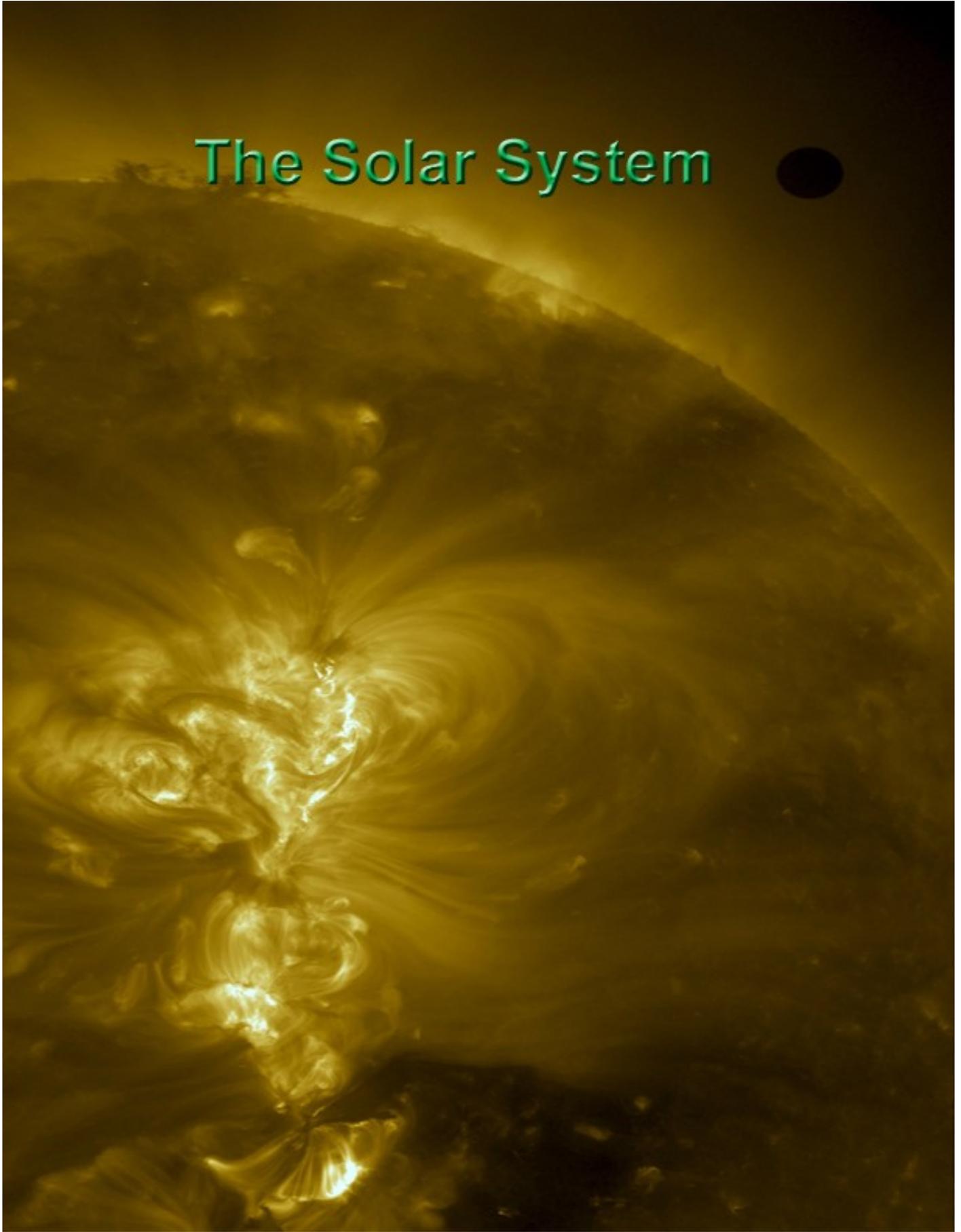


# The Solar System





## The Solar System

**{Abstract** – *In this segment of our video book, we cover distances inside our Solar System.*

*We start out with a brief history beginning with how Nicolas Copernicus used planetary retrograde motion to help move us from the Earth-centric view to the Sun-centric view of our Solar System. We work our way through the contributions made by: Tycho Brahe and his detailed observations made with mural quadrants and sextants; Kepler and his mathematics of elliptical orbits; and Galileo and his observations using the newly invented telescope. We conclude this history with Newton and his theory of gravity. Gravity gives us the first opportunity to explain the inverse square law that will play such a central role in celestial distant measurements as we move out to the stars.*

