1.1 Introduction

The study of planets could be rather mundane if one were to go from one planet to the next and describe them each in gory detail. Instead of doing that, a better method to study planets is via comparative planetology. Here the various features that make up each planet are compared/contrasted as a whole. There is so much overlap in terms of features and physical processes that going from one planet to the next is a bit of a waste of time.

It is also worth noting that the study of planets requires a greater breadth of knowledge than any other part of astronomy. Generally most astronomers have a solid background in Astronomy (duh) and Physics, however to understand planets you need to also have a solid understanding of Geology, Chemistry, Meteorology and in some cases Biology (though right now that’s only true for one planet).

This course will also cover some non-planetary topics, including objects such as natural satellites (moons), asteroids, comets, meteors, meteorites, meteoroids and a little bit about the Sun. But before we look at that, let’s remember a few basics about the planets.

**Mercury**
- closest to the Sun
- orbit effected by General Relativity
- rocky and dense
- smallest planet
- currently being explored by the *MESSENGER* spacecraft

**Venus**
- hottest surface, toxic atmosphere
- superficially similar to the Earth
- rocky and dense
- volcanically active
- currently being explored by the *Venus Express* spacecraft

**Earth**
- largest terrestrial planet
- volcanically active
- moderate atmosphere, abnormally high in oxygen
- life – yes (intelligent – debatable)
- has a large natural satellite

**The Moon**
- tidally locked
- no atmosphere
- some footprints

**Mars**
- lowest density terrestrial world
- thin atmosphere
- seasonal weather/ice caps
- extinct volcanoes
- currently being studied by a bunch of spacecraft and rovers

**Jupiter**
- largest planet
- low density
- long term weather patterns
- powerful magnetic field
- most satellites, including 4 large ones – *Galilean Satellites*

**Saturn**
- second to Jupiter (in most respects)
- spectacular ring system
- diverse satellites
- currently being studied by the *Cassini* spacecraft

**Uranus**
- tilted system
- rings, moons

**Neptune**
- similar to Uranus in most respects, but not as tilted

**Asteroids**
- in the asteroid belt and other locations
- composition
- threat of an impact?

**Comets**
- Oort cloud, Kuiper belt
- Source of meteor showers

The study of only the planets is rather limited when viewed in terms of how significant they are in the solar system. Practically all of the material in the solar system is found in the Sun (99.8% of the mass). After that Jupiter is the largest thing (with 0.1% of the mass), then Saturn (0.03% of the mass), and Uranus and Neptune together make up only 0.01%. So you and all of the stuff on the Earth and the other 3 small planets, all of the asteroids, etc, make up only 0.001% of the mass of the solar system. So studying only the planets means that we’ll be looking at only 0.2% of the stuff in the solar system.

While the Sun is not a planet, it is an important part of our solar system. Of course it has the most mass in the solar system, but it also interacts in various ways with the planets -

- Gravitational – dictates the motion of objects in the solar system (mainly)
Radiative – the energy from the Sun impacts all planets in a variety of ways, including seasonal effects, and can even alter the motion of objects

Particles/rays – the influence of the solar winds on planetary magnetic fields is important for planetary development (or death), and can interact with surfaces resulting in chemical reactions

Formation history – the formation of the solar system is tied up with the formation of the Sun.

Ultimate demise – when the Sun dies, so does our solar system.

While most of you may think of the solar system and the planets as large objects, it should be remembered that the distances between all of these objects is huge – the odds of a collision between objects is very small (not zero, but really, really small). Most of the solar system is comprised of empty space. Consider the fact that even in the inner solar system where the space between the planets is relatively small, the light travel time between each object is several minutes, and distances can be measured in 10 of millions of km. Even places that you might imagine as being very tightly packed, like the asteroid belt, the Kuiper belt, or the Oort cloud has vast distances between each object. It is just that when we graph up these objects, the sizes of the dots are finite and the resulting images look congested. Also it doesn’t help that movies like The Empire Strikes Back show asteroids that appear to be packed tightly in a relatively small space. The reality is that there is a good distance between all objects in the current solar system.

1.2 Important Terms

As always there are very specific terms that need to be used to describe things in science and most of these terms have been discussed in introductory courses, but some might be new to you.

