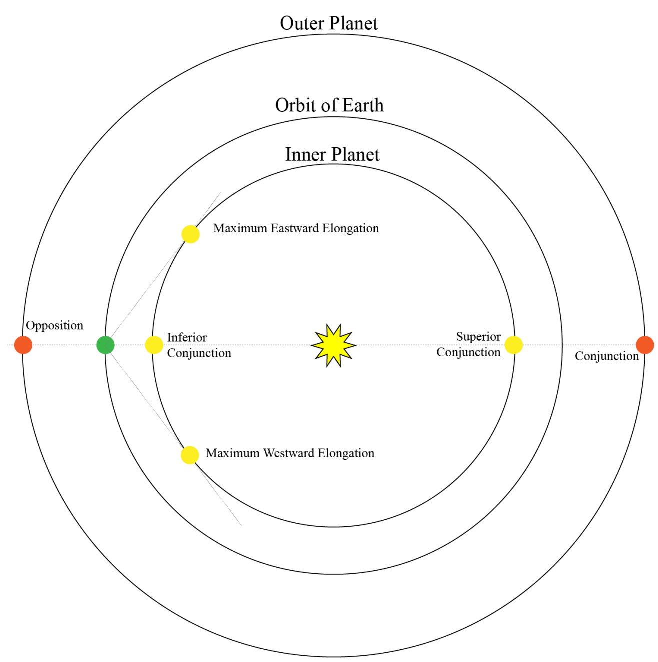
ASTR 1010 – Spring 2016 – Study Notes
Dr. Magnani

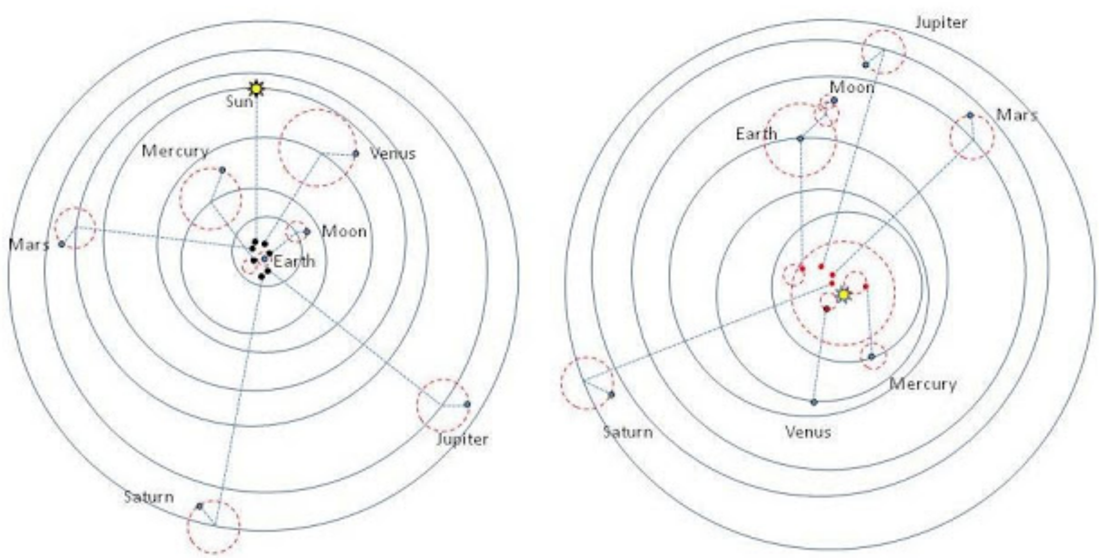
The Copernican Revolution

The Copernican Revolution is basically how the West intellectually transitioned from the Ptolemaic geocentric model of the Universe to the heliocentric model (originally proposed by Aristarchus). The man who resurrected the idea that the heliocentric model was the correct one was Nicolaus Copernicus (1473-1543), a Polish mathematician who also had a doctorate in canon law and so was deeply connected to the Catholic Church. In the early 16th century he devised a heliocentric model which looked a lot like Aristarchus' model from the third century BC. However, although Copernicus lived through the height of the Renaissance his mode of thinking was deeply shaped by the Middle Ages and so he insisted that the planets in his model follow circular orbits and move at constant rates. He believed, like the ancient Greeks, that motion in the heavens had to be perfect; this meant circular orbits and uniform speeds.

Unfortunately, these choices forced him to add the infamous epicycles from the Ptolemaic model. In his model, the epicycles were not introduced to explain retrograde motion or the proximity of Mercury and Venus to the Sun, but, rather, to make sure the planets could move at constant rates on the various epicycles and still appear from our viewing platform on the Earth to speed up and slow down with respect to the background stars on the celestial sphere. The epicycles also allowed the planets to be at various distances from the Earth at key alignment points such as opposition. For example, at opposition, the Earth is directly between an exterior planet and the Sun (see below).



Mars was brighter at some oppositions than others and the explanation for this was that the planet had to be closer to the Earth when it appeared brighter in the sky. If you have a circular orbit for Earth and a circular orbit for Mars, there is no way the distance between can change from one opposition to the next. Because of his insistence on circular orbits, Copernicus had to postulate that Mars was on an epicycle so its distance at opposition could vary from one opposition to the next (see below).



Ptolemaic Model Copernican Model

In this way he explained the observed changes in brightness of the planets. In 1543, he published his theory in the famous book, *De Revolutionibus*, which was published during the last few months of his life. Because of the epicycles in the model, Copernicus' heliocentric model was no less cumbersome than Ptolemy's geocentric model (which had been described in Ptolemy's book *Almagest*) and the natural elegance of the heliocentric theory was obscured.

