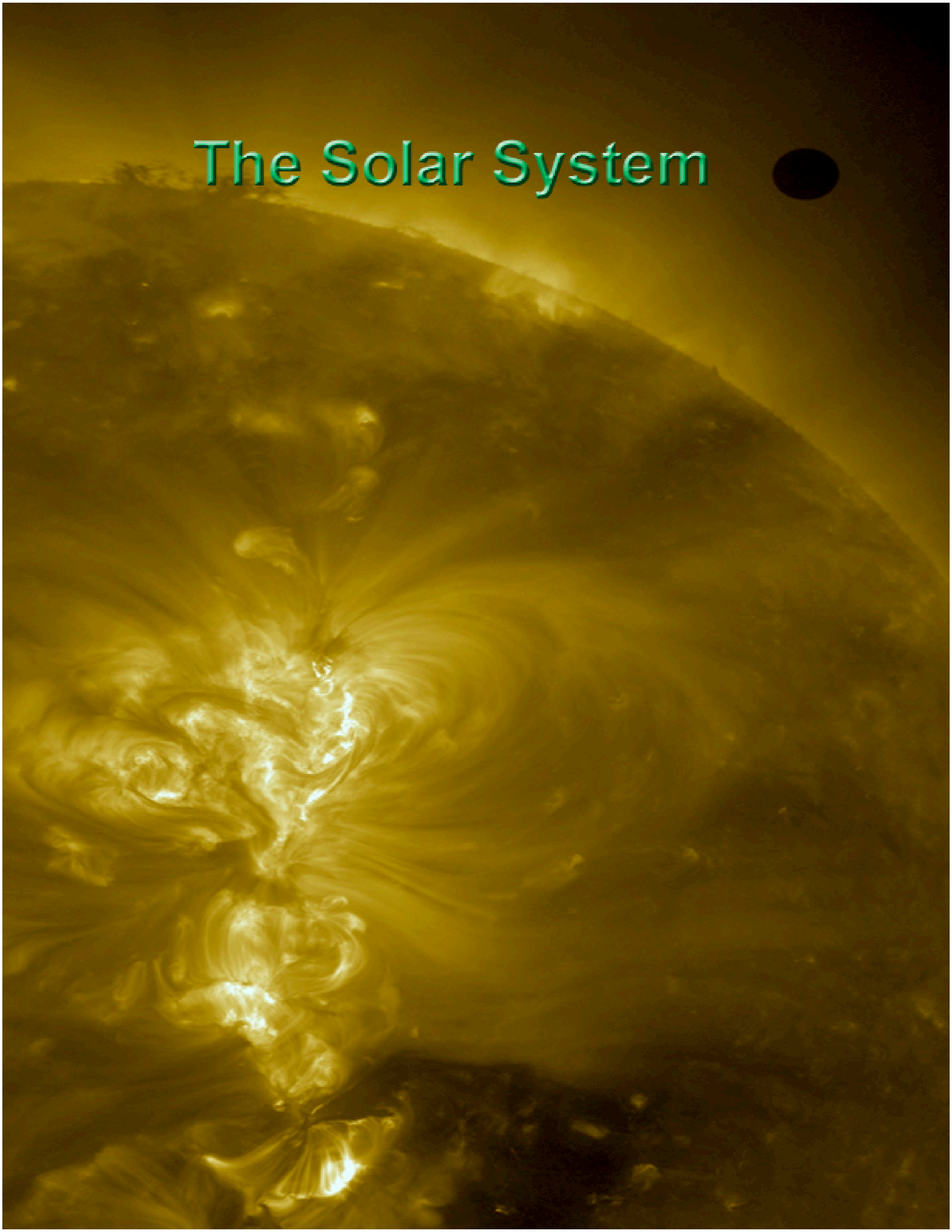

The Solar System

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 with 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 orbit of Mars and the Earth and the distance of Mars from the Sun, followed by distances of all the planets and dwarf planets from the Sun. During this segment we cover the major moons around each planet. We then focus on the Asteroid Belt. We explain Lagrange Points and cover Jupiter's Trojan asteroids orbiting two of these points. This takes us to Earth's Trojan asteroid, 2010 TK7.

We then 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.

