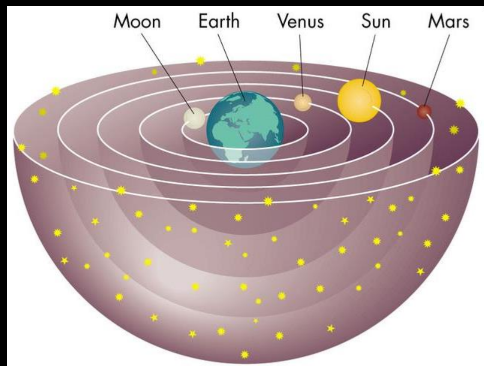
Upcoming Astronomy-themed Talks and Events

Thursday, 1/16, 3:45-5:00p Astronomy Colloquium – Phys-Astr A102 – Kailash Sahu (STScI) – "Study of White Dwarfs and Black Holes through Relativistic Bending of Light".

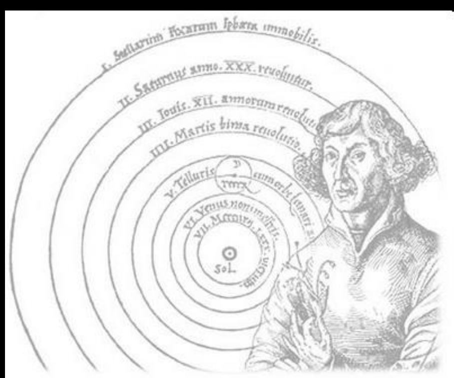
Quick Recap: Early ***Models*** of the Universe

Last week we saw how early astronomers identified and used the patterns of motions they saw in the heavens to keep time and develop a sense of predictability in their environment.

In particular we saw how Greek philosophers, seeking to explain those motions in a physically meaningful sense, had by 150 AD developed a “geocentric model”– mathematically rigorous and based on Aristotelian physical principles – with the Earth at the center of nested and concentric spheres that held the Sun, Moon, planets, and stars.



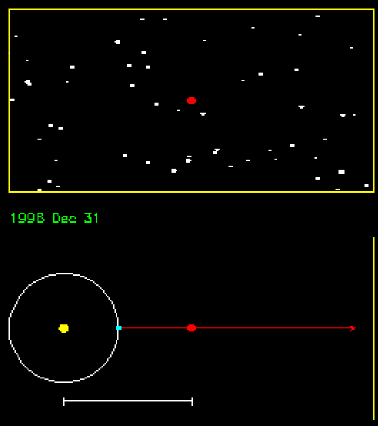
The basic idea of the geocentric, or “Ptolemaic” model – if not to scale and missing a few planets!



Engraving of Copernicus, showing his Sun-centered system – including the Earth (“Telluris”) with its own orbit.

This view of the universe persisted for over a millennia before being challenged directly in the late 1500s by the “Copernican Model”, developed in northern Europe by a group of intellectuals led by Nicolas Copernicus, and first published in 1543. It was an equally mathematically rigorous explanation for the patterns of motion seen in the sky, but with the Sun at its center (“heliocentric”),.

Such ideas had been presented before, and had always faced serious criticisms – for example, the fact that astronomers of that time could not detect ***parallactic motion***, the back-and-forth shift of nearby stars compared to more distant stars that should be seen if the Earth were orbiting the Sun.



Animated GIF of the parallactic motion of a nearby star (red dot) as the Earth (blue dot) orbits the Sun (yellow dot).

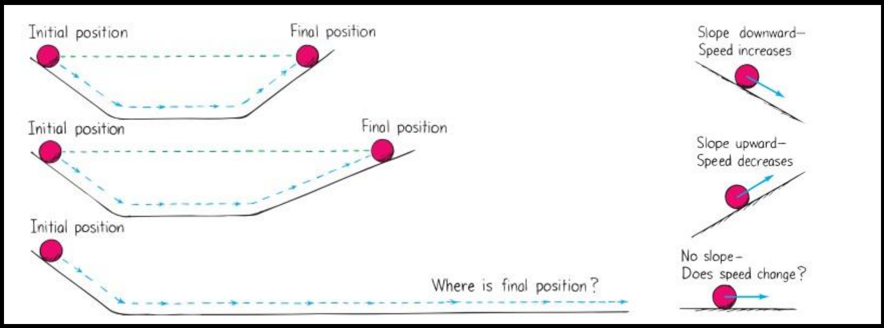
But a far, ***far*** deeper issue had to do with the idea of the Earth moving at all! The heliocentric model suggested that the Earth was rotating and revolving through space at many 1000’s of kilometers per hour – which certainly doesn’t ***feel*** like it’s happening, and would seem to suggest some bizarre possibilities!