The next two players in the story are Tycho Brahe (1546-1601) and Johannes Kepler (1571-1630). Tycho was a Danish astronomer who was the foremost observational astronomer of the pre-telescopic era (ushered in by Galileo in 1609-1610). His tables with the positions of the planets at various times over the years was the best dataset of its kind that had ever been compiled and when he died, his assistant, the German astronomer Kepler, inherited the data. Kepler had read Copernicus' book and was a staunch defender of the heliocentric model. In trying to make Copernicus' model more efficient, Kepler spent 20 years analyzing Tycho's data, especially for the planet Mars. When he was finished he could sum up the orbital behavior of the 5 planets, plus the Earth, in 3 simple rules that became known as Kepler's Laws:

1) Planets move around the Sun in elliptical orbits with the Sun at one focus.
2) Equal areas in a planet's orbit are swept out by the planet in equal times.
3) The period of a planet squared equals the semimajor axis of its orbit cubed.

The last Law can be simply written as $p^2 = a^3$. While Kepler's achievement is monumental, it was not intellectually satisfying in that his Law's explained *how* the planets moved, but not *why* they moved in that manner. To explain why the planets moved in the way that they did requires the last two participants in the Copernican revolution: Galileo Galilei (1564-1642) and Sir Isaac Newton (1642-1726).

Galileo, an Italian mathematician, engineer, astronomer, and physicist, revised the ancient theory of motion (mechanics) and set the foundation for Newtonian Mechanics (which is still taught today – you can learn it by taking PHYS 1111 or 1211 at UGA). In addition, he used the newly-invented telescope for astronomical observations which provided much backing for the Copernican model (which Galileo strongly believed was right). Among his discoveries were craters and mountains on the Moon, the stellar content of the Milky Way, the 4 large moons of Jupiter (called the Galilean satellites in his honor), and the phases of Mercury and Venus. The last two discoveries were particularly strong evidence for the Copernican model. For example, the 4 Galilean moons proved that even in a geocentric model where everything was supposed to orbit the Earth, there were 4 objects that were orbiting Jupiter, instead.

Galileo set the stage for Newton, who devised his theory of motion (Newtonian Mechanics) to explain how things move on Earth and in the heavens. The key concepts were those of force and gravity. Newton devised three general laws of motion:

1) Objects in motion stay in motion at constant velocity, unless a force acts on them.
2) $F = ma$ (This is known as the Law of Inertia)
3) For every action there is an equal and opposite reaction.

When he added his Law of Universal Gravitation (we are avoiding vectors and are only concerned with magnitudes):

$$F = GM_1M_2/r^2$$

his system of mechanics was complete. He now could explain why bodies moved on Earth and in the sky using the same physical laws for both. In other words, there was no difference between the Earth and heaven as far as physics was concerned. To sum up, according to Newton, objects moved because they were responding to the application of forces and, as far as the planets were concerned, the force being applied was that due to gravity.

Let's look at some basic results from the 4 Laws described above.

You can calculate the acceleration due to gravity at the surface of the Earth:

Look at a body with mass m_1 (recall that mass is NOT weight). Let the mass of the Earth be M_E (6.0×10^{24} kg – where kg is kilograms) and its radius be R_E (6400 km where km is kilometers). We can then look at how the body with mass m_1 accelerates:

$$F = m_1 a \quad \text{and} \quad F = G m_1 M_E / R_E^2$$

Set F = F and you get

$$m_1 a = G m_1 M_E / R_E^2$$

The m_1 cancels on both sides of the equation so you end up not only with the acceleration of the mass m_1, but with that of all other bodies that are dropped at the Earth's surface. It doesn't matter if you are dropping a piece of chalk or a 45-pound barbell. They both fall accelerating at the same exact rate (neglecting air resistance). That acceleration doesn't even have to be measured; you can calculate it using the equation above. Just cancel out m_1 from both sides and you get

$$a = G M_E / R_E^2$$

To get a numerical value, convert 6400 km to 6.4×10^6 meters (Question: Why MUST we do this?) and plug in M_E and $G = 6.67 \times 10^{-11}$ Nt m^2/kg^2 and you will get the value of the acceleration as 9.8 m/s^2. Confirm this right now with your calculator.

If you carefully measured the rate at which things accelerate at the Surface of the Earth, you would get exactly the same number. Newton's theory is confirmed at this level by observation.

Now look at the tables in the back of your book or online and calculate the acceleration on the surfaces of Mars, Jupiter, Neptune, and the Moon.

Now, let's talk about the difference between mass and weight. Mass is the amount of "stuff" that some object possesses. Weight is a FORCE and so it must be a mass times an acceleration (Newton's second law). The mass of an object is given in kg and the acceleration depends on where the object is. On the surface of the Earth, we calculated that the acceleration is 9.8 m/s^2, so the weight of a 50 kg object would be $50 \times 9.8 = 490 \text{ kg m/s}^2$. The physical unit kg m/s^2 is known as the *Newton*. What would be the weight of the same 50 kg object if you moved it to the surface of Mars? Of Jupiter? Of Neptune?

Talk to a friend (if you have one) and explain to them the difference between mass and weight. If you can't find a friend, explain the difference in your own words to a sibling, a parent, or a dog (don't bother with cats, they don't want to hear it).

Several other questions to ponder: When we set F = F a few pages above and got the m_1 to cancel out on both sides of the equation, we implicitly made the assumption that the inertial mass has exactly the same value as the gravitational mass. Explain to your friend the difference between inertial mass and gravitational mass.

Find another friend, because the previous one undoubtedly left by now, and explain to them why the statement 1 kg = 2.2 pounds is problematic.

Finally, prove to yourself that in the equation

$$F = Gm_1M_E/R_E^2$$

the units of G can be expressed as $\text{Nt m}^2/\text{kg}^2$ or as $\text{m}^3/(\text{s}^2 \text{ kg})$.