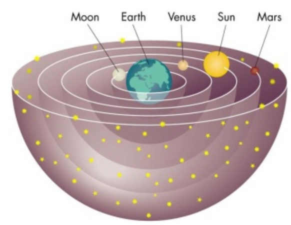
We end by adding the parallax rung to our distance ladder.}

> **[Music @*00:00* -** *Rachmaninov, Sergei: Rhapsody on a Theme of Paganini – Variation 18; Cecile Ousset (Piano), City of Birmingham Symphony Orchestra / Sir Simon Rattle, 1984; from the album "The most relaxing classical album in the world…ever!"***]**

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.

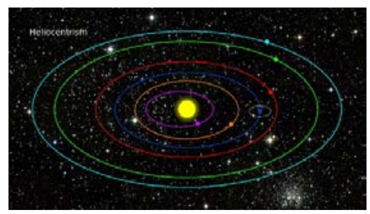
The ancient Greeks such as Plato, Aristotle and culminating in Ptolemy constructed a cosmology with the earth surrounded by a number of celestial spheres that rotated around the Earth each day. There was a sphere for the moon, one for the sun, one for each planet, and one for all the fixed stars.



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.

Copernicus

This Earth centric model stood the test of time for over 15 hundred years! It wasn't until the 16th century that things started to change when Nicolas Copernicus proposed to put the Sun at the center of the solar system. [Others in other cultures had figured this out as well.]

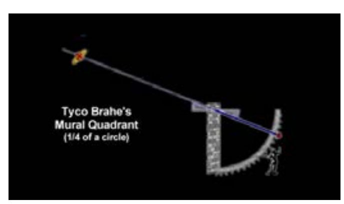


In so doing, he put the Earth into rotational motion about an axis **[***to account for days***]**, and he put the Earth into revolutional motion around the Sun **[***to account for years***]**.

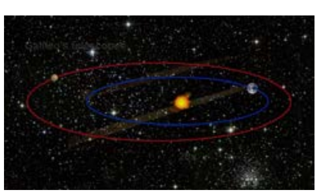
But putting the Earth into motion was hard to swallow for most people. Copernicus' ideas didn't really start to take hold until the early 17th century when considerable evidence for the Copernican model was compiled by the likes of Tycho Brahe, Johannes Kepler and Galileo Galilei.

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!

*[**Music @03:01** - Bizet, Georges: Entracte to Act III from "Carman"; Orchestre National de France / Seiji Ozawa, 1984; from the album "The most relaxing classical album in the world…ever!"]*

Newton

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

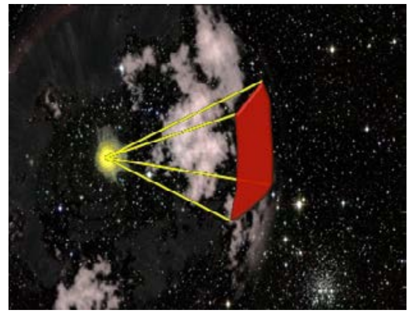
We're all familiar with his formula that Force = Mass times Acceleration.

Newton's Equations

Inertial Force	**Centripetal Force**
$F = ma$	$F = mv^2/r$
Where:	Where:
F = force	F = centripetal force
m = mass	m = mass
a = acceleration	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.

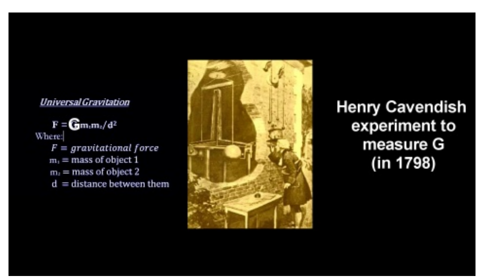
Universal Gravitation

$F = Gm_1m_2/d^2$

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)^2

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.

[Music @*05:13* - *Satie, Erik: Gymnopedie No. 1; City of Birmingham Symphony Orchestra – Louis Fremaux, 1974; from the album "The most relaxing classical album in the world…ever!"***]**

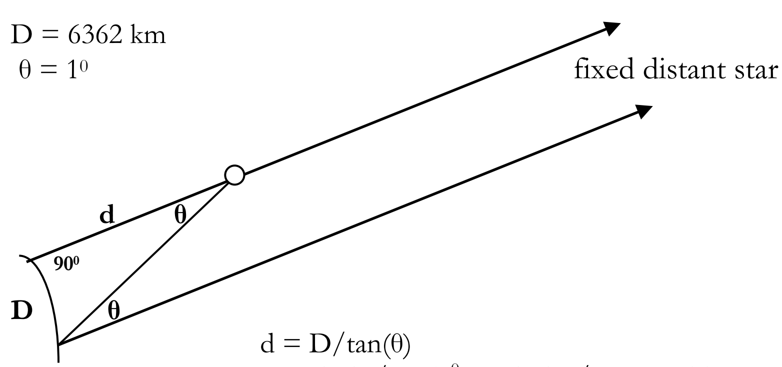
<u>Parallax</u>

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 **[**6362 km = *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 364,480 km to the moon. With just over 1.6 km in a mile, that comes to 226,477 miles.

