Astronomy 101 - Test 2 Review

SOLAR SYSTEM INTRODUCTION AND FORMATION

The Solar System contains the Sun, the planets, their moons, rings, and various types of space debris such as asteroids and comets. The nine planets all orbit the Sun in the same direction, and almost all spin on their axes in this same direction (Venus and Uranus excepted). The shapes of the orbits are elliptical, but for all planets except Mercury they are almost circular. The Asteroid Belt exists between the orbits of Mars and Jupiter. The Solar System is also very flat.

The planets divide well into two classes: the Terrestrials and the Jovians. The Terrestrials (Mercury, Venus, Earth, Mars) are closer to the Sun, are smaller, have a rocky/metallic composition, have higher average densities, spin slower on their axes, have few moons and no rings. The Jovians (Jupiter, Saturn, Uranus, Neptune) are the opposite in all of these regards. Their gaseous envelopes, which make up most of their mass, are composed primarily of hydrogen and helium, reflecting the composition of the cloud out of which the Solar System must have formed, and in fact the entire universe.

To explain how our Solar System formed, we need a good theory since we did not see it happen. We also need to check our theory against other forming stars and solar systems, to the extent made possible by current observations. We must explain why the Solar System is so flat, why almost everything orbits and spins in the same direction, why there is only a handful of well-separated planets, and the Terrestrial-Jovian distinction.

The best theory goes as follows: it began with a cold, relatively dense cloud (or more precisely, part of a much larger cloud) of interstellar gas which started collapsing under its own gravity. Such clouds are observed elsewhere, and various stages of the star formation process are seen in some of them. These clouds are observed to be rotating through use of the Doppler Shift. When a rotating object collapses, it rotates faster (like the ice skater). This is called conservation of angular momentum. The faster rotation makes the cloud collapse into a flattened disk, because working against the collapse is the tendency for gas to be flung outwards because of the faster rotation (like tossing pizza dough).

All interstellar clouds consist of gas (about 98% of the mass), and dust grains (about 2%). This collapsed rotating disk of gas and dust is dense enough so that gas atoms frequently run into the dust grains and stick, causing them to grow. Eventually, the growing dust grains collide with others, often sticking together, leading to a larger piece. In this way, the earliest chunks of solid matter were built. This kept going until chunks were large enough (many km) so that their gravity became significant. The gravitational attraction of these so-called planetesimals enhance their collision rates. Large planetesimals had stronger gravity, so collided more often, growing ever larger. The result was only a few large chunks left - the Terrestrial planets and the solid cores of the Jovian planets.

The Terrestrial/Jovian planet contrast is basically due to the fact that the inner part of the forming Solar System was much hotter than the outer part as it received much more radiation from the forming Sun. This meant that the dust grains were the only solid material to begin the accretion/growth process there. But the outer part was cold enough so that some of the gas would freeze into ice crystals. This meant much more solid material for accretion/growth and thus the growth of larger planets. The solid cores of the Jovians are probably about 10-15 Earth masses. Their stronger gravity also meant that they could sweep up and retain large gaseous envelopes which contain most of the mass of those planets. The Terrestrials were too small to retain much gas. The Terrestrials and the solid Jovian cores are mostly made up of the elements found in interstellar dust grains: carbon, iron, silicon, etc. The Jovian gas envelopes reflect the composition of interstellar gas: mostly hydrogen and helium.

The Asteroid Belt is probably the remnant of failed planet formation. Most planetesimals there probably had their orbits disrupted by gravitational encounters with the growing Jupiter, and were ejected from the Solar System or plunged into the Sun. What remains is a tiny fraction of the planetesimals that were once there. Finally, there was probably a lot of gas left over after the planet formation process which was almost entirely swept out of the Solar System by a powerful wind from the young Sun. Such winds are observed in other forming stars.

EARTH

The Earth's interior consists of: 1) a metallic core, which is divided into an inner, solid core and an outer, molten core, 2) a mantle surrounding the core, which is mostly basalt, and 3) a crust, only 5-50 km thick, which is mostly granite. The lower parts of the crust are covered by the oceans. The atmosphere extends to about 100 km above the surface.