*We then explain planetary parallax as an extension to triangulation and use it to determine the distance to the Moon. We also illustrate all the additional information that becomes available once the distance is known, such as diameter, area and volume. Next, we take a look at the surface of Mars, the orbit of Mars and the Earth and the distance of Mars from the Sun, followed by distances of all the planets and Pluto from the Sun. We then focus on Jupiter to gain a feel for its size. We watch the comet Shoemaker Levy collide with Jupiter. We explain Lagrange Points and cover Jupiter's Trojan and Greek asteroids orbiting two of these points. This takes us to Earth's Trojan asteroid, 2010 TK7.*

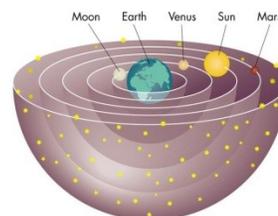
*Then, after covering the Kuiper Belt, we turn our attention to the Sun. We triangulate the Sun with Venus to calculate our distance from the Sun – one Astronomical Unit. With distance to the Sun known, we calculate its diameter, surface area and volume; the length of Earth's orbit; the Earth's velocity around the Sun; and with that, the Sun's mass. Next, we use Jupiter's moon Io to calculate the speed of light and with that we calculate how long it takes the Sun's light to reach the Earth.*

*We end by adding the parallax rung to our distance ladder.}*

### The ancient solar system

Look up at the night sky. See the stars move across the sky. The Moon and Sun do the same thing: They rise and set. It's not surprising that ancient peoples viewed the Earth as fixed and all celestial objects revolved around us.

The ancient Greeks such as Plato, Aristotle and culminating in Ptolemy constructed a cosmology with the earth surrounded by a number of celestial spheres that rotated around the Earth each day. There was a sphere for the moon, one for the sun, one for each planet, and one for all the fixed stars.



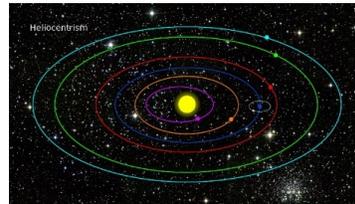


Planets were identified as different from stars because they changed their position over time, whereas the stars were seen to be eternally fixed in place.

*[Music: Simon Wilkinson's "Exodus": This is the soundtrack music for Randy Halverson's "Plains Milky Way" video. It is dramatic atmospheric orchestral music perfect for star gazing.]*

### Copernicus

This Earth centric model stood the test of time for over 15 hundred years! It wasn't until the 16<sup>th</sup> century that things started to change when Nicolas Copernicus proposed to put the Sun at the center of the solar system.

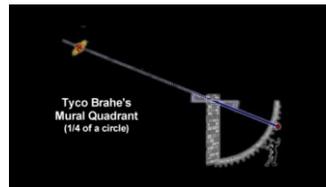


In so doing, he put the Earth into rotational motion about an axis [*to account for days*], and he put the Earth into revolutionary motion around the Sun [*to account for years*].

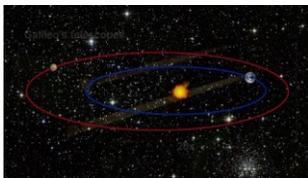
But putting the Earth into motion was hard to swallow for most people. Copernicus' ideas didn't really start to take hold until the early 17<sup>th</sup> century when considerable evidence for the Copernican model was compiled by the likes of Tycho Brahe, Johannes Kepler and Galileo Galilei.

### Tycho Brahe

Tycho Brahe, with mural quadrants, sextants and his naked eye, used parallax measurements to find distances to the planets. He focused on Mars and tabulated volumes of data on a daily bases.



### Kepler



Using this information, Kepler found that the orbits of the planets including the Earth were ellipses.

### Galileo

And Galileo, using the newly invented telescope, discovered:

- That the Milky Way cloud is actually stars,
- That the Sun has spots that indicate the Sun is rotating
- That Venus has phases just like the Moon, indicating that it goes around the Sun, and
- Jupiter has four moons!



Imagine how it must have felt, when Galileo first saw these moons. All the world believed that everything revolved around the earth, and here you are looking at moons that are orbiting Jupiter and not the Earth!