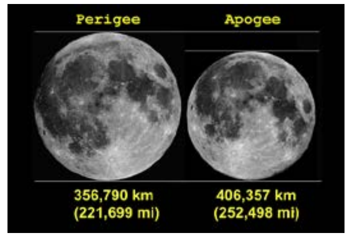
<u>Lunar Parallax</u>

D = 6362 km
$\theta = 1^0$



$$d = D/\tan(\theta) = 6362/\tan(1^0) = 6362 / 0.017455 = 364480 \text{ km} = 226467 \text{ mi}$$

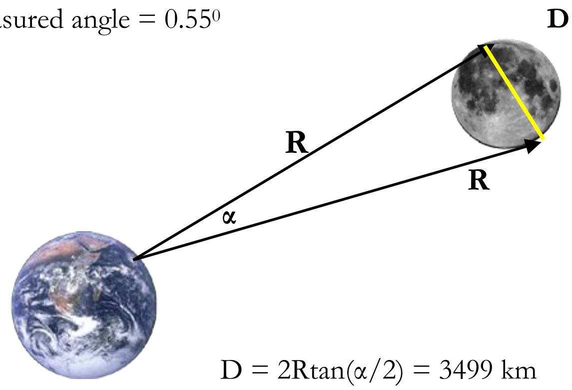
Of course, the moon travels in an elliptical orbit around the Earth, so its distance varies. Here's how different full Moons look between the closest and furthest points.



It's important to note that, once you know the distance, there are a number of other things we can learn about an object. For example, given the distance and the angular displacement of the object in the sky, we can calculate its size. Here we see the Moon's diameter is almost 35 hundred km. That's 2,174 miles. **[**That's about the distance between San Diego and Atlanta.**]**

<u>Moon Diameter</u>

D = Moon diameter
R = distance to the Moon = 364,480 km
α = measured angle = 0.55^0

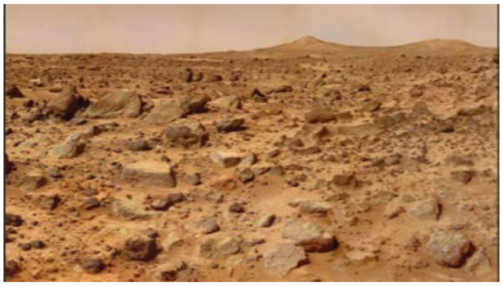


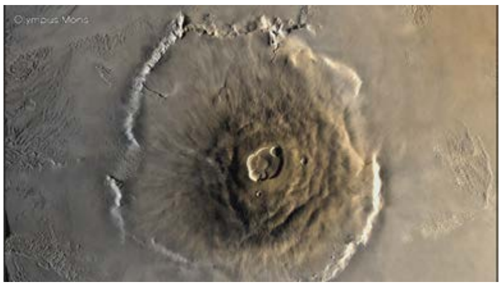
$D = 2R\tan(\alpha/2) = 3499$ km

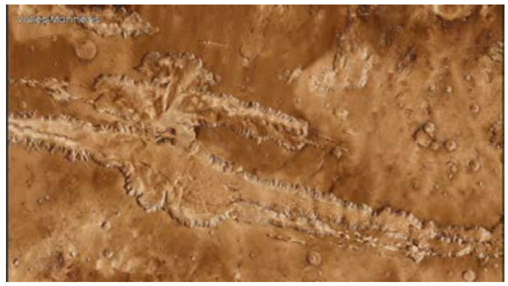
*[**Additional info:** Today high-precision measurements of the lunar distance are made by measuring the time taken for light to travel between stations on Earth and reflectors on the Moon. These confirm the numbers calculated by Parallax methods. This helps establish Parallax as a key rung on our 'distance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

<u>Distance to Mars</u>

Mars is our second closest neighbor next to Venus, and our space craft and landers have explored it in great detail. Iron oxide in the dirt and rocks gives the planet a reddish color. It's tilted like the Earth giving it seasons. Olimpus Mons, its biggest mountain, is 3 times higher than Mt. Everest, and Valles Marineris, its giant gorge, is 3 times longer than the Grand Canyon.