The main constituents of the atmosphere are nitrogen and oxygen. Earth probably had an original atmosphere richer in hydrogen and helium, but this was lost because Earth's gravity is not strong enough. The nitrogen came from volcanoes and the oxygen from early ocean life. These elements are heavier and do not escape Earth's gravity. The atmosphere is divided vertically into four zones: the troposphere, extending to about 10-15 km from the surface, where all the weather occurs, and the temperature drops with altitude; the stratosphere, extending to about 50 km, where the temperature rises somewhat with altitude again; the mesosphere, to about 80 km, where the temperature starts falling again; and the ionosphere above that, where the temperature shows a slight rise. The upper stratosphere and lower mesosphere contain the ozone layer: ozone is O_3 (three oxygen atoms joined into a molecule), which is very good at absorbing solar UV radiation. The energy it absorbs goes into heating this layer somewhat, which is the reason for the temperature rise in the stratosphere. The ionosphere is directly exposed to sunlight, and the UV photons are able to ionize the gas up there, hence the name of this layer.

The Earth's surface is heated by the Sun, and must get rid of that energy as fast as it gets it to stay at a constant temperature. The way it does this is convection (in the troposphere): warm pockets of air expand, become less dense than the average air, and thus rise because of their buoyancy, releasing their heat near the top of the troposphere, and cooler, denser pockets of air fall to fill their place. In this way a cycling of rising hot air and falling cool air is set up (like a boiling pot). This circulation causes small scale turbulence and large scale wind patterns in the Earth's atmosphere. Convection is a common process and we will see it again in several contexts.

The Greenhouse Effect is due to CO_2 and H_2O in the atmosphere, gas molecules that are efficient at trapping the infrared radiation that Earth's surface gives off (because it is warmed by the Sun). The effect keeps the surface and lower atmosphere temperature about 40 degrees C warmer than it would otherwise be.

Earthquakes occur when rocky material below the Earth's surface shifts or dislocates. This causes waves to be sent through the Earth, often violent and destructive, just like plucking a guitar string sends waves along it. The main waves that travel through the Earth are called P-waves (which are compressional waves like sound waves) and S-waves (which are more like shaking a string). How they travel through the Earth is the main way in which we know about Earth's interior structure. Like all waves, they bend when they encounter a change in density. Also, S-waves are unable to travel through a liquid. Studying what kinds of waves reach various parts of the Earth's surface after an Earthquake goes off allowed us to determine how the density of the interior changes with depth, and also that the outer core is molten (so S-waves don't get through) and the inner core solid. The density increases with depth, which indicates that "differentiation" must have occurred early in the Earth's history, i.e. it must have been all molten at one point, with denser chunks of molten material sinking down, and less dense chunks rising, before the Earth cooled and mostly solidified.

Earthquakes and volcanoes outline the boundaries of continental plates. These plates drift around the Earth's surface over tens of millions of years, taking the land masses and the oceans along with them (plate tectonics). They move at only a few cm/yr, which can be measured using laser ranging. At plate boundaries, the plates may be colliding, subducting (one slides under the other), moving apart (a rift zone), or sliding past each other. Mountain ranges, volcanoes, earthquakes and trenches are all found at such boundaries. The continental drift is probably caused by convection in the Earth's interior. The mantle is not quite fully solid, allowing rock to flow very slowly. The convection is just the Earth's way of getting rid of its internal heat. Warmer rock rises and cooler rock slows, setting up circulation patterns lasting about 100 million years, on top of which the solid plates ride. 200 million years ago, all the continents were together in a huge land-mass now called Pangaea.

Finally, high tides and low tides are mostly due to the Moon's gravity. The average force of gravity between the Earth and the Moon is what keeps them orbiting around each other. But the side of the Earth closer to the Moon feels somewhat stronger gravity from the Moon (remember the inverse-square law for gravity) and thus bulges out towards it a bit. The side of the Earth furthest from the Moon consequently bulges away from the Moon a bit. Oceans, being able to slosh around, experience this much more than land, where the rock is firmly bonded together and unable to bulge out so much. Now the Earth is rotating once a day while this bulge in the oceans always points to or away from the Moon (which moves very little in its 27-day orbit in one day). So from our point of view the bulges move across the oceans. When they reach a shoreline we get a high tide at that coast, and so on. The Sun also causes tides, but the Moon's effect is actually bigger.

