"My dear Kepler, what would you say of the learned here, who, replete with the pertinacity of the asp, have steadfastly refused to cast a glance through the telescope?

What shall we make of this? Shall we laugh, or shall we cry?"

--Letter from Galileo Galilei to Johannes Kepler
Before the invention of the telescope, the only information that astronomers could obtain about the stars and planets was their position in the sky.

This relied on instruments that typically measured its position in the sky with respect to the horizon at a particular time (azimuth and altitude), or its position with respect to the “fixed stars” (declination or right ascension).
Azimuth is an angle that describes the direction of an object in the sky as seen from the surface.

North is 0°
East is 90°
South is 180°
West is 270°
Altitude is an angle that describes the direction of an object in the sky from the horizon. Horizon is 0° and Zenith is 90°.
Declination

Declination (Dec) is the angle from the equator. This is analogous to Latitude on the Surface.

An object along the ecliptic has declination of $0^\circ$, above the North Pole $90^\circ$, and $-90^\circ$ above the South Pole.
Right Ascension

Right Ascension is the angle from the Vernal Equinox.

This is analogous to Longitude on the Surface.

The exception is that Right Ascension (RA) is given in hours rather than degrees.
The Astrolabe

Historians credit either Hipparchus or Hypatia of Alexandria around 200 - 300 BC.

Brass astrolabes were developed in the Islamic world from the 8th-10th centuries.

They were reintroduced into Europe in the 1100s.

A Persian Astrolabe (1700s)
http://en.wikipedia.org/wiki/Astrolabe
The Astrolabe

The astrolabe is made of 4 main parts:

1. The mater or base plate.
2. The rete or web-like plate that shows the ecliptic, and bright stars using a stereographic projection.
3. The plates, which are made for each latitude. Each plate has a stereographic projection of lines of equal azimuth and altitude.
4. The alidade or sight, which enables one to line the astrolabe up with an object and take measurements
Using the Astrolabe

With a star or planet sighted in the alidade, its position could be read off of the instrument.

http://www.physics.ncsu.edu/courses/astron/astrolabe.gif
Using the Astrolabe

http://www.hps.cam.ac.uk/starry/isaslabepoemsmed.jpg

The Biblical Astronomer, 1998, vol 8, no 85
A Simple Astrolabe

http://cse.ssl.berkeley.edu/AtHomeAstronomy/activity_07.html
http://cse.ssl.berkeley.edu/AtHomeAstronomy/activity_08.html
Time Line (1450 – 1750 AD)

- Leonardo da Vinci (1450–1519)
- William Shakespeare (1564–1616)
- Copernicus (1450–1543)
- Tycho Brahe (1546–1601)
- Galileo Galilei (1564–1642)
- Johannes Kepler (1571–1630)
- Christiaan Huygens (1629–1695)
- Issac Newton (1642–1727)
- Gian Domenico Cassini (1625–1712)
- Edmund Halley (1656–1742)
- Ben Franklin (1706–1790)

Historical Events:
- 1607 Virginia founded by the English
- 1608 Quebec founded by the French
- 1608 Invention of the Telescope
- 1612 New Amsterdam (New York) founded by the Dutch
Tycho Brahe (1546 – 1601)

Tycho Brahe was a Danish nobleman born in Skane Sweden in 1546. His twin brother died before being baptized, and Tycho wrote an ode to him which was his first publication in 1572.

Tycho’s aunt and uncle were childless, and his uncle stole him from his parents when he was two years old. Apparently, his parents never disputed the abduction.

In 1559, Tycho started at the University of Copenhagen to study Law, but became interested in Astronomy.
Tycho’s Nose

On the 10\textsuperscript{th} of December in 1566, while studying at the University of Rostock in Germany, he attended a party at a professor’s house.

The 20 year old Tycho got into a drunken argument with Manderup Parsbjerg. They parted angry with one another.

On December 27\textsuperscript{th}, their argument started again. This argument resulted in a duel with rapiers… in the dark. Tycho lost a portion of his nose.

For the rest of his life, Tycho wore a gold and silver nose, blended to look a flesh tone, which he kept on with glue.
“Tycho was said to own one percent of the entire wealth of Denmark at one point in the 1580s and he often held large social gatherings in his castle. He kept a dwarf named Jepp (who Tycho believed was clairvoyant) as a court jester who sat under the table during dinner.

Pierre Gassendi wrote that Tycho also had a tame Moose, and that his mentor the Landgraf Wilhelm of Hesse-Kassel asked about an animal faster than a deer. Tycho replied writing there were none, but he could send his tame Moose.

When Wilhelm replied he would accept one in exchange for a horse, Tycho replied with the sad news that the Moose just died on a visit to entertain a nobleman at Landskrona. Apparently during dinner the Moose had drunk a lot of beer, fell down the stairs, and died.”

http://en.wikipedia.org/wiki/Tycho_Brahe
Tycho became interested in astronomy during an eclipse. The fact that it had been predicted impressed him. After studying the subject, he wrote:

*I've studied all available charts of the planets and stars and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What's needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years.* — Tycho Brahe, 1563 (age 17).