### Newton

But resistance to change is strong, and it wasn't until the 18<sup>th</sup> century that Newton turned the tide for good.

**[Music: Vangelis' "Conquest Of Paradise": Recorded in 1992, the lyrics to this march "in the night afoot - in the night found" fit our subject where planets and stars are only found at night. Our march is a conquest of ignorance.]**

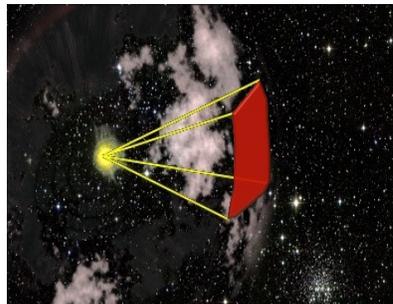
We're all familiar with his formula that Force = Mass times Acceleration.

<u>Newton's Equations</u>	
<u>Inertial Force</u> $F = ma$	<u>Centripetal Force</u> $F = mv^2/r$
Where: F = force m = mass a = acceleration	Where: F = centripetal force m = mass v = orbital velocity r = orbital radius

But for our distance ladder, it was Newton's better understanding of gravity that was the key. A good way to view gravity is to think of it as a gravitational field surrounding the object. The intrinsic strength of the field is set by the fixed mass of the object.

But as you can see in this illustration, when distance from the object increases, the surface area over which the field is spread increases as well. This effectively weakens the force of gravity felt at the more distant point.

We know by the geometry for a sphere that the area is proportional to the square of the radius. So the gravitational field strength is reduced by a factor of 4 every time the radius increases by a factor of 2.





We call this the “inverse square law”. We’ll see this law again when we discuss Standard Candles in our section on Stars.

### Gravity

#### Universal Gravitation

$$F = Gm_1m_2/d^2$$

Where:

F = force due to gravity

$m_1$  = the mass of object 1

$m_2$  = the mass of object 2

d = the distance between the two objects

G = the universal gravitational constant  
 =  $6.674 \times 10^{-11}$  Newtons(meters/kilogram)<sup>2</sup>

It’s interesting to note that the constant of proportionality (G), in Newton’s universal gravitation formula, was not known to Newton. It took another hundred years before physicist had instruments sensitive enough to measure this number. But once we had it, it become possible to measure the mass of the Earth at 6,600,000 trillion tons.



Newton broke Aristotle’s two thousand year old dictum that there are two sets of rules for nature: one set for here on Earth and another set for the havens. With Newton, we came to understand that there is only one set, and it applies everywhere.

### Parallax

In 1752, the French astronomers Lalande and La Caille used the parallax method to calculate the distance to the Moon. Here’s how it works:

- 1) Draw a line from a point on the earth to the moon directly overhead.
- 2) Extend this line to a distant star.
- 3) From a measured distance across the Earth [*3953 miles*], draw another line to the distant star, and another to the Moon.
- 4) Measure the angle between these two lines. In our case, it is one degree. This is the parallax.
- 5) Note that this line to the Moon crosses the two parallel lines drawn out to the distant star. From simple geometry, we know that the parallax angle theta is also the angle between the two lines at the Moon.
- 6) Now we have all the angles of the Earth Moon triangle and we know the length of one side. Simple trigonometry gives us the rest.
- 7) Our parallax calculation gives us 226,467 miles to the moon.



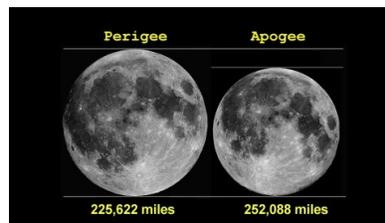
**Lunar Parallax**

$D = 3953$  miles  
 $\theta = 1^\circ$

fixed distant star

$d = D/\tan(\theta)$   
 $= 3953/\tan(1^\circ) = 3953 \times 0.017455$   
 $= 226,467$  miles

Of course, the moon travels in an elliptical orbit around the Earth, so its distance varies. Here's how different full Moons look between the closest and furthest points.



An interesting note on distance is that once you know the distance, there are a number of other things we can learn about an object. For example, given the distance  $R$  and the angular displacement of the object in the sky, we can calculate its size. Here we see the Moon's diameter is 2,174 miles. [That's about the distance between San Diego and Atlanta.]