THE MOON

First, realize that we always see the same face of the Moon (although it may be daytime (full moon) on that face, nighttime (new moon) or something in between). This means that the Moon spins exactly once per orbit around the Earth. This is due to "tidal locking": the Earth produces a tidal bulge on the Moon, even though the Moon is solid, which wants to point to and away from the Earth. Earlier, the Moon probably had a faster spin, but then the tidal bulge would have to migrate around the planet. This would create a lot of friction in the rock which started to slow down the rotation until the current situation where the tidal bulge doesn't have to migrate around the surface. This will also happen to the Earth, but in billions of years.

The Moon's average density is less than Earth's, indicating that it doesn't have such a prominent dense metallic core as does the Earth. The Moon's metallic core is small and possibly molten, and is surrounded by an extensive mantle and a crust thicker than Earth's. Any flowing part of the mantle is restricted to a small volume around the core. The Moon is much cooler and more solid than the Earth. This is because it is smaller and was thus able to lose almost all of the heat it may have once had relatively quickly. It also has no atmosphere, its gravity being too weak to retain one. Thus there is no wind or erosion, so the surface reflects the entire history of the Moon.

The surface has two types of terrain: maria and highlands. The maria are dark and more featureless, and several km below the highlands typically. The latter are much more heavily cratered (due to impacts). Impacts occur at speeds of several km/sec, and crater diameters are about 10 times the size of the impacting meteoroid. The impact pulverizes a lot of rock around the crater, creating an ejecta blanket. The entire lunar surface is covered by a layer of pulverized rock to a depth of about 20 meters from impacts. Small meteoroids are common, large ones are rare, so the same is true for craters.

Evidence for past lunar volcanism includes: 1) the maria, which are the result of old, widespread lava flows. The lower lying basins into which the lava flowed are probably the result of the earliest, largest impacts; 2) Rilles, which are ditches carved out by flowing lava, and 3) linear chains of craters, which probably mark fissures in the crust through which lava emerged in places to form lava domes (as on Earth), which later collapsed to make the craters (these are not impact craters).

From radiometric dating of rocks brought back by the Apollo astronauts, the maria are younger than the highlands, being 3.2-3.9 billion years old vs. over 4 billion years old. So the Moon is about as old as the Earth, and during the first few million years suffered heavy bombardment by meteoroids which made most of the craters, including the large basins that were filled in by flowing lava up until about 3.2 billion years ago, when the Moon cooled off enough for lava to stop flowing. Since then, cratering has continued at a much reduced rate, which is why the maria are so much less heavily cratered than the older highlands. The Moon is basically geologically dead.

How did it form? The theory that the Moon formed out of the same material as the Earth at the same time is rejected because of the different density and composition of the Moon. The theory that the Moon was a stray object captured by Earth's gravity is rejected because it is an extremely unlikely event. So the favored theory is that the Moon formed early on in the Solar System when a lot of largish planetesimals were still around, and a Mars-sized object struck the Earth. Some of the matter was flung outwards into orbit around the Earth, where it coalesced to form the Moon. This is very speculative but is at least much more possible than the other theories.

MERCURY

Relatively little is known about Mercury, the second smallest planet. We had only ever sent one probe there on a fly-by before the current Messenger mission. It is a cold, dead world like the Moon. Being small, it cooled off fast. It probably had volcanic activity that ended about 4 billion years ago. No dark maria were formed, but regions called "intercrater plains" may be ancient lava fields. Craters are also not as densely packed together as on the Moon, which may be due to some being covered by lava flows.

The tidal force due to the Sun has caused a bulge in Mercury, and led to a strange form of "tidal locking" like the Moon. Instead of always keeping the same face towards the Sun, it always has its tidal bulge pointing towards the Sun when it is closest to the Sun (its orbit is quite elliptical). By settling into this situation, it has ended up with a rotation period exactly 2/3 of its orbital period.