Another problem for the Copernican model was that it was not terribly accurate – because Copernicus had focused on simplicity, not accuracy, he kept all of the orbits perfectly circular, with perfectly constant orbital speeds. These did not match up well with the increasingly precise measurements being made by Renaissance astronomers, who for the first time in history had access to mechanical clocks!

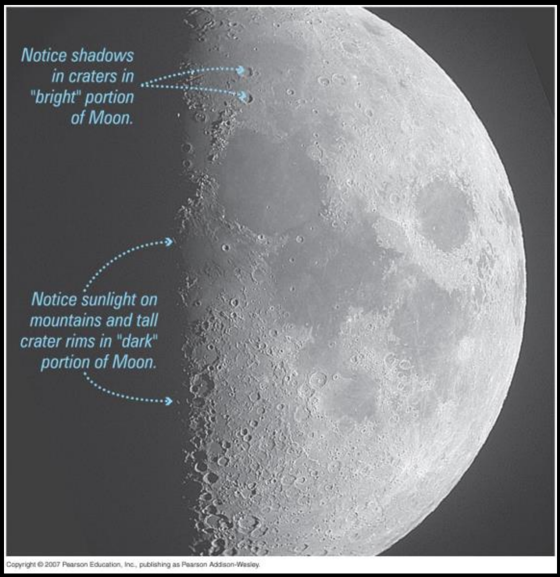
A clock in Strasbourg, Germany, showing one of the great technological advancements of the 15th Century – the minute hand!

Galileo Galilei in the Cathedral of Pisa (Luigi Sabatelli, ca. 1841)

Nevertheless, the Copernican model appealed to many of a growing class of intellectuals in Europe, including an ambitious young student at the University of Pisa by the name of Galileo Galilei. In 1592 he accepted a position at the University of Padua where he would become well known – somewhat notorious even – for his work refuting basic tenets of Aristotelean physics.

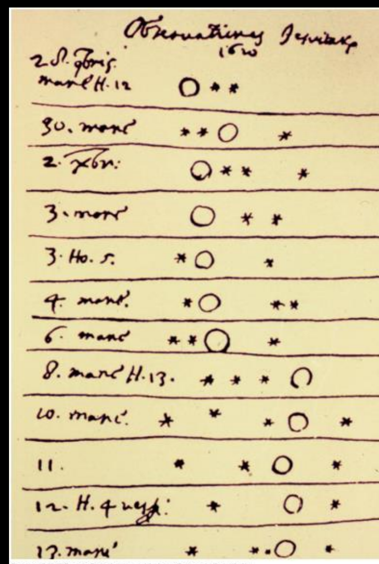


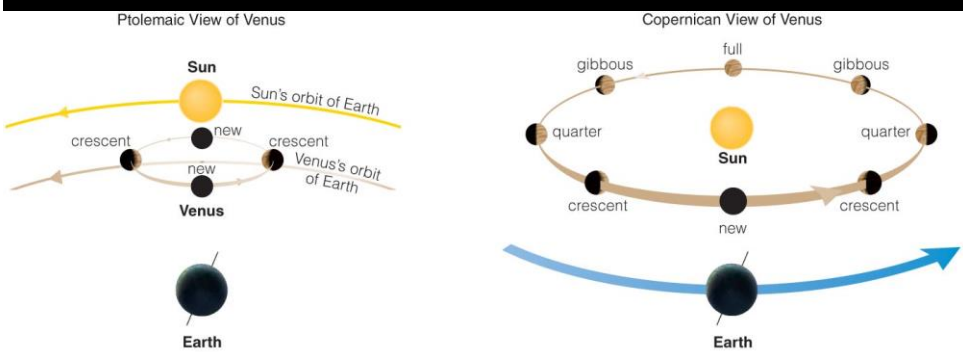
He devised experiments to showed that heavier objects do not fall faster than lighter ones, for example, and was amongst the very first to argue against the Aristotelean idea that objects in motion, instead of coming naturally to rest, tend to stay in motion – suggesting that plants and animals would not be 'left behind' by a moving Earth.