**Moon Diameter**

$D =$  Moon diameter  
 $R =$  distance to the Moon = 226,467 miles  
 $\alpha =$  measured angle =  $0.55^\circ$

$D = 2R\tan(\alpha/2) = 2174$  miles



**[Additional info:** And, as we did with the Earth, we can calculate the surface area and volume of the moon:

- The surface area  $A$  is 4 times the radius squared times  $\pi$ 
  - $A = 4 \pi R^2 = 4 \pi (D/2)^2 = \pi D^2 = 4.12 \times 2174^2 = 15$  million sq. miles
- The volume  $V$  is 4/3 the radius cubed times  $\pi$ 
  - $V = (4/3) \pi R^3 = (4/3) \pi (D/2)^3 = (1/6) \pi 2174^3 = 5.4$  billion cubic miles]

***[Additional info:** Today high-precision measurements of the lunar distance are made by measuring the time taken for light to travel between stations on Earth and reflectors on the Moon. These confirm the numbers calculated by Parallax methods. This helps establish Parallax as a key rung on our 'distance ladder'.]*

### Mars

Here we are on the surface of Mars. Mars is the furthest planet from the Sun where a person can actually find dry land to stand on.



This is the photograph taken by Curiosity that's currently roaming around the surface of Mars digging into the surface looking for water and past signs of life.

It's April, 2013 about mid-day and the temperature is just about freezing. In a few hours, it will drop to 100 below, so I better go find some shelter.

Given that the orbits of Mars and the Earth are ellipse and their orbital velocities are different, the distance between the two can vary from 34 to 250 million miles. Back in 2003, the two planets reached a near minimum distance of 35 million miles. The last time that they were that close, was over 50,000 years ago.

Rather than list all the ranges of distances between the Earth and the various planets, a good way to report planetary distance is to



use an average distance from the Sun. For Mars, it's 142 million miles. Here are the distances to the other objects in our solar system.

**Mercury**, a hot cratered rock not much bigger than the moon is only 36 million miles from the sun.



**Venus**, with its sulfuric acid atmosphere and surface temperatures that can melt lead is 67 million miles from the sun.

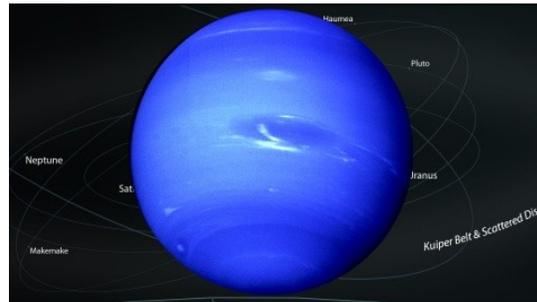
**Jupiter**, the largest planet by far is 483 million miles from the sun. We'll come back to Jupiter in a minute.

**Saturn**, with its beautiful rings is 886 million miles from the sun.

**Uranus**, with its extremely cold hydrogen and helium atmosphere is 1.78 billion miles from the sun.

**Neptune**, a veritable twin of Uranus, is the farthest planet from the sun at 2.79 billion miles.

**[Additional info:** Neptune was the first planet found by mathematical prediction rather than by empirical observation. In 1821, unexpected deviations from Newton's equations in the orbit of Uranus led Alexis Bouvard to deduce that its orbit was subject to gravitational perturbation by an unknown planet. In 1846, three years after Bouvard died, Neptune was discovered. I am most impressed when someone predicts the existence of a thing before it is discovered. ]



**Pluto**, as with other dwarf planets, is in the Kuiper Belt at 3.66 billion miles from the sun.

### Jupiter

Let's take a closer look at Jupiter. It is the giant solar system vacuum cleaner, eating up the Sun's early debris to become larger than all the rest of the planets combined. An example of this was the comet Shoemaker Levy's colliding with Jupiter in 1994.

The first impact occurred at 20:13 on July 16, 1994, when fragment A of the nucleus entered Jupiter's southern hemisphere at a speed of about 37 miles per second. Instruments



on the nearby Galileo spacecraft detected a fireball plume that reached a height of almost 2,000 miles. Remember that our atmosphere extends only a few hundred miles above us.

Observers soon saw a huge dark spot after the first impact - 3,700 miles across. Over the next 6 days, 21 distinct impacts were observed, with the largest coming on July 18. This impact created a giant dark spot over 7,500 miles across. The whole Earth could fit into the mark.