VENUS

Venus is almost as large as the Earth, but its proximity to the Sun has led to a very different planet. Venus rotates very slowly, taking 243 days to spin on its axis, and does so in the opposite sense of most everything else in the Solar System. Its sidereal day is therefore longer than its 225 day year. The reason is unknown. Perhaps an early collision with another large object almost stopped it spinning. Its spin axis is not tilted like Earth's.

Venus has a very thick atmosphere, with the pressure at the surface being about 90 times that of Earth's. It is so thick that we can't see the surface. It is almost all CO_2, although its yellowish color may come from particles of sulfur suspended in the atmosphere. There are also layers of corrosive sulfuric acid clouds. The surface temperature is about 730 K. The thick atmosphere keeps the surface much hotter than it would otherwise be because of the strong Greenhouse Effect of all that CO_2. Venus is probably close enough to the Sun for a runaway Greenhouse Effect to occur. If it ever had oceans, then the proximity to the Sun probably caused them to start to evaporate, releasing a lot of water and CO_2 into the atmosphere. This raised the surface temperature and increased the evaporation rate, and so on in a runaway process, until the surface was dry and all the water vapor and CO_2 had gone into the atmosphere. Meanwhile, the water vapor was rather easily broken into its constituent hydrogen and oxygen atoms, and the hydrogen (being the lightest element) was able to escape the planet, while the oxygen reacted with other atoms. The CO_2 remained, however, and is still there today.

There have been many missions to Venus. Some of the Soviet Venera probes attempted to land on the surface unsuccessfully, until one survived for a few hours to send back some photos and chemical analysis before succumbing to the heat. It showed that the rocks are mainly basalt and granite, i.e. volcanic. The Magellan mission returned a very detailed elevation map of the surface of Venus, using the radar echo technique. It bounced radar signals off the surface of the planet and measured how long it took for the signals to return to the probe. For instance, if the signal bounces off a high mountain, it takes less time to return. In this way, the elevation map of the entire surface can be made. The surface turns out to be generally flatter than Earth, with no signs of plate boundaries or plate tectonics. There is plenty of evidence for volcanism, however, and it may be ongoing at some level. But structures such as "shield volcanoes" (which is what the entire Big Island of Hawaii actually is), lava domes and even larger "coronae" (where the mantle seems to have pushed up the surface) are very common and reveal an active volcanic history. It is not clear why Venus should have been more volcanically active than Earth, given that it is about the same size. The crust may be soft or brittle, allowing volcanic rock to easily break through the surface. However, the density of impact craters indicates little volcanic activity in the last 500 million years.

MARS

Mars' mass is about 0.1 times the Earth's and has about half the radius. Its orbit is more elliptical, so that it ranges from 1.38 to 1.66 AU from the Sun. This range is big enough to affect Mars' seasons, unlike the Earth case.

Mars' atmosphere is very thin, with the pressure at the surface only 0.006 that of Earth's. But like Venus, it is almost completely CO_2. A "reverse runaway Greenhouse Effect" may have occurred on Mars: it almost certainly once had a warmer, thicker atmosphere, more volcanic activity and possibly oceans, but because the planet is further from the Sun than Earth and also cooled faster (because of its smallness), the atmosphere may have gradually dissolved into the oceans and combined with rocks, reducing the Greenhouse gases and thus causing the surface to cool, which enhanced the loss of atmosphere, etc. Mars also has dust storms which sometimes envelop most of the surface for months.

The two hemispheres are rather different: the southern one being about 5 km higher elevation, and more heavily cratered, like the lunar highlands. The cratering rate indicates the southern hemisphere's surface is about 4 billion years old. The northern hemisphere is less cratered, like the lunar maria, and about 3 billion years old. The Tharsis Bulge is the highest (10 km) and youngest (2 billion years) part of the surface, and was probably pushed up by upwelling lava. The Valles Marineris is a 4000 km long, up to 7 km deep crack in the crust, the origin of which is not clear, but may be related to the volcanic activity which resulted in the Tharsis Bulge. Olympus Mons is a shield volcano, as found on Earth and Venus, but three times the height of Mount Everest. It is not active.