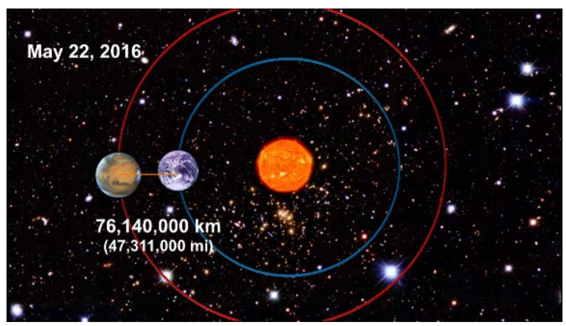




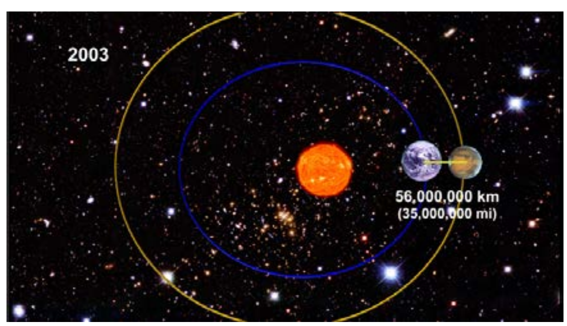


On May 12, 2016, the Hubble Space Telescope captured this image.

The observation was made just a few days before Mars opposition on May 22, when the sun and Mars were on exact opposite sides of the Earth. This phenomenon is a result of the difference in orbital periods between Earth's and Mars' orbit. While Earth takes 365 days to travel once around the sun, Mars takes 687. As a result, Earth makes almost two full orbits in the time it takes Mars to make just one, resulting in a Martian opposition about every 26 months.



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 55 to 402 million km (That's 34 to 250 million miles.) Back in 2003, the two planets reached a near minimum distance of 56 million km (35 million miles). The last time that they were that close, was over 50,000 years ago.



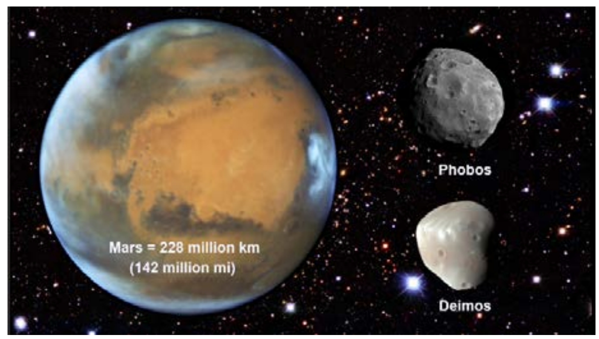
[Music @09:37 - Vangelis: Conquest of Paradise from the album "1492 - Conquest of Paradise", 1992]

Planets and Moons

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. An Astronomical Unit (AU for short) is the average distance from the Earth to the Sun. That's 150 million km or 93 million miles. We'll cover a way to measure AU in our segment on the Sun.

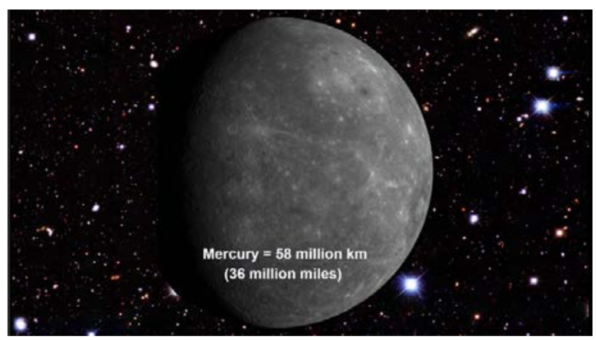
Mars is 1 and a half AU or 228 million km. (That's 142 million miles.)

Mars has two small moons: Phobos and Deimos. The moons appear to have surface materials similar to many asteroids in the outer asteroid belt which we'll cover shortly. This leads most scientists to believe that both moons are captured asteroids.