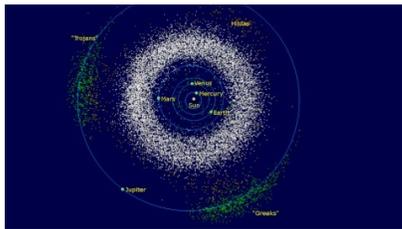
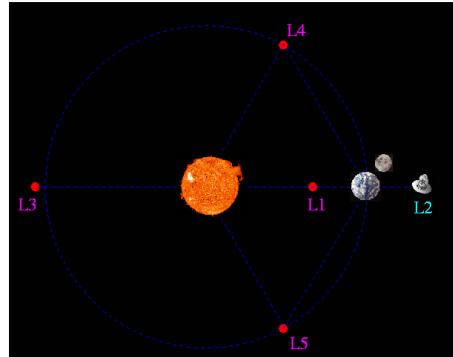


Jupiter absorbed them all. The changes to the planet were dramatic but disappeared after a few months.

## Lagrange Points

The Jupiter – Sun gravitational system sets up an interesting phenomena called Lagrange Points.

In 1772 French mathematician Louis Lagrange discovered 5 points around orbiting objects where gravitational and centripetal forces cancel themselves out. L1, L2 and L3 are unstable, but L4 and L5 are stable and Lagrange claimed that small objects could orbit these Lagrange points. 134 years later, between 1906 and 1908, four such minor planets were found around Jupiter's L4 and L5 Lagrange points:



Take a look at the asteroid belt and you can see the smarms of asteroids in the L4 and L5 points for Jupiter. Such objects have also been observed in the orbits of Mars, Neptune and several moons of Saturn. In L4, these are called Trojan asteroids. In L5, they're called Greeks.

## Earth's Trojan

In 2010, we discovered a Trojan asteroid orbiting Earth's L4 point, 60 degrees ahead of Earth called 2010TK7. Here we see an animation of 2010 TK7's orbit. The clock at the upper left shows how the orbit changes over time. Over the next 10 thousand years, it will not approach Earth any closer than 12.4 million miles – that's 50 times further away than the Moon.

Our Space program takes advantage of these points when we position satellites to observe the Sun. We'll cover this a bit more in our section on the Heliosphere.

We'll also see Lagrange points in our discussion of binary star systems because they play a key role in their evolution into Super Novae, a key rung in our distance ladder for distant stars and galaxies.

***[Additional info:** Hundreds of thousands of asteroids are currently known, and the total number ranges in the millions or more, depending on how small you go. It is interesting to note that because the volume of space between Mars and Jupiter is so large, the asteroid belt is mostly empty. The high population of the asteroid belt makes for a very active environment,*



*where collisions between asteroids occur frequently (on astronomical time scales). Collisions between main-belt bodies are expected to occur about once every 10 million years.]*

### Kuiper Belt

The **Kuiper belt** is a region of the Solar System beyond the planets extending from the orbit of Neptune to 5.1 billion miles from the sun. It is similar to the asteroid belt, although it is far larger—20 times as wide and 20 to 200 times as massive.

**[Additional info: Comets** - *Until the middle of the 16<sup>th</sup> century, Comets were thought to be luminous vapors in the earth's atmosphere. Many held that they were poisonous vapors and bad omens. But in 1577, Tyco Brahe studied a bright comet and found that he could not see any parallax. This showed that it was far further away from earth than the moon. This took it out of the earth's atmosphere and started people thinking differently about comets.*

*But it wasn't until much later that their real nature was determined. In 1705 Edmund Halley studied recorded paths for the comets of 1531, 1607, and 1682. He proposed that they were all re-appearances of the same comet and that it would be back again in 1758. It was. This was a spectacular vindication of his bold conjecture and of Newton's gravitational theory. For his success, the comet was named after him – Halley's Comet. I saw it in 1986. Its orbit goes out past Pluto, so it won't be back again until 2061.]*

### The Sun

The Sun is the final object we'll cover. It defines the entire Solar System. But figuring out how far away it is difficult. This is because we cannot see any nearby stars for parallax measurements. The Sun is just too bright.