The Viking probes in the 70's, Pathfinder and its robot Sojourner in the late 90's, the current Mars Exploration mission with its Spirit and Opportunity rovers, and the current Mars Phoenix mission all landed on the surface, revealing a dry, desert-like planet. The red color of the rocks is due to a high iron content (just like rust). On Earth, most iron, a heavy element, is in the core. The iron on the Martian surface indicates that Mars didn't go through as major a molten phase as Earth and did not differentiate as heavily. The sky has a butterscotch hue due to dust in the atmosphere.

There is clear evidence for past surface water on Mars: "runoff channels" or dry rivers, "outflow channels" resembling dry river deltas, possible erosion of craters by standing water, and teardrop shaped "islands" in the outflow channels which suggest water flow and erosion around them. Pathfinder landed in an outflow channel, and its pictures revealed rocks which have probably been shaped by water and others appearing volcanic. There is no current evidence for flowing water on Mars, but how recently it flowed is still debated. Underneath the surface is probably a layer of permafrost, for which "splosh craters" provide evidence: the impact apparently caused water from this layer to splosh out around the crater. Another crater shows evidence for a water-rich outflow between 2001 and 2005. The Mars Phoenix lander recently found that there is in fact ice just below the dusty surface at its landing site near the north pole. The question of life on Mars is still an open one. Water is certainly an essential ingredient for life, but the some of the water on Mars may have had too high a salinity or acid content.

Mars cooled faster than Earth because it is smaller, and thus most volcanic activity ended on Mars about 2 billion years ago. Most of the atmosphere froze out into the surface and the rocks. There is no evidence for plate tectonics. Most of the entire northern hemisphere may once have been ocean, and the outflow channels, located in the equatorial regions where the elevation is dropping as you go from the southern to northern hemisphere, may mark flows associated with catastrophic floods which fed the ocean.

Mars' two moons, Phobos and Deimos, are probably asteroids captured by Mars' gravity. Their properties are very similar to the asteroids.

THE JOVIAN PLANETS

These are Jupiter, Saturn, Uranus and Neptune (from closest to furthest from the Sun), which are similar in many ways, being the most massive planets, being composed mostly of large gas envelopes, and having rings and many moons. Uranus was discovered in 1781 by William Herschel, and Neptune in 1845 by Johann Galle, after Adams and Leverrier had both predicted its existence based on slight irregularities in Uranus' orbit. We have learned much from missions to these planets, particularly the two Voyager probes in the 70's and 80's and Galileo (to Jupiter) in the 90's. Cassini will arrive at Saturn this summer.

Jupiter and Saturn rotate rapidly, causing a significant bulge at their equators. The gas envelopes of these and Uranus also spin faster at their equators compared to near their poles. This is called differential rotation. Uranus' rotation axis is so tilted that the planet is basically "on its side" compared to the others. It is not clear why this happened. Like the case for Venus, maybe it was caused by a collision early on in the Solar System's history.

Jupiter's atmosphere consists mainly of hydrogen and helium, with tiny amounts of other elements. However, many of these other elements react with hydrogen to form molecules such as ammonia ice (a nitrogen and three hydrogens), water ice, and ammonia hydrosulfide (sort of an ammonia molecule joined to a water molecule). The latter is probably responsible for the red, yellow and brown hues so prominent in Jupiter. The ammonia ice probably causes the white colors, and sits higher in the atmosphere. Hence the color you see is related to the depth your looking down into. On other Jovian planets, different chemistry causes different coloration. Saturn's upper cloud layer is thicker and more uniformly spread out, making the whole planet appear a rather uniform yellow. That color comes from ammonia ice in the atmosphere. The striking blue of Uranus and Neptune is due to methane (a molecule of one carbon and four hydrogen atoms), which reflects blue light from the Sun very well. What happened to their ammonia? These planets are colder, and the ammonia has all frozen and sunk down deeper.

Jupiter is marked by its banded appearance. The lighter colored ones are called zones, and the darker ones belts. They slowly change over the years, but the banded appearance remains. The zones and belts are Jupiter's high and low pressure systems and mark a convection cycle. Warm gas rises and reaches higher in Jupiter's atmosphere. Cooler gas is sinking. The molecules that tend to form higher up (such as ammonia) have lighter colors, while those that form lower down (such as ammonia hydrosulfide) have darker colors, hence the difference in color between the zones and belts. It's just because the chemistry is different at different heights. Winds flow in opposite directions in the zones vs. the belts, with differences of hundreds of km/hour. Other Jovians also have this band structure, but it is less distinct due to a more smooth, uniform coverage of clouds high up in their atmospheres.