But Galileo's most significant contributions began in 1609 when he turned a new invention – the "telescope" – up to the skies and found mountains and valleys on the supposedly perfect, supposedly made-of-magic Moon…

…as well as four tiny worlds orbiting around the planet Jupiter, which proved that the Earth was not the center of all orbits in the sky!

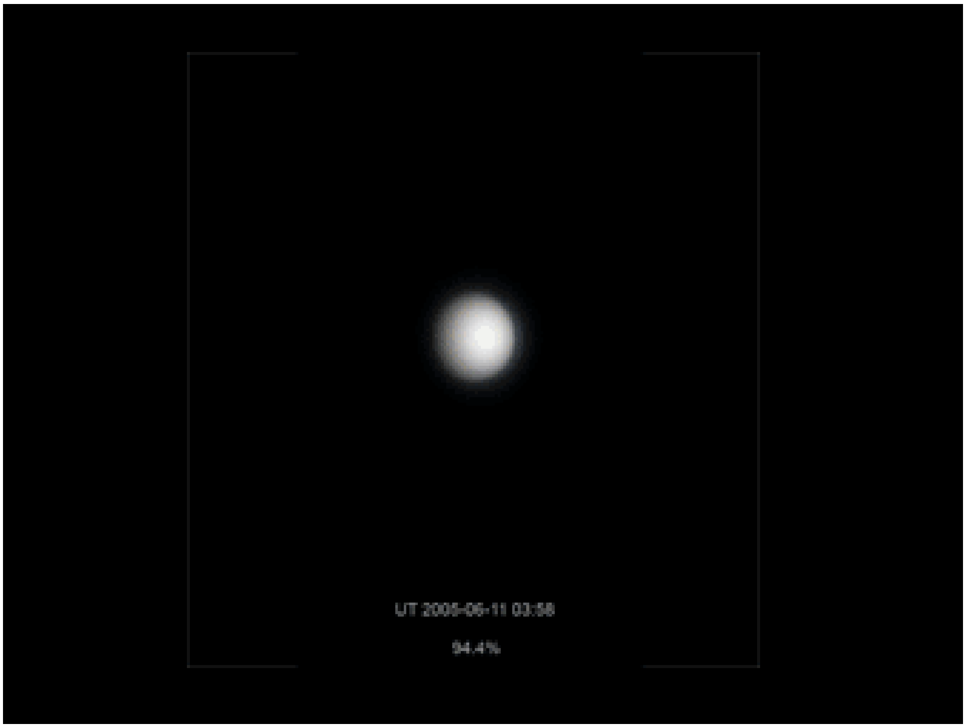




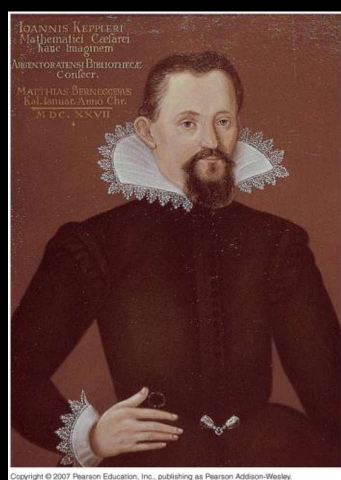
a In the Ptolemaic system, Venus orbits Earth, moving around a small circle on its larger orbital circle; the center of the small circle lies on the Earth-Sun line. Thus, if this view were correct, Venus's phases would range only from new to crescent.

b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus really does orbit the Sun.

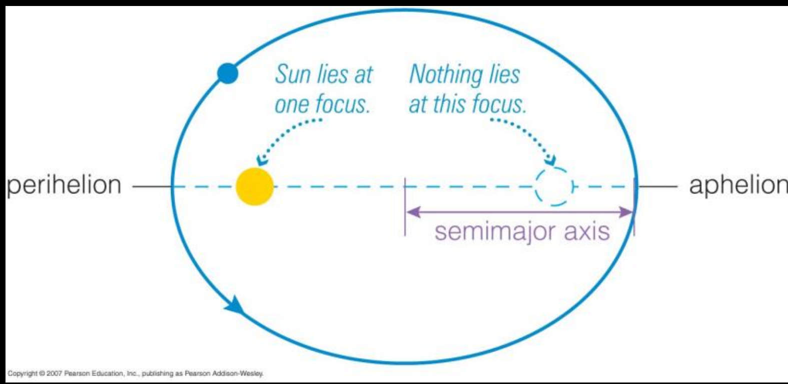
Further, he made detailed observations of the ***phases*** of Venus and showed that Venus (at least) clearly had to be orbiting ***the Sun***!