He decided on it as a career when on November 11, 1572 he saw the appearance of a new star in the constellation of Cassiopeia. This is now known as Supernova SN 1572.

Tycho went on to take the most meticulous and detailed measurements of his time.
Tycho’s Observatory

Tycho constructed an observatory called Uraniborg where he conducted his detailed observations… without a telescope!

http://en.wikipedia.org/wiki/Tycho_Brahe
Tycho who still agreed with Aristotle did not wholly accept Copernicus' model of the universe.

Instead he had his own model.

http://en.wikipedia.org/wiki/Tycho_Brahe
Johannes Kepler (December 27, 1571 – November 15, 1630)

Johannes Kepler was born into a tumultuous time period in Weil der Stadt, Württemberg, in the Holy Roman Empire (which is now Germany).

His father was a mercenary, and left home when Johannes was five years old. It is believed that he died in the war in the Netherlands.

His mother was the daughter of an innkeeper. She was an herbalist (sold drugs) and did not get along well with her neighbors, which led to her being arrested for witchcraft. She was imprisoned and tortured for six years while Kepler worked for her release. He finally won it based on the fact that the torture she received was not entirely in accordance with the law.
Kepler wrote the first science fiction called the *Somnium* (Dream).

Kepler understands that the Earth’s atmosphere does not extend to the Moon, so he has the problem that he can not conceive of any way to fly to the Moon. Instead he uses a supernatural alternative…demons.

In the story an Icelandic boy Duracotus and his mother travel to the Moon with the help of the Daemon of Lavania who is an acquaintance of sorts of his mother. They travel the four hours which according to Kepler is "most difficult and fraught with the greatest danger to life."

Unfortunately, the story had much to do with arrest of Kepler’s mother as a witch. However, this is the first time anyone thought of the Moon as a place, rather than an object in the sky.
Johannes Kepler (December 27, 1571 – November 15, 1630)

Kepler was a deeply religious man, but he did not agree entirely with the Lutheran orthodoxy.

In particular, he could not agree with the interpretation of the Eucharist as he had trouble with the differentiation between spirit and body.

This may have affected his view of astronomy, since he did not agree with the idea that the Sun exerted a magical “force” at a distance on the Earth.

Kepler was excommunicated in 1612. He was deeply saddened by this.
Why Six Planets???

Kepler was convinced that the fact that there were six planets was somehow meaningful. He came to the idea that their orbits were defined by the five Platonic solids.

This idea was so beautiful that he could not let it go. He was able to arrange the solids so that the orbital distances of the planets were within 10% of the measured values at the time.

To have access to better data, he teamed up with Tycho Brahe.
Johannes Kepler visited Tycho for a year before Tycho’s death. Kepler was frustrated because Tycho had lots of data, but only gave him a little at a time.

Tycho’s data was instrumental in guiding Kepler to developing his laws of planetary motion.

“Tycho died on October 24, 1601, eleven days after suddenly becoming very ill during a banquet. For hundreds of years, the general belief was that he had strained his bladder. It had been said that to leave the banquet before it concluded would be the height of bad manners, and so he remained, and that his bladder, stretched to its limit, developed an infection which he later died of. This theory was supported by Kepler’s first-hand account.

Recent investigations have suggested that Tycho did not die from urinary problems but instead from mercury poisoning: extremely toxic levels of it have been found in his hair and hair-roots. Tycho may have poisoned himself by imbibing some medicine containing unintentional mercuric chloride impurities [3]. There is substantial circumstantial evidence that Tycho may have been murdered, possibly by Kepler, who had the means, motive, and opportunity, and who on Tycho's death took immediate possession of Tycho’s data that he had been seeking access to for years, in defiance of Tycho’s specific deathbed request that his data be left to his family. [4] The latter study also strongly contradicts the theory that Tycho could have poisoned himself, since he was very familiar with mercuric chloride's high toxicity compared to other forms of mercury.”

http://en.wikipedia.org/wiki/Tycho_Brahe
Kepler’s “War with Mars”

Kepler’s idea based on the Platonic Solids was wrong. The orbit of Mars gave Kepler the biggest trouble. From the data Tycho had acquired, it was obviously not a circular orbit.

After much trouble, and continuing after Tycho’s death, Kepler decided to try to describe the orbit of Mars as an ellipse with the Sun at one focus. IT WORKED!!!

He then verified that it also worked for the other planets!

“The actual process of calculation for Mars was immensely laborious - there are nearly a thousand surviving folio sheets of arithmetic - and Kepler himself refers to this work as 'my war with Mars', but the result was an orbit which agrees with modern results so exactly that the comparison has to make allowance for secular changes in the orbit since Kepler's time.”

http://www.gap-system.org/~history/Biographies/Kepler.html
Kepler’s First Law

The orbit of each planet is an ellipse, with the Sun at one focus.
Parts of an Ellipse

The orbit of each planet is an ellipse, with the Sun at one focus.
Eccentricity

The orbit of each planet is an ellipse, with the Sun at one focus.

The eccentricity $e$ describes how flattened the ellipse is.

For a circle $e = 0$

For an ellipse $0 < e < 1$
Apo and Peri

The orbit of each planet is an ellipse, with the Sun at one focus.