Jupiter's Great Red Spot is basically a hurricane, but one that has persisted for at least 300 years. It is twice the size of the Earth. Somewhat smaller are the brown oval (in the north, and occurring lower in the atmosphere because they're brown) and white oval (in the south, and higher in the atmosphere) storms, which last for years or decades. Storms last so long because unlike on Earth there are no land masses to disrupt the smooth flow of gas. Neptune's Great Dark Spot was an Earth-sized storm discovered by Voyager 2 in 1989, but it disappeared in a few years.

Internally, Jupiter consists of a rocky core of maybe 15 Earth masses, surrounded by a layer of hydrogen molecules in liquid form, which is a good conductor of electricity, surrounded by the outer envelope of gas, which is mostly hydrogen. At the center, the density is as high as 25 grams/cm^3, the temperature 40,000 K, and the pressure 50 million times that of our atmospheric pressure. Other Jovians have similar internal structures.

MOONS, RINGS OF JOVIAN PLANETS, PLUTO AND SPACE DEBRIS

Our main focus was on the four large "Galilean" (discovered by him) moons of Jupiter: Io, Europa, Ganymede and Callisto, from closest to furthest from Jupiter. Ganymede is the largest moon in the Solar System. The closer to Jupiter, the higher the average density for these moons, meaning a higher fraction of rock and metal relative to ice. This is a bit like the Solar System itself, and the formation of these moons may have been like the formation of the Solar System, with the heat from the forming Jupiter causing different moon make-ups.

Io has frequent volcanoes lasting months or years. They are rich in sulfur and sulfur dioxide (SO_2). Sulfur can be orange, red or black depending on temperature, while SO_2 on the surface becomes frozen white snowflakes. Hence the rich colors of Io's surface. The surface can be seen to change over the years. Volcanism is a sign of internal heat. These moons should be cold and dead given their size. But Io's orbit is responsible for its heat. It is in a "resonance orbit" with Europa (orbiting twice for every one Europa orbit), and this has pulled Io into an elliptical orbit. It has a significant tidal bulge, which always points to and from Jupiter. Thus it wants to swing around the surface faster when Io is closer to Jupiter and going faster (Kepler's second law). But Io spins at a constant rate, so the bulge moves back and forth across its surface, leading to friction in the rock, and thus heat, and thus volcanoes.

Europa may have a warm ocean beneath its icy surface. The surface shows many signs of ice flowing, as well as cracks through which material from the interior probably erupts (water with some rock). The interior warmth comes from the same effect as for Io, but this time it is Ganymede that has pulled Europa into an elliptical orbit (Europa orbits twice for every one Ganymede orbit). A warm ocean is one of the best possibilities for life in the Solar System.

Ganymede and Callisto are heavily cratered, indicating older surfaces. There are no signs of recent volcanism. Ganymede may have had water eruptions in its first billion years. Saturn's moon Titan is unusual in having a thick atmosphere (of nitrogen mostly). We know a lot more about Titan now because of the Cassini mission to Saturn and the Huygens probe that landed on the surface of Titan. The atmospheric pressure is high enough so that liquids can exist on the surface, and there seem to be lakes of ethane (C_2H_6), as well as methane (CH_4) rain in the atmosphere. These are the building blocks of organic molecules, although Titan is probably too cold for life. Titan may undergo catastrophic methane and ethane flooding periodically.

Saturn's rings are composed of icy chunks ranging from less than 1 mm to greater than 10 meters, but most are a few cm. The rings are only about 100 m thick. There are some gaps in the rings, the most prominent is the Cassini division. Voyager found that there are actually 10,000's of concentric ringlets. The Cassini Division has been mostly swept clean of material due to the gravitational influence of the moon Mimas, which lies just beyond the rings. This is another resonance orbit effect: Mimas makes the orbits of chunks in the Cassini Division elliptical, making them collide with other chunks, where they end up in circular orbits at larger or smaller radii, thus sweeping clean the gap. Other gaps have similar origins.

