnight sun" (or "midday dark" for the other side of the globe) are progressively longer. For example, at the military and weather station called Alert on the northern tip of Ellesmere Island, Canada (about 450 nautical miles or 830 km from the North Pole), the sun begins to peek above the horizon in mid-February and each day it climbs a bit higher, and stays up a bit longer; by 21 March, the sun is up for 12 hours. However, mid-February is not first light. The sky (as seen from Alert) has been showing twilight, or at least a pre-dawn glow on the horizon, for increasing hours each day, for more than a month before that first sliver of sun appears.

In the weeks surrounding 21 June, the sun is at its highest, and it appears to circle the sky without ever going below the horizon. Eventually, it does go below the horizon, for progressively longer and longer periods each day until, around the middle of October, it disappears for the last time. For a few more weeks, "day" is marked by decreasing periods of twilight. Eventually, for the weeks surrounding 21 December, nothing breaks the darkness. In later winter, the first faint wash of light briefly touches the horizon (for just minutes per day), and then increases in duration and pre-dawn brightness each day until sunrise in February.

7.1.3.3.6 The Other Planets

Every planet in the solar system has seasons[11]. Most have four like the Earth—called Winter, Spring, Summer and Autumn—but that's where the similarities end. Extraterrestrial seasons are hardly noticeable on some planets (Venus), extreme on others (Uranus) and in some cases simply impossible to define (Mercury). The table below gives the dates (*ca* 2000) of the seasons for 8 of the 9 planets in our solar system. Pluto is missing because it's so far away that we don't yet know much about its seasons[12]. By convention, the equinoxes and solstices are named after the corresponding season in the northern hemisphere. The Summer Solstice occurs when the north pole of a planet is tilted toward the sun, and the Winter Solstice when the south pole is tilted toward the sun. As on Earth, the seasons are always opposite in the two hemispheres.

Seasons on Other Planets

			Vernal Equinox	**Summer Solstice**	**Autumnal Equinox**	**Winter Solstice**
PLANET	Orbital Eccentricity	Spin Axis Tilt (deg)	Spring begins	Summer begins	Autumn begins	Winter begins
Mercury	0.21	< 28	n/a	n/a	n/a	n/a
Venus	0.01	3	Feb 24, '00 1930 UT	Apr 1, '00 1600 UT	May 28, '00 0400 UT	Jul 22, '00 1800 UT
Earth	0.02	23.5	Mar 20, '00 0735 UT	Jun 21, '00 0148 UT	Sep 23, '00 1727 UT	Dec 21, '00 1337 UT
Mars	0.09	24	May 31 '00	Dec 16 '00	Jun 12 '01	Nov 2 '01
Jupiter	0.05	3	August 1997	May 2000	March 2003	March 2006
Saturn	0.06	26.75	1980	1987	1995	2002
Uranus	0.05	82	1922	1943	1964	1985
Neptune	0.01	28.5	1880	1921	1962	2003

(Note: Seasonal names refer to the northern hemisphere of each planet)

As mentioned above, planetary seasons are caused by two factors: axial tilt and orbital eccentricity (variable distance from the sun). Earth's orbit is nearly circular, so eccentricity has little effect on climate. It's our planet's axial tilt that causes almost all seasonal changes. When the north pole is tilted toward the Sun, it's northern summer (and southern winter). Six months later the north pole tilts away from the Sun and we experience northern winter (and southern summer). On planets that have very small axial tilts—Mercury, with essentially no tilt, Venus and Jupiter, with just 3°—seasonal changes are correspondingly small. Spring on Venus isn't much different from autumn. The planet's dense, acidic atmosphere produces a runaway greenhouse effect that keeps the surface at 750 K year-round—hot enough to melt lead.