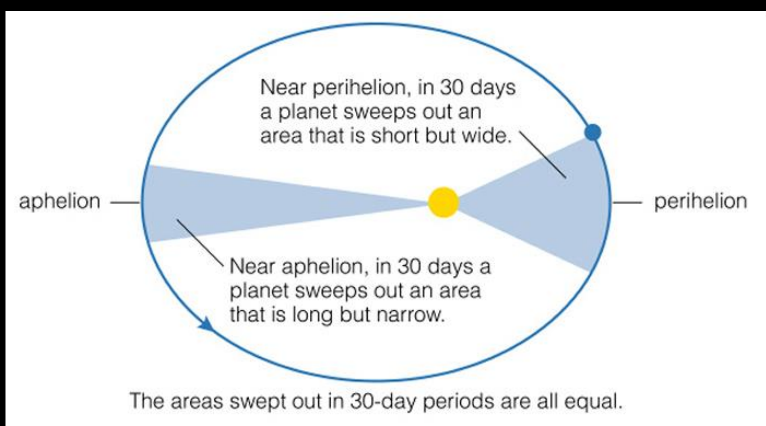
While all this was happening in southern Italy, at the University of Tübingen another young intellectual – and particularly gifted mathematician – named Johannes Kepler was also working to defend and extend the heliocentric model. He had been fascinated by astronomy since his youth, and in 1596 had published ***Mysterium Cosmographicum***, a lengthy defense of Copernicus' ideas.



Johannes Kepler, 1571-1630

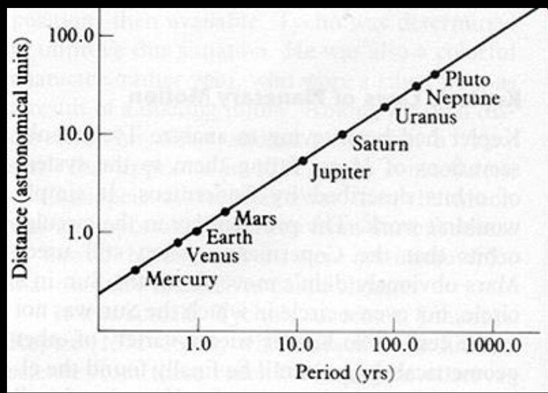


Between 1605 and 1609, Kepler used the careful planetary observations of Tycho Brahe – by far the most famous astronomer of his time – to develop a series of "laws of planetary motion", the first of which made the key theoretical leap of using ***ellipses*** instead of circles to describe how planets orbit the Sun.



Kepler's 2nd law is generally presented in terms of planets 'sweeping out equal areas in equal times', but it's really just an accurate description of the changing rate at which planets appear to move in their orbits – faster when they are nearer to the Sun, and slower when they are farther away.

Kepler's 3rd law extends this idea and reveals how planets with smaller orbits – which keep them closer to the Sun – move faster than those with larger and more distant orbits, with a clear, simple mathematical relation between orbital period and semi-major axis.

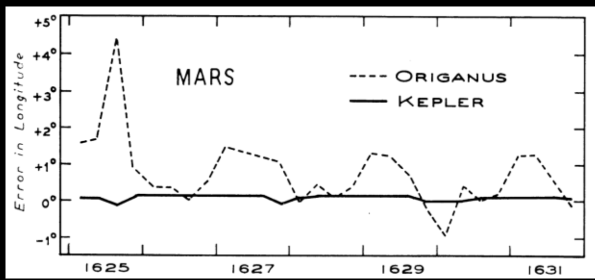


This latter point was extended by Kepler ten years later with the publication of his 3rd Law of planetary motion:

$$P^2 = a^3 \quad *$$

where ***P*** is the planet's period in years, and ***a*** is the planet's average distance from the Sun in AU. This incredibly useful relationship would soon be shown to be a general result of orbits in a gravitationally bound system – more on that later!

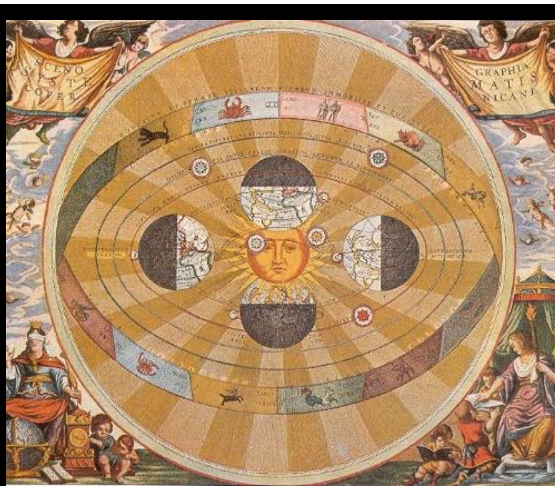
* Technically, this is an approximation, not an equality.