Planet – a few years ago there was not specific rule for what exactly a planet was. Since many things orbit a star, including comets and asteroids, some guidelines had to be developed to help astronomers decide which objects get “planet” status and which get reclassified as other types of objects. This was mainly brought about by the discovery of several large objects in the outer solar system. So in 2006, the International Astronomical Union (the group that defines astronomical standards) voted on the criterion for what makes a planet. Here is the final description –

A celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighborhood around its orbit.

So basically it has to be big enough to be round and dominates it location around the Sun. This definition rules out asteroids, Pluto and the other objects found in the area of Pluto, as well as comets (not big enough).

Planetismals – these are the planetary building blocks that were common in the early solar system. There are no specific guidelines for the sizes of these things, so they can be anywhere from microscopic to about 1000 km in size. Over time many of these became incorporated into the planets or satellites in our solar system, but some survived to the present day as other objects (asteroids, dust, comets).

Satellite – A “smaller” object that orbits a planet, or other larger object in the solar system, also referred to as a “moon”. Planets have satellites (both natural and man-made), but so do asteroids, and it is even possible that comets could have satellites as well

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Asteroid – A “small” rocky/metalllic/icy object – note the order of the materials, since that gives the likely order of their dominance. Asteroids tend to be mainly rocky, though a fraction appear to have a rather metallic composition. It is also likely that there is quite a bit of icy material within asteroids, but it is difficult to estimate how much. It is also worth noting that “icy” is a general term for things that are volatile – they evaporate/melt easily under even moderate conditions. All known asteroids are less than 1000 km in size.

Comet – A “small” icy/rocky object, so in this case there are more volatiles in the objects than rocky material. It is sometimes the case that a comet is misclassified as an asteroid since it may be discovered at a location where its volatile material doesn’t evaporate – so it looks like a rock in space. When comets get close to the Sun they become more comet-like developing a halo of gas and evaporated material around them, as well as forming tails. But when they are far from the Sun (which is most of the time), they are considered dormant.

Rings – small particles in orbit about a planet. These would tend to be a collection of small objects in orbit, not solitary objects. The composition and sources of ring particles are varied, and rings may be made of either icy or rocky material, or a mix of both.

Planet Groups – Odds are you learned that there are two types of planets, Terrestrial and Jovian. Well that’s not entirely accurate. There are actually 3 types of planets in our solar system – Terrestrial, Gas Giants and Ice Giants.

Terrestrial – group of planets like the Earth, including the first four planets in the solar system in order from the Sun, Mercury, Venus, Earth and Mars.

Gas Giants – objects comprised of mainly low density gases, includes Jupiter and Saturn.

Ice Giants – objects with a good fraction of ice in their interiors, includes Uranus and Neptune.

It might seem like I’m splitting hairs to break up the outer planets into the gas and ice giants, but their structures are distinct enough that breaking them apart in this way is logical.

And now onto terms that define location, motion and other aspects of planets…. 

Ecliptic – The plane of the Earth’s orbit about the Sun. This is how we define our location in the solar system and we reference the location of all other objects relative to this plane. It is also seen as the apparent “path of the sun, planets” in the sky, and the location along which we see eclipses (hence its name).

Revolution – the orbit of an object, as in “the Earth revolves around the Sun”, or “The Moon revolves around the Earth”. Don’t confuse it with the next term.

Rotation – the spin of an object along an axis. “The Earth rotates once in approximately 24 hours”, or “the rotation of Venus is in the opposite direction to that of the Earth”.

Perihelion – The location in an objects motion about the Sun where the object is closest to the Sun.
Aphelion – The location in an objects motion about the Sun where the object is furthest from the Sun.

And there are similar terms for an object being closest/furthest from other objects -

Perigee, Apogee – the location that an object is closest/furthest from the Earth

Periapse, Apoapse – the location that an object is closest/furthest from a planet

Perijove, Apojove – the location that an object is closest/furthest from Jupiter

Similar terms exist for the other planets as well as the Moon. But that’s overkill.

And speaking of orbits, some other terms pop up quite a bit. Most of these are defined as orbital terms about the Sun.

Inclination \((i)\) - angle of the plane of an object’s orbit with respect to the ecliptic. This is basically a measure of how “tilted” the orbit of the object is compared to our orbit about the Sun.

Eccentricity \((e)\) – a measure of the elongation of the object’s orbit about the Sun. Values range typically from between 0 (circular) to 1 (straight line). For comets values of \(e\) can be greater than 1, in which case the orbit is hyperbolic.