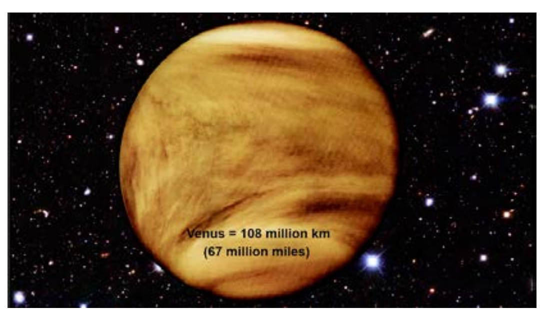


Here are the distances to the other planets in our solar system.

Mercury, a hot cratered rock not much bigger than the moon, is only 58 million km from the sun. (That's 36 million miles.) Its daytime surface temperature is 430 degrees Celsius (that's 800 degrees Fahrenheit). That's hot enough to melt lead. Mercury has no moons.



Venus, with its sulfuric acid atmosphere, is 108 million km from the sun. (That's 67 million miles). It's around 80% of the size of the Earth and as hot as Mercury. This ultraviolet view of the planet's clouds was taken by the Pioneer Venus Probe in 1979. The probe found that, like Mercury, there are no moons.



Jupiter, the largest planet by far, is 778 million km from the sun. (That's 483 million miles.) Its mass is 317 times greater than the Earth. 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.

Scientists think Jupiter has at least 69 moons. The most interesting are the four discovered by Galileo – Ganymede, Callisto, Io and Europa. Ganymede is the largest moon in the solar system, and is the only moon known to have its own internally generated magnetic field.

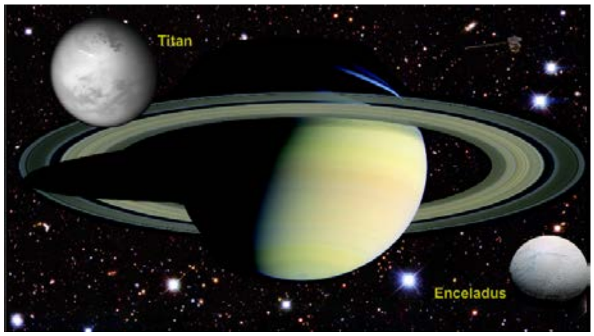
Callisto's surface is extremely heavily cratered and ancient -- a visible record of events from the early history of the solar system.

Io is the most volcanically active body in the solar system. As Io travels in its orbit, Jupiter's immense gravity causes "huge tides" in the solid surface like our moon effects the oceans. This generates the heat for volcanic activity.

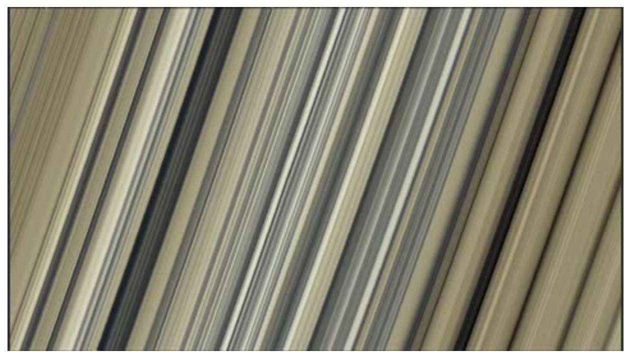
Europa's surface is mostly water ice, and there is evidence that it may be covering an ocean of water. It is thought to have twice as much water as we have here on Earth. This water, along with subterranean volcanoes may have created a zone where life can form.

Saturn, with its beautiful rings, is 1.4 billion km from the sun. (That's 886 million miles.) Its mass is 95 times greater than the Earth. The Cassini probe has been taking pictures of the planet, its rings and moons for 13 years.

Saturn has at least 62 moons and every one of them have been probed by the Cassini spacecraft over the last 13 year. Here are two of them. Titan is the largest. It is the only moon in the solar system known to have a significant atmosphere. Enceladus has more than 100 water geysers at its south pole from a subsurface ocean that may be friendly to life.



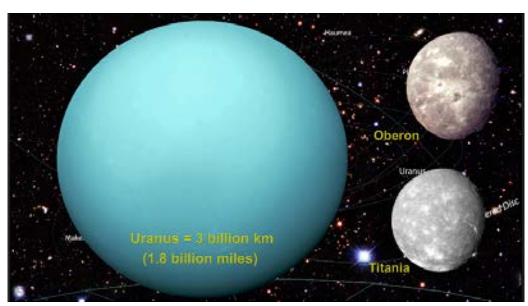
Saturn's rings are absolutely beautiful. There are billions of ring particles in the entire ring system ranging in size from tiny, dust-sized icy grains to a few particles as large as mountains. It's about one kilometer (3,200 feet) thick, and they range out to 282,000 km (175,000 miles) from the center of the planet. That's about three quarters of the distance between the Earth and the Moon. This Cassini image, shows a portion of the inner-central part of the planet's B Ring.