**[Music: Dmitry Lifshitz:** *This is the music used for NASA SDO's Ultra-HD view of the 2012 Venus transit across the Sun. It's an appropriate piece for our section on the Sun.]*

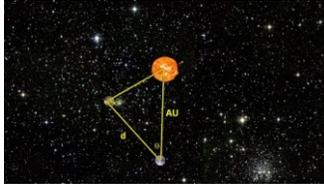
But total eclipses and the passage for Venus across the face of the Sun as viewed from Earth have enabled excellent measurements. Here is a method that uses parallax to find the distance to Venus that in turn enables us to triangulate the distance to the Sun.

Let's look at the motion of Venus in the sky relative to the Earth: as Venus orbits the Sun, it gets further away from the Sun in the sky, reaches a maximum separation from the Sun (corresponding to the greatest elongation) and then starts going towards the Sun again.



Now, by making observations of Venus in the sky, one can determine the point of greatest elongation. At this point, the distance between the Earth and Venus can be determined via Parallax (64.6 million miles). Also at this point, the line joining Earth and Venus will be tangential

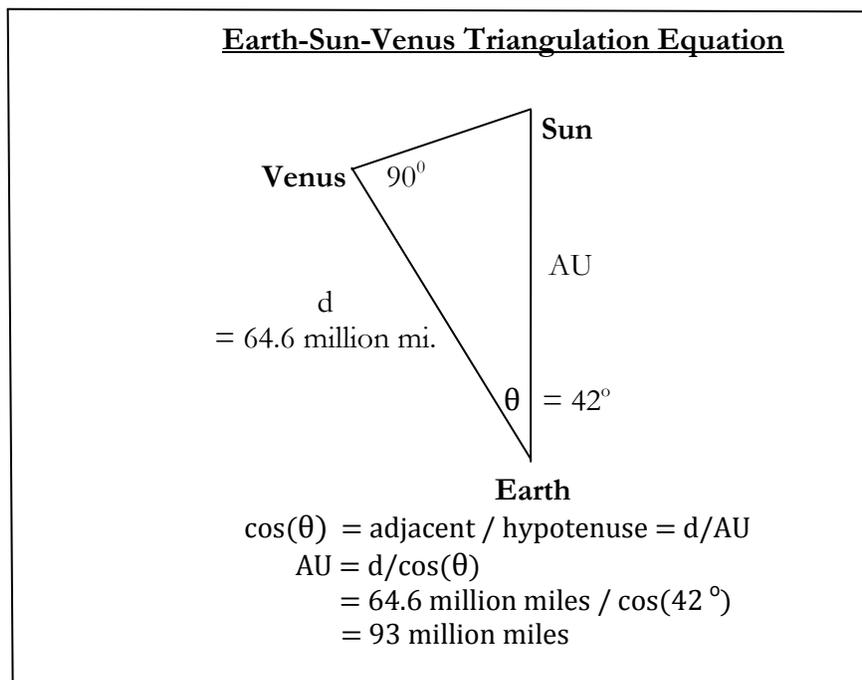
to the orbit of Venus. Therefore, a line from Venus to the Sun at this



point of greatest elongation is 90 degrees from the line between the Earth and Venus.

Drawing the line between the Earth and the Sun fills out the triangle. We call the length of this line that represents the distance between the Earth and the Sun an Astronomical Unit or AU for short.

The angle at the Earth is easily measured (46 degrees). Now, using trigonometry, one can determine the distance  $AU = 93$  million miles.



**[Additional info:** *Parallax measurements of the distance to Venus have been verified by radar measurements, where a radio wave is transmitted from Earth bounces off Venus and comes back to Earth. By measuring the time taken for the pulse to come back, the distance can be calculated as radio waves travel at the speed of light.*]

Once the distance between the Earth and Sun is known, one can calculate a number of other parameters. We know that the Sun subtends an angle of just over  $\frac{1}{2}$  degree. As we did with the Moon, we can calculate the diameter of the Sun at 860,000 miles; the surface area at 2.3 trillion square miles; and the volume 330,000 trillion cubic miles.