A comparison of errors in predicting the position of Mars based on Kepler's elliptical orbits and circular orbits with epicycles (Gingerich, 1971).

With these simple ideas, Kepler was able to produce the most accurate predictions of planetary motions ever made – noticeably more so than those of the Ptolemaic model or original Copernican model. This had a profound effect on many intellectuals, even if many still saw Kepler's work as "interesting math", but not a ***real*** description of the heavens.

Nevertheless, because of these developments, by 1650 most of the physical astronomers of the world had shifted from believing the geocentric model to accepting the motion of the Earth through space. This sort of amazing ("revolutionary"!) change can be seen again and again in science as ***new ideas*** and ***new technologies*** interplay to yield new understandings of the universe!



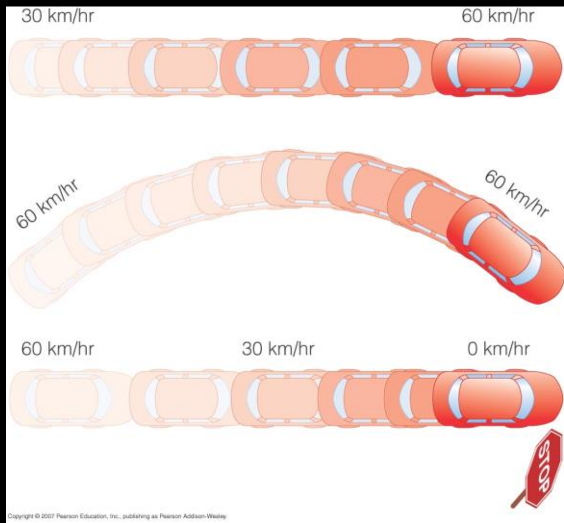
The next major step forward was to explain **<u>why</u>** the models of Copernicus and Kepler so accurately described the observations of Galileo and Brahe. What was the underlying physical cause of the motion of the planets – including the Earth – around the Sun?

Newton, looking ever so roguish…

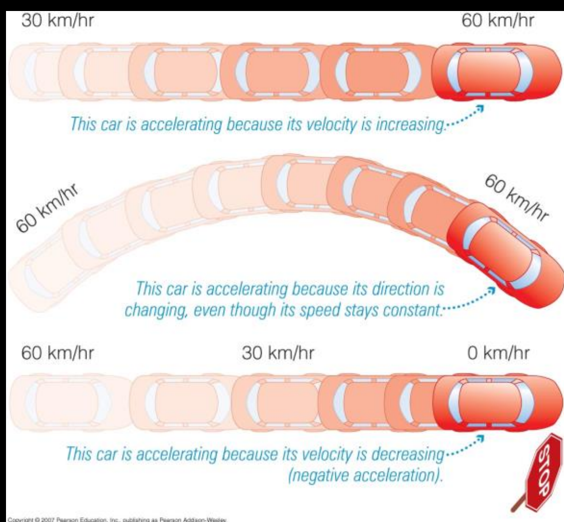
The answer to that question began to take shape quickly. Between 1665 and 1690, a young British scholar named Isaac Newton, developed a set of theoretical descriptions that offered a *physical explanation* for the observed motions of not only the planets, but arguably the entire universe.

The path to this began by examining the relationship between acceleration and mass…

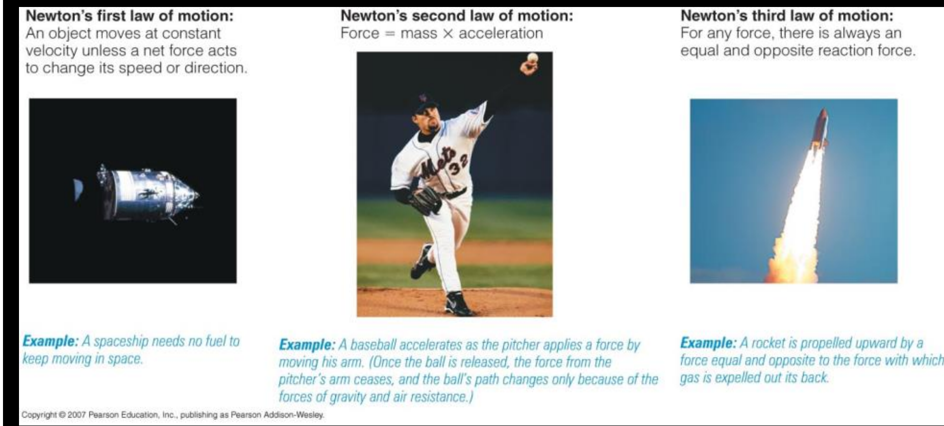
(Basic Definitions – Velocity vs. Acceleration)