[Two tiny moons orbit in gaps Encke and Keeler in the rings and keep the gaps open. The origin of the rings of Saturn have puzzled astronomers since Galileo Galilei discovered them with his telescope in 1610. One guess is that they are pieces of comets, asteroids or a shattered moon that broke up before they reached the planet.]

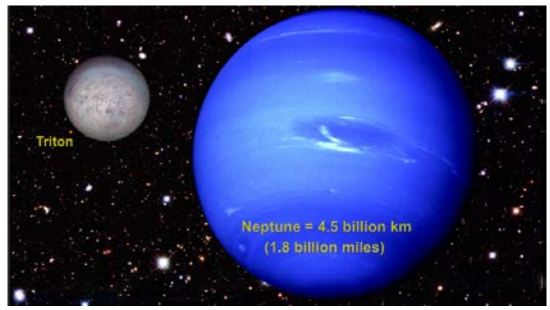
Cassini ended its mission on September 17th, 2017 with a plunge into Saturn's atmosphere.

Uranus, with its extremely cold hydrogen and helium atmosphere, is 3 billion km from the sun. (That's 1.8 billion miles.) Its mass is 14 times greater than the Earth. Uranus has 27 known moons. The largest are Oberon and Titania. They were photographed by Voyager 2, the only spacecraft to visit Uranus.



Neptune, a twin of Uranus, is the farthest planet form the sun at 4.5 billion km (that's 2.8 billion miles.) Its mass is 17 times greater than the Earth. It takes 164 years to revolve around the sun. Neptune has 13 moons that we know of. Triton is the largest. It has ice volcanoes that spout what is thought to be a mixture of liquid nitrogen, methane and dust, which instantly freezes and then snows back down to the surface.

[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. **]**



***[Music @16:39** - Elgar, Edward: Nimrod from 'Enigma' Variations Op. 36; London Symphony Orchestra / Sir Adrian Boult, 1986 - from the album "The most relaxing classical album in the world…ever!"]*

Dwarf Planets

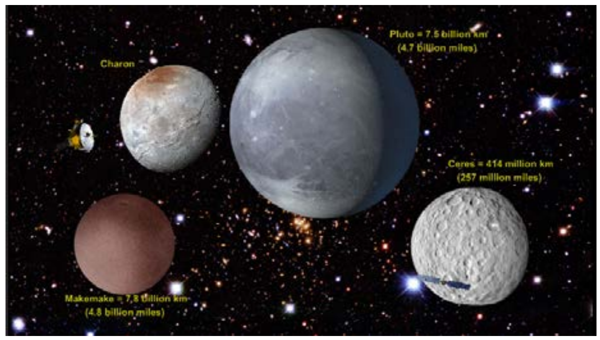
In addition to the eight main plants in our solar system, there are a number of large bodies too small to clear the debris in their orbit. These are called minor or dwarf planets. We know of five, but there could be dozens more. Here are three of them.

Pluto, with its methane ice surface, is out in the Kuiper Belt at 7.5 billion km (that's 4.7 billion miles) from the sun. At that distance, it takes almost 250 years for one revolution. Pluto is 450 times smaller than the Earth. It was reclassified as a dwarf planet in 2006 when other objects its size were discovered.

Charon is the largest of Pluto's five moons. With an unexpectedly interesting surface, it is half the size of Pluto. This photograph was taken by the New Horizons spacecraft in 2015.

Ceres, the only dwarf planet in the asteroid belt, is 414 million km (that's 257 million miles) from the Sun. It was discovered in 1801 and classified as an asteroid. Once the Dawn spacecraft entered orbit around Ceres in 2015, and its true size was understood, it was reclassified as a dwarf planet. Its diameter is approximately 945 kilometers (or 587 miles) making it around 14 times smaller than Pluto.