The point at closest approach is periapsis or pericenter.

The furthest point is called apoapsis or apicenter.

Related Terms:
- Perihelion
- Aphelion (helion = Sun)
- Perigee
- Apogee (geo = Earth)
Kepler’s Second Law

A line from the Sun to the planet sweeps out equal areas in equal times.

This is a consequence of the conservation of angular momentum.

Planets move faster near Perihelion and slower near Aphelion.
Kepler’s Third Law

The orbital period of the planet squared is proportional to the length of the semi-major axis cubed.

\[ P^2 \propto a^3 \]

Easiest to compute with periods in units of Earth years, and semi-major axis distance in Astronomical Units (AU).

1 AU = semi-major axis of Earth’s orbit.
Time Line (1450 – 1750 AD)

1450

Leonardo da Vinci

1500

William Shakespeare

1550

Johannes Kepler

1600

Galileo Galilei

1650

Christiaan Huygens

1700

Issac Newton

1750

Edmund Halley

Ben Franklin

1607 Virginia founded by the English
1608 Quebec founded by the French
1608 Invention of the Telescope
1612 New Amsterdam (New York) founded by the Dutch
Isaac Newton (4 January 1643 – 31 March 1727)

Nature and nature's laws lay hid in night; 
God said "Let Newton be" and all was light.

- Newton’s Epitaph
  Alexander Pope
  (English Poet)

Isaac Newton was an English physicist, mathematician, astronomer, natural philosopher, and alchemist.

In 1687 he published Philosophiae Naturalis Principia Mathematica, (The Mathematical Principles of Natural Philosophy) where he describes his three laws of motion, his theory of gravity and derives Kepler’s Laws.

This is the beginning of Classical Mechanics and the idea that we can describe the universe with a small set of basic principles.

Sir Isaac Newton in Godfrey Kneller’s 1689 portrait
Wikipedia
Newton’s Law of Gravitation

Masses attract one another with a force proportional to the product of their masses and the squared distance between their centers.

\[ F = G \frac{M_1 M_2}{R^2} \]

Where

\[ G = 6.67 \times 10^{-11} \text{ M m}^2 / \text{kg}^2 \]

mass is measured in kilograms
distance in meters
force in Newtons
1 Newton = 0.22 pounds
Circular Orbits

Using Newton’s Second Law, and his theory of gravity, you can predict that objects can orbit one another. More impressive, you can calculate their orbital speeds!

1. **Law of Gravitation**
   \[ F = G \frac{M m}{R^2} \]

2. **Second Law of Motion** along with the fact that centripetal acceleration is \( \frac{v^2}{R} \)
   \[ F = ma = \frac{mv^2}{R} \]

Result

\[ v = \sqrt{\frac{GM}{R}} \]
Acceleration of Gravity

Forces cause accelerations, so gravity accelerates objects

\[ F = ma \quad \Rightarrow \quad a = \frac{F}{m} \]

Using Newton’s Law of Gravitation to get the force…
(writing \( M_1 \) as \( M_p \), and \( M_2 \) as \( m \))

\[ a = G \frac{M_p}{R_p^2} = g_p \]

Where
- \( g_p \) is the gravitational acceleration of the planet (or moon)
- \( M_p \) is the mass of the planet (or moon)
- \( R_p \) is the radius of the planet (or moon)
- \( G = 6.67 \times 10^{-11} \text{ M m}^2 / \text{kg}^2 \)

mass is measured in kilograms
distance in meters
force in Newtons
1 Newton = 0.22 pounds
Weight

Weight is the force of gravity acting on your mass

\[ w = G \frac{M_p m}{R_p^2} \]

\[ w = mg_p \]

Where
- \( m \) is your mass
- \( M_p \) is the mass of the planet (or moon)
- \( R_p \) is the radius of the planet (or moon)
- \( G = 6.67 \times 10^{-11} \text{ M m}^2 / \text{kg}^2 \)

mass is measured in kilograms
distance in meters
force in Newtons
1 Newton = 0.22 pounds
Weightless

What we feel as weight is the normal force of the surface we are sitting or standing on pushing back on us.

In orbit, the force of gravity, which is our weight, keeps us from flying off into space. Gravity keeps us in orbit.

But because there is no normal force, we feel no weight. This is what we mean by being weightless.
Results Derivable from First Principles!

What is remarkable about all of this, is that a handful of mathematical relationships allow you to predict and understand a wide variety of phenomena.

This is the great success of science!

Newton was encouraged by Edmund Halley (who discovered that comets orbit the sun) to publish his findings. Philosophiae Naturalis Principia Mathematica (The Mathematical Principles of Natural Philosophy) Edmund Halley even paid the publication costs!
Escape Velocity

If you jump up by giving yourself some acceleration (which gives you a velocity) in the upward direction, you will go up a little ways, but gravity will pull you back down.

But it is not always true that “what goes up must come down”.

If you give yourself enough velocity, you will escape off to infinity. This is called the escape velocity.

\[ v_{\text{escape}} = \sqrt{2GM/R} \]

This is the speed that you need to be going to get away from an object (like a planet, moon, star, whatever…).