(Basic Definitions – Velocity vs. Acceleration)



…and led to the so-called "Newton's Three Laws of Motion".



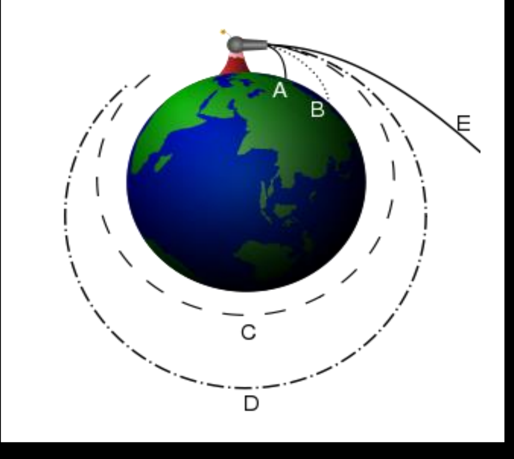
The key concern for us here is Newton's 2nd law, which states that any accelerating mass must be experiencing a net force on it. The Moon, for example, is orbiting the Earth – is it accelerating?

Of course it is, Newton thought, just as the Earth is also orbiting the Moon – and therefore there ***must be*** an unseen force operating on the Earth, the Moon, the planets, and in fact all objects in the Solar System…

…including apples!

The deeper meaning behind this fanciful story (which Newton himself vouched for) isn't about Newton "discovering gravity" thanks to a fortuitous bop on the head, but instead about the realization that the forces that affect apples here on Earth are the very same forces that affect the Moon and other objects in the Universe!

In fact, said Newton, the orbits of the planets were ***exactly*** like apples falling from trees – or being shot from cannons! His "cannonball thought experiment" neatly demonstrates how the gravitational attraction of objects could lead to closed orbits.

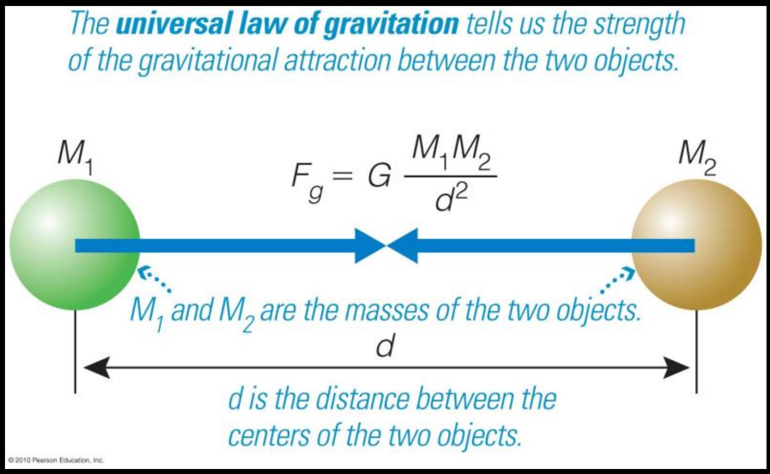


Earthbound satellites such as the Moon, for example, can accurately be described as "falling around the Earth"!

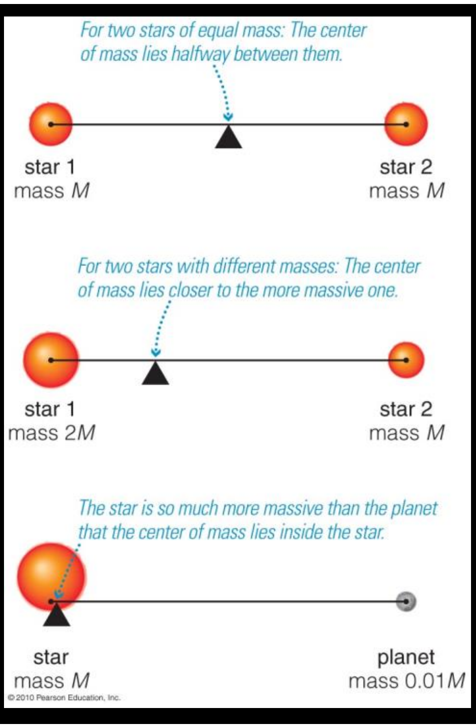
This constant state of "falling" is why an astronaut in the space shuttle (floater on the left) is effectively weightless – it is **NOT** because there isn't gravity in outer space! That falling motion is reproduced for astronauts in their training airplanes ("vomit comets" – floaters on the right), resulting in the same effect!