Saturn's rings were probably formed when a moon, perhaps after suffering a collision, got too close to Saturn. Due to the tidal force, the side of the moon closer to Saturn felt stronger gravity than the side furthest from it, stretching the moon until it shattered into many fragments. There is a limit, depending on the properties of the planet mostly, within which a moon can't approach and stay intact. This is called the Roche limit. Saturn's rings are inside this limit, supporting this idea for their creation. The amount of matter in the rings would make a nice moon of 250 km diameter. The rings of Uranus were discovered by "stellar occultation": when we watch the rings pass over a distant star, the star's light dims as each ring blocks it. This gives information on the number, width, and composition of the rings. Jupiter's, Uranus' and Neptune's rings may be material blasted off of moons by impacts. Rings probably only last up to 100 million years (cf 4.5 billion year age of Solar System) before they disperse. Therefore, given that all four Jovians have them, their formation must be relatively common.

The Dwarf Planet Pluto is a tiny (20thus with more in common with Jovian moons than with planets. It has a moon, Charon, which is half its diameter. Pluto was predicted to exist by remaining irregularities in Uranus' orbit (after Neptune was found), and discovered by Clyde Tombaugh in 1930. Ironically, the irregularities were later found to be incorrect. Pluto's rather elliptical and tilted orbit is also unusual. It is more likely to be the one of the largest of a class of objects called Kuiper Belt Objects. These were only found beginning in 1992, but now 100's are known, with one discovered in 2003, called Eris, recently found to be larger than Pluto. Their orbits and composition are similar to Pluto's. They are all probably leftover planetesimals from the Solar System's formation, that may have been flung to the far reaches by interactions with the Jovian planets.

Comets are another form of Solar System debris. They divide into two classes: short (50-200 years) period and long period (10^5-10^6 years) comets. The short period ones have prograde orbits (like the planets) and originate in the Kuiper Belt. The long period ones have randomly oriented orbits and originate in an even larger cloud of debris called the Oort Cloud (which hasn't been discovered but we're pretty sure it must be the reservoir for these). Most objects in Kuiper Belt and Oort Cloud stay out there, but once in a while a gravitation encounter with one of the Jovian planets (for the Kuiper Belt) or a star (for the Oort Cloud) may send one or more objects into the inner Solar System. When these comets are far from the Sun, they only consist of the solid icy/dusty "nucleus" of size 10 km or so. But if they reach the inner Solar System, the solar radiation and Solar Wind strip off tails of gas and dust, which is what we can easily observe. The nucleus is also surrounded by a "coma" of gas and dust, about a million km in size. Because of their origin, the tails always point away from the Sun, even if the comet is moving away from the Sun. There may be both a gas tail (blue) and a dust tail (white), as comet Hale-Bopp well demonstrated.

Over the course of many orbits, comets slowly break up because of the Solar wind, radiation and the tidal force, leaving a trail of debris that gets spread along its orbit. If the Earth's orbit crosses the comet's, then you might get a Meteor Shower due to debris entering and burning up in Earth's atmosphere, depending on how much debris there is and how it is spread around the comets orbit. "Meteor" just refers to the visible streak as the rock burns up in the atmosphere. This explains why there are meteor showers that occur at the same time every year, such as the Perseids in August.

The asteroids are rocky fragments, most of which orbit 2-3 AU from the Sun, between Mars and Jupiter. The largest is Ceres, at 940 km across. The smallest are less than 100 m. There are roughly 100,000 known. The Trojan asteroids share Jupiter's orbit, but are 60 degrees ahead and behind Jupiter. These are special locations known as Lagrange points, and asteroids can be trapped there due to a complex effect having to do with the combined gravity of Jupiter and the Sun. Other asteroids cross Earth's orbit. They were probably disrupted out of the Asteroid Belt by Jupiter's gravity. The total mass of all the asteroids is small, only 0.07 of our Moon's mass. Finally, meteoroids are even smaller rocky fragments left over from Solar System formation. If one is found on Earth, we call it a meteorite.