**Sun Diameter**

D = Sun diameter  
 R = distance to the Sun = 93,000,000 miles  
 $\alpha$  = measured angle =  $0.53^\circ$

$D = 2R \tan(\alpha/2) = 860,279$  miles  
 Radius =  $R = D/2 = 430,000$  miles  
 Area =  $A = 4 \pi R^2 = 2.3 \times 10^{12}$  mi.<sup>2</sup>  
 Volume =  $V = 4/3 \pi R^3 = 330,000 \times 10^{12}$  mi.<sup>3</sup>

The Earth's orbit is very close to circular. So, with the Earth's orbital radius around the Sun being 93 million miles, the distance traveled in a year is the circumference of the circle. That's 584 million miles.

$$[C = 2\pi R = 6.28 \times 93 \text{ million miles} = 584 \text{ million miles}]$$

Dividing by the time 1 year, we get the velocity of the Earth around the Sun = 66,700 miles per hour.

$$[v = \text{distance/time} = 584 \text{ million miles} / ((24 \text{ hours/day}) \times (365 \text{ days/year})) = 66,700 \text{ mi/hr}]$$

Now, with the distance to the Sun and our velocity around the Sun known, we can use Newton's equations, to calculate the mass of the Sun at 2.2 billion trillion tons! In fact, the Sun is 99.98% of the mass of the entire solar system.

**Mass of the Sun**

Let:  $v$  = the velocity of the Earth around the Sun = 66,700 mi/hr  
 $R$  = distance to the Sun = 93,000,000 miles  
 $G$  = the Gravitational constant =  $1.88 \times 10^{-10}$   
 $M_s$  = mass of the Sun

We have:  $M_s = v^2 R / G = 2.2 \times 10^{27}$  tons

So, as vast as the planet earth is, over a million Earths can fit into the Sun!



## Speed of Light

So, how long does it take light from this magnificent Sun to reach the Earth?

Until early in the 18<sup>th</sup> century, it was generally believed that the speed of light was infinite. This view was held by Aristotle in ancient Greece, and vigorously argued by the French philosopher Descartes and agreed to by almost all the major thinkers over the two thousand years that separated them.

Galileo was an exception. But when he tried to measure the speed of light, he failed. Light was either too fast or possibly infinite.

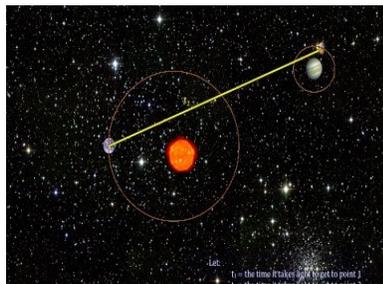
But Galileo did set the stage for the first measurement. After he discovered the first 4 moons of Jupiter, he suggested that the eclipse of the moon Io would make a good celestial clock that navigators could use to help determine their location.



In 1676, the Danish astronomer Ole Roemer was compiling extensive observations of the orbit of Jupiter's moon Io to see if Galileo was correct.

The satellite is eclipsed by Jupiter once every orbit, as seen from the Earth. Timing these eclipses over many years, Roemer noticed something peculiar. The time interval between successive eclipses became steadily shorter as the Earth in its orbit moved toward Jupiter and became steadily longer as the

Earth moved away from Jupiter.



In a brilliant insight, he realized that the time difference must be due to the finite speed of light. That is, light from the Jupiter system has to travel farther to reach the Earth when the two planets are on opposite sides of the Sun than when they are closer together.

Using what he knew about planetary orbits from Kepler, he estimated that light required twenty-two minutes to cross the diameter of the Earth's orbit. The speed of light could then be found by dividing the diameter of the Earth's orbit by the time difference.

The actual math was done by others after Roemer's death in the early 1700s. Those who did the first arithmetic, found a value for the speed of light to be 141,000 miles per second. Not too bad for the instruments of the 18<sup>th</sup> century. The modern value is 186,000 miles per second as determined by bouncing laser light off the Moon.



**Speed of light**

$t_2 - t_1 = 22 \text{ minutes} = 1320 \text{ seconds}$   
 $d = 186 \text{ million miles}$

Speed of light =  $c = d / (t_2 - t_1)$   
 $= 186 \text{ million miles} / 1320 \text{ seconds}$   
 $= 140,909 \text{ miles/sec}$   
 Modern value = 186,000 miles/sec

So, to answer our question about how long it takes light from the Sun to reach the Earth, we simply divide the 93 million miles to the Sun by 186,000 miles per second to get 8.3 minutes.

**Distance Ladder**

In this segment, we built the second rung of our Distance Ladder – parallax. We can now use the diameter of the orbit of the Earth around the Sun as our Baseline, 186 million miles. Combined with direct measurement and geometry from the first rung, we are set to measure distance to the stars! But first, we'll close out our chapter on the Solar System by taking a look at the Heliosphere.