But unpack these ideas a bit more – what Newton's theory of gravity really did was no less than provide a physical, consistent, and mathematically precise explanation for both the movement of cannonballs and the Moon! Without ever touching or visiting the latter!

The very ***notion*** that from the Earth we could observe the Universe and develop physical explanations for incredibly remote events – in both time and space – was ***itself*** revolutionary, a "Newtonian Revolution" that opened up the whole universe to our exploration.



You began some of this exploration yourself in readings this week, reviewing Newton's "universal law of gravitation".

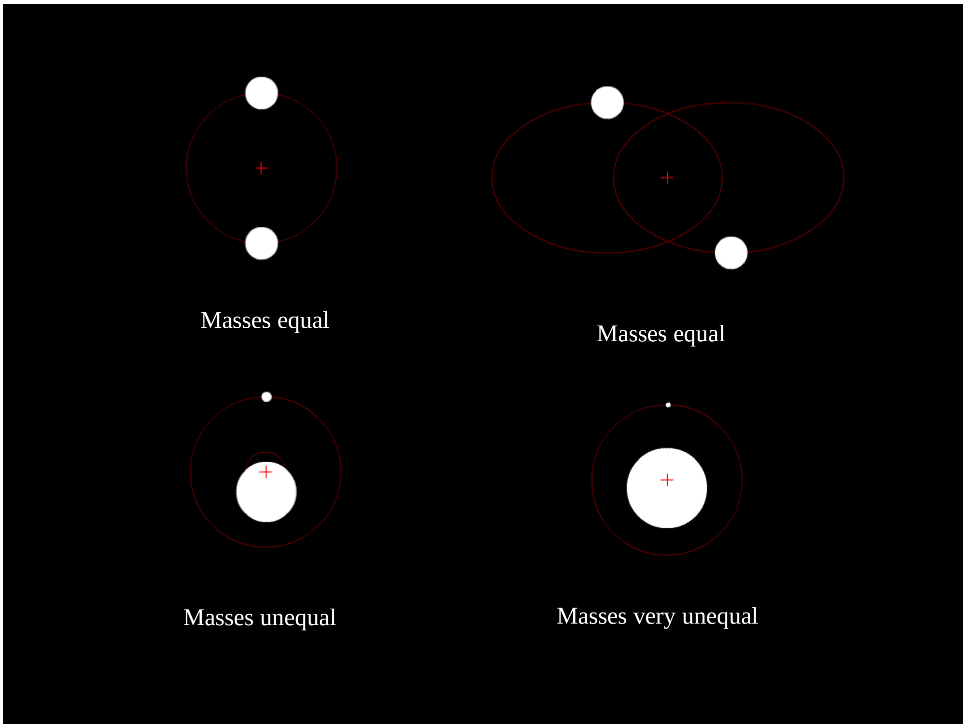


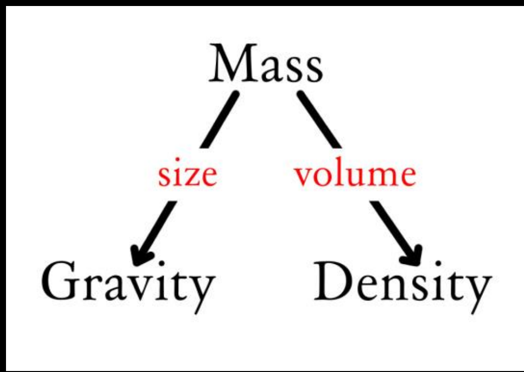
One of the many beautiful things about Newton's law of gravitation is it's simplicity – the force only depends on the distance between the centers of the objects, and their masses. And the motions induced by this force only depend on the ratio of the objects' masses, which determines the center-of-mass of the bodies.