Our second-nearest planetary neighbor Mars has the highest orbital eccentricity of any world except Pluto. Its distance from the Sun varies between 1.64 and 1.36 AU over the Martian year. This large variation, combined with an axial tilt greater than Earth's gives rise to seasonal changes far greater than we experience even in Antarctica. From the point of view of an Earth-dweller, one of the strangest effects of seasons on Mars is the change in atmospheric pressure. During winter the global atmospheric pressure on

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[11] http://science.nasa.gov/headlines/y2000/interplanetaryseasons.html

[12] In 2015 the NASA New Horizons spacecraft (launched in January 2006) will rendezvous with Pluto and return the first close-up images of this distant planet. See: http://pluto.jhuapl.edu/

Mars is 25% lower than during summer. This happens because of the eccentricity of Mars's orbit and a complex exchange of carbon dioxide between Mars's dry-ice polar caps and its CO_2 atmosphere. Around the summer solstice when the Martian north pole is tilted away from the sun, the northern polar cap expands as carbon dioxide in the polar atmosphere freezes. At the other end of the planet the southern polar cap melts, giving CO_2 back to the atmosphere. This process reverses half a year later at the winter solstice. At first it might seem that these events occurring at opposite ends of Mars would simply balance out over the course of the Martian year, having no net effect on climate. But they don't. That's because Mars is 10% closer to the Sun in winter than it is in summer. At the time of the winter solstice the northern polar cap absorbs more CO_2 than the southern polar cap absorbs half a year later. The difference is so great that Mars's atmosphere is noticeably thinner during winter. Martian seasons also vary in duration more than those on Earth.

Seasons on Earth vs. Seasons on Mars

Season (Northern Hemisphere)	**Length of Season on Earth** (Earth Days)	**Length of Season on Mars** (Martian Days)
Spring	93	194
Summer	93	178
Autumn	90	142
Winter	89	154

While Martian seasons are peculiar by Earth standards, those on Uranus are even more so. Like Earth, the orbit of Uranus is nearly circular so it keeps the same distance from the Sun throughout its long year. But, Uranus's spin axis is tilted by 82 degrees. This gives rise to extreme 20-year-long seasons and unusual weather. For nearly a quarter of the Uranian year (equal to 84 Earth years), the sun shines directly over each pole, leaving the other half of the planet plunged into a long, dark, frigid winter.

Once considered one of the more bland-looking planets, Uranus is now revealed as a dynamic world with the brightest clouds in the outer Solar System. The Northern Hemisphere of Uranus is just now coming out of the grip of its decades-long winter. As the sunlight reaches some latitudes for the first time in years, it warms the atmosphere and triggers gigantic springtime storms the size of Australia with temperatures of 300 degrees below zero. Uranus does not have a solid surface, but is instead a ball of mostly hydrogen and helium. Absorption of red light by methane in the atmosphere gives the planet its cyan color. Uranus was discovered March 13, 1781, by William Herschel. Early visual observers reported Jupiter-like cloud belts on the planet, but when NASA's Voyager 2 flew by in 1986, Uranus appeared as featureless as a cue ball. In the past 13 years, the planet has moved far enough along its orbit for the sun to shine at mid-latitudes in the Northern Hemisphere. By the year 2007, the sun will be shining directly over Uranus' equator.

Mercury's seasons—if they can be called that—are also remarkable. Until the 1960s it was thought that Mercury's "day" was the same length as its "year" keeping the same face to the Sun much as the Moon does to the Earth. We now know that Mercury rotates three times during two of its years. Mercury is the only body in the solar system tidally locked into an orbital-to-rotational resonance with a ratio other than 1:1. This fact and the high eccentricity of Mercury's orbit would produce very strange effects for an observer on Mercury's surface. At some longitudes the observer would see the Sun rise and then gradually increase in apparent size as it slowly moved toward the zenith. At that point the Sun would stop, briefly reverse course, and stop again before resuming its path toward the horizon and decreasing in apparent size. All the while the stars would be moving three times faster across the sky. Observers at other points on Mercury's surface would see different but equally bizarre motions. Temperature variations on Mercury are the most extreme in the solar system ranging from 90 K at night to 700 K during the day.