Period \((P)\) – how long does it take to go around once.

Semi-major axis \((a)\) – for non-hyperbolic orbits, the average distance an object is from the Sun and is equal to half of the widest length in the orbit.

Prograde, Retrograde - whether the motion is “normal” with respect to the Earth’s motion (prograde), or backwards (retrograde). This can be applied to all motions including orbital, rotational and the motions of moons as well. In our common view of the solar system we see objects from above the north pole of the Earth, and in this case prograde motion is counterclockwise and retrograde motion is clockwise. You may have also seen retrograde used in reference to the apparent motion in the sky of objects such as Mars when it spends a few months appearing to move backwards (westward).

And finally,

Obliquity - tilt of a planet’s rotation axis with respect to its orbital plane. And of course if a planet’s orbital plane is tilted relative to our orbital plane, then there can be some serious tilts out there.

1.3 Measuring Physical Properties

What are the various properties of solar system objects, and how do we go about measuring or determining them?

Orbital Properties

This is all physics, and depends upon the relationships originally derived by Johannes Kepler (Kepler’s laws). Put simply, Kepler’s three laws describe how objects orbit about the Sun. It wasn’t until Isaac Newton made a few adjustments to the formulae that the laws could be expanded to all objects in orbit
about other objects. So not only do planets going around the Sun obey these laws, but also satellites orbiting their planets, dust orbiting around the solar system, and comets going around the Sun.

While Newton and Kepler could predict the majority of the motions in the solar system, to really understand the motions it is necessary to bring in Einstein and his theory of General Relativity to provide a cause for the motion. Einstein was also able to provide some insight into the unusual motions of things near the Sun like Mercury.

Typically we define orbits in ways that are most convenient for the situation. You can either show how things orbit about the Sun as viewed from the location of the Sun (pretty easy), or as we see it from the Earth (not so easy, since the objects aren’t generally going around the Earth). In some situations it might be easier to define the motions around the planet or other body that is the dominant object, like a comet orbiting Jupiter, or one of the moons of Mars.

Generally speaking, it is relatively easy to determine orbital properties, since it basically requires just direct observation and position measurement.

**Mass**

Since we have yet to build a bathroom scale large enough to hold a planet, we need to find another method to determine the masses of objects in the solar system. And right now the best way is to use Newton’s version of Kepler’s law to derive the mass based upon the motions of objects near it. Typically if you have a satellite around an object, either natural or artificial, you can easily determine the object’s mass by measuring the orbit size and period. It is a bit more difficult if the object in orbit is a good fraction of the mass of the main body, since its mass cannot be ignored.

You also have to consider the impact of mass on all objects in the solar system. Generally speaking most of the time it is the direct effect of the “surface gravity”, or the ability of one object to keep other objects in orbit. But gravity has no limits. We have objects that influence more distant objects due to their mass. This is how Neptune was discovered — by the perturbations that it caused in Uranus’ orbit. Even though they are very far apart, the deviation in the motion of Uranus was measurable and Neptune was revealed.

Today we use small motion perturbations in stars to detect the presence of exoplanets, which often requires long observations to see the motion over days, months or years. Even though we can’t see the planet, we can measure its mass based upon the amount it causes its star to move.

There are continuous perturbations in the motions of objects due to short term effects. These are mainly seen in the way that objects may alter their motion after close encounters with massive objects. Comet Shoemaker-Levy 9 was brought into orbit about Jupiter after it got too close and became trapped. Later orbits ripped it apart and altered the motion so that it eventually impacted into Jupiter. Today we use the alteration in the orbit of objects to guide and accelerate spacecraft. It’s cheap and low-fuel! One group of objects that are continually changing orbits that are of concern to us are the asteroids that come close to the Earth. Each passage by the Earth can alter their orbits and we have to calculate how much influence we have on their motion, which depends on our mass as well as their mass.
Other mass measurements are due to resonance effects – sort of how masses cause harmonies or rhythms to develop. This isn’t very accurate, but it is possible to measure the masses of some of Saturn’s moons based upon how much they cause ripples in the rings of Saturn.

In the cases of comets it is very difficult to measure masses. On occasion there will be eruptions of material from comets which alter a comet’s orbit. These non-gravitational motions can be used to measure the masses of the comets by seeing how much the motion is altered.