One can even use this formulation of gravity to derive a general form of Kepler's 3rd Law – and to see why its more simple form works so well in the Solar System:

$$P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)} \right] a^3$$

Because the mass of the Sun is so much larger than that of any of the planets, the term in brackets is effectively a constant, so the approximation of Kepler is very good indeed!





Of course, mass is also important in many other physical ways. The mass of a large body is undoubtedly the most key characteristic in shaping its features, and the amount and precise composition of that mass determines a body's overall size – and the interplay of mass and size is reflected in the both the "***surface gravity***" and the total ***density*** of the object.

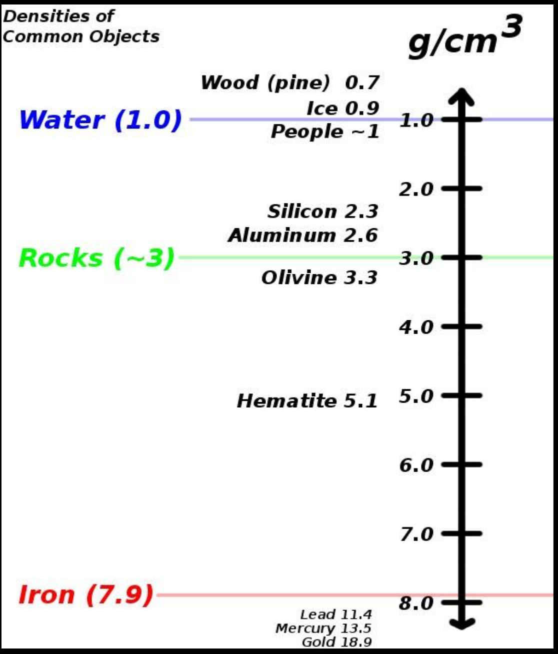
Density

$$\rho = \frac{Mass}{Volume}$$

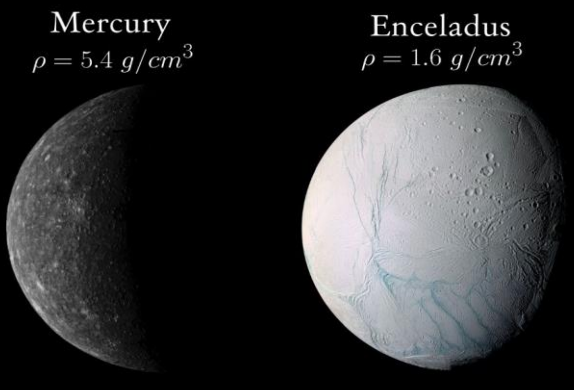
This latter value, generally expressed in units of g/cm^3, is largely independent of the total amount of material in a body, and can tell us a lot about the material that an object is made of.

Water, for example, has a density of ~ 1 g/cm^3, while rocks are generally closer to around 3 g/cm^3.

What's your density?



Here's a graphic showing the densities of some things you might be familiar with (and some you might not be!).

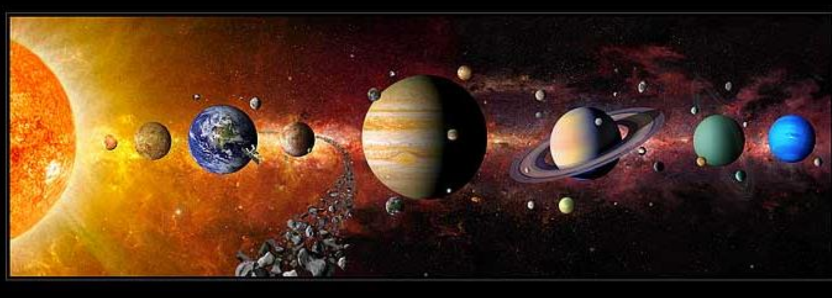


Now then – you already know that we can measure the mass and size of large bodies in the solar system (like Mercury and Enceladus, above) and therefore their densities. From these data, what do you think these objects are most likely made of?

And just like that, you have now personally participated in the Newtonian Revolution – you have, with only the information available to you here on Earth, been able to say something fundamental about the physics on a world you've never visited (and may have never even seen before today)!

BWAA HA HA HA HA!!!

Awesome? Yes! But for more, we'll need to actually visit some of these other worlds, and we'll begin that process next time by launching into a grand tour of the Solar System!



To accommodate this move we'll need to jump ahead to Chapters 7-11, skipping 5 and 6 for now – be sure to keep up carefully with the reading assignments online!

See you Tuesday!!