Size

This could refer to diameter or radius, but you have to remember, that in the cases of many object they are not spherical, so multiple dimensions may have to be measured. The simplest size to observe is the angular size. This is the apparent size of an object and it depends upon the distance and the actual size. The relation that is often used is the Small Angle Formula which oddly enough only really works best for apparent sizes that are less than 10°. If measured in degrees the formula is

\[ S = 0.0175 \times R \Theta \]

where \( S \) = actual size, \( R \) = distance, \( \Theta \) = angular size (measured in degrees). You can measure “S” and “R” in any units, but they must be in the same units (meters, km, etc).

It is also possible to measure the size of an object if it passes in front of another, particularly if it passes in front of a bright object like a star. This is known as an occultation. The passage of a planet, satellite, or an asteroid in front of a star can help to determine the planet’s, satellite’s or asteroid’s size depending upon how fast it moves and how long the occultation lasts. In the case of some objects this may be complicated if the object is not spherical. And for accuracy there should be multiple observations of the duration of occultation to determine the size of the object. If the object passes in front of the Sun, this is called a transit. There aren’t too many objects that you can observe passing in front of the Sun, but it is a direct observation.

Sizes can be determined using some high tech methods. One is radar – yes, the same thing that got you a speeding ticket. This is really only effective for nearby objects since the signal that is sent out decreases in intensity with the square of the distance. There have been several radar mappings of asteroids that have passed relatively close to the Earth.

If you have a lot of money you could use a spacecraft and lander to determine the size of an object. This would be via triangulation of locations using the orbiter. But that’s rather pricy.

Rough estimates of the sizes of objects can be made by measuring the light coming from them – this would be photometry. Of course objects with irregular shapes or unusual surface features will provide rather complex information about sizes and shapes, so this method is filled with quite a bit of error.

While it may be possible to combine whatever you determine about the size of an object and it mass together to get a density, the value is really only an average. But at least it is a value!

Shape
You have to remember that not all objects in the solar system are spherical. And that means you have to find ways to determine their shapes. Some of these were mentioned in the discussion of size (since that will sort of help you figure out the shape). It would be easiest to directly observe objects to see what sort of shape they have, but unfortunately most objects are too far away to see much detail in their forms. Therefore techniques/technology such as occultation, radar and photometry are helpful.

There is a rather nifty effect that can be used for objects that have atmospheres. When the object passes directly in front of a distant star, the atmosphere will refract light into a centralized light source. This central flash will have a shape that depends upon the shape of the object. This is a rather difficult thing to observe since it requires a very specific alignment to occur. But it could be used...

Rotation

While it appears that planets rotate in a simple manner (one axis of rotation), that isn’t actually the case. There are long term variations in the motions of planets. For things like comets and asteroids, rotation can be along multiple axes. So determining how objects rotate can be rather complex. Again if you could just watch them directly, that would be useful. But that’s not always possible. Sometimes other methods are needed, such as following the motion of the magnetic field. Planets with very strong magnetic fields will trap charged particles and emit radio waves. Observations of the changing radio signature of a planet will reveal its rotation rate. With asteroids astronomers usually use photometry or radar to measure the rotation of the objects.

It should be noted that the direction of rotation has to be defined as either prograde or retrograde. An object has a prograde rotation if its tilt (obliquity) is less than 90°. If it is greater than 90° than it is retrograde.

Temperature

The surface/top layer of an object can actually have a wide range of temperatures, but often only an “average” for the object is given in tables of data. While many objects’ temperature is directly dependent upon the Sun (external) some can also have an internal source of energy which produces the observed temperatures. These internal sources include things such as the radioactive decay of material or the release of gravitational energy. They may manifest themselves in a variety of ways and can be either very localized (like a volcanic hot spot) or larger scale (atmospheric heating).

Measuring the temperature isn’t always easy. It would be easiest to stick a thermometer in everything, but that would be a tad expensive. So in situ measurements are rather rare. Generally we depend upon the light that is reflected or emitted by an object to determine the temperature that it has. Analyzing the thermal spectrum of an object will help determine the temperature but also likely sources (since they have different signatures).

As with any measurement, there are always complications. One is how well objects reflect or absorb energy – or the albedo effects. Different areas may look hotter or cooler depending upon the local albedo values. Also as some objects get more or less exposure to the Sun you have a variation in temperatures that can be seasonal. Objects with dramatic differences in elevation can also give different values for temperature, as well as composition variations. In general no object will have one

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temperature that remains consistent across the surface over time or location – there are always hot spots or cold spots caused by a variety of effects.

**Magnetic Fields**

You may think that only planets have magnetic fields, but that’s not the case. And the sources of the magnetic fields also vary. Most planetary magnetic fields are produced by the *dynamo effect* (the motion of electrically charged particles/electric fields). Other magnetic fields that we see today are shadows of their former glory – weak *remnant ferromagnetism* may exist if charges are bound to atoms and locked into a specific alignment. Ferromagnetism is generally pretty weak and not long lasting (it decays over time). It is also possible for an object to pick up a magnetic field through interactions of charged particles (like from the Sun) with an object that has a conducting surface layer. This interaction could result in a short term magnetic field and, like ferromagnetism, the field is pretty weak.

Observations of magnetic fields can be done by observations of particles trapped in the field as mentioned above in the discussion about rotation, or through the use of instruments such as a magnetometer, or a compass. Obviously another way to observe a magnetic field is to see the display of aurora features. This varies with the strength of the field and the amount of material being given off by the Sun.

**Surface composition**

It would be best to directly sample a surface, but we are a bit limited in this by the great distances to objects in the solar system. So again we need to look at them remotely and glean from their light information about what these objects are made of. The best method is *spectral reflectance*, which is basically looking at the spectra of the light that is reflected from the surface. Different elements on the surface will absorb some of the light at specific wavelengths resulting in an absorption spectrum. Generally infrared wavelengths are needed since most material that does the absorbing is rather large in size and this effects the longer wavelength light. It is also possible to determine some information about the composition based upon how well it reflects heat – though this is a very rough method. Speaking of rough, using radar can help describe the surface of an object, since radar reflectivity will produce different signatures. This was used to a great degree in the mapping of Venus.

If you have the money to send a spacecraft or a lander to a planet you can get some direct measurements through a variety of instruments. One is via x-ray/gamma-ray fluorescence. Basically photons from the Sun will react with different materials in different ways and give off light with a specific signature. This is a common instrument on the Mars rovers and it is used to directly measure the compositions of interesting rocks. So far we have only a few samples of material from other planets, such as rocks from the Moons, meteorites that we think are from Mars and perhaps even Venus, and of course the Earth has a bunch of rocks as well that we study. Recently the Japanese spacecraft *Hayabusa* landed on an asteroid and brought back a sample (June 2010). The material is still being studied. Also the *Stardust* spacecraft flew through the tail of a comet and came back with samples of comet material.

**Atmosphere Characteristics**
Most planets have atmospheres so we need to study those as well. Again, we’re stuck here on this planet so most observations are done from afar. The analysis of the reflection of light from the clouds/atmosphere is quite common (spectral reflectance). This can be done at visible wavelengths and provides a great deal of information. In order to understand the characteristics of the atmosphere’s structure, it is necessary to see how layers vary in their density and temperature. This is best done by looking at the thermal spectra and photometry from the atmosphere, though it is sometimes difficult to measure if the temperature range is very narrow. Typically temperature information is found in the IR or radio part of the spectrum. In some cases it is possible to analyze planetary atmospheres during an occultation event. The starlight is altered as it passes through the planet’s atmosphere and this gives a direct measure of the composition and density (though it can be rather rough in terms of density). In only a few situations have we directly measured planetary atmosphere characteristics (temperature, density composition), and that has happened on the Earth, Venus, Mars, Jupiter and Saturn’s largest satellite, Titan.

**Planetary Interiors**

This is probably the least well known area of study since it depends almost entirely upon external observations. You can measure all of the parameters you can concerning the mass, size, temperature, magnetic field properties, and estimate the composition (based upon the location in the solar system in which it resided at formation) and still be quite uncertain about a planet’s interior. Of course most of the information has to be combined into a physical model that would predict how all of these features would interact or be visible on the surface, but even at this time there is a great deal of uncertainty about many objects. In only a few cases can you get information from the interior of planets through seismic events, such as volcanic eruptions, earthquakes, moon-quakes and impacts (like comet Shoemaker-Levy 9 with Jupiter). It is theoretically possible to use oscillations in the gas and ice giants to model their internal structures, since they should wiggle in a certain way based upon their internal composition. However such oscillations are very low level and not easy to observe at this time.