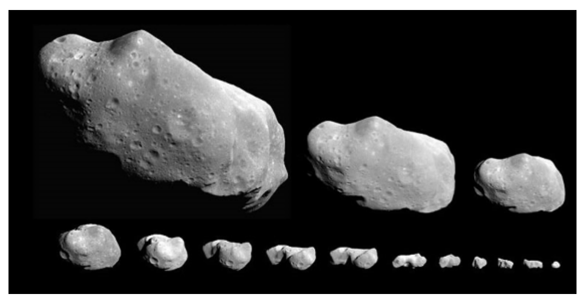
Makemake was discovered in 2005, by a team at the Palomar Observatory. It is in the Kuiper Belt at 7.8 billion km (that's 4.8 billion miles) from the Sun. It is thought that Makemake's reddish-brown color comes from a layer of methane at its surface.



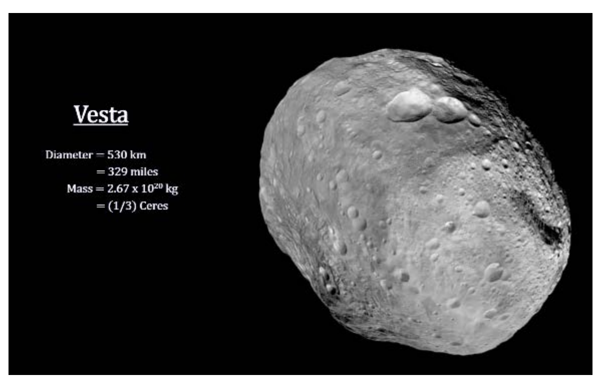
[Music @18:44 - Massenet, Jules: Meditation from 'Thais'; Hans Kalafusz (violin), Stuttgart Radio Symphony Orchestra / Sir Neville Marriner, 1987 EMI Electrola GmbH - from the album "The most relaxing classical album in the world…ever!"]

Asteroids

Asteroids are relatively small rocky worlds that revolve in elliptical orbits around the sun. There are billions of them in the Solar System, ranging in size from a few meters across to the size of dwarf planets.



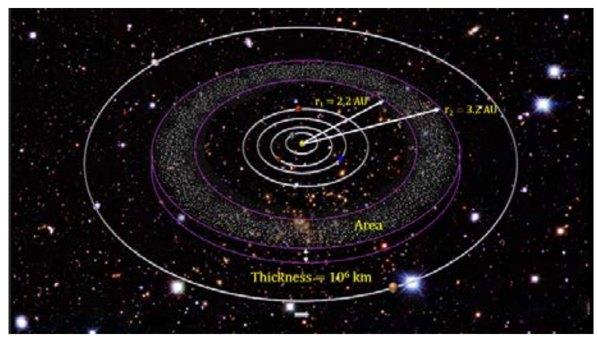
[Vesta is the brightest asteroid and the second largest behind dwarf planet Ceres. It's 250 million km (that's 156 million miles) from the sun.]



Asteroids have stayed mostly unchanged for billions of years, so research into them could reveal a great deal about the early solar system. To that end, a probe called OSIRIS-Rex launched in September 2016 will travel to a near-Earth asteroid called Bennu and bring a small sample back to Earth for study. If all goes as planned, the spacecraft will reach Bennu in 2018 and return a sample to Earth in 2023.

Asteroid Belt

Most asteroids lie in a vast ring between the orbits of Mars and Jupiter called the Asteroid Belt. It ranges from 2.2 astronomical units to 3.2 astronomical units from the Sun and is around a million km thick. It's estimated to contain around 30 billion asteroids larger than 100 meters across. But the entire mass of the asteroid belt comes to little more than 4 percent of the mass of our moon with Ceres accounting for almost half of it.



With as many as 30 billon asteroids in the belt larger than 100 meters in diameter, it is interesting to calculate the average volume of space each one has around it. Although the density varies, we can get an average by dividing the asteroid belt volume by the number of asteroids. We get 12.7 trillion cubic km of space for each asteroid. That's 3 trillion cubic miles.

Volume per Asteroid

$V_a = V/N = AT/N$

Where

V = volume of belt

V_a = volume per asteroid

T = thickness of belt

$= 10^6$ km

A = area of belt

$= \pi (r_2)^2 - \pi (r_1)^2$

N = number of asteroids 100 m in diameter

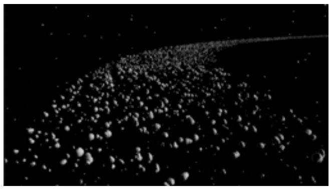
= 30 billion

We have

$V_a = (38 \times 10^{22}\ \text{km}^3) / 3 \times 10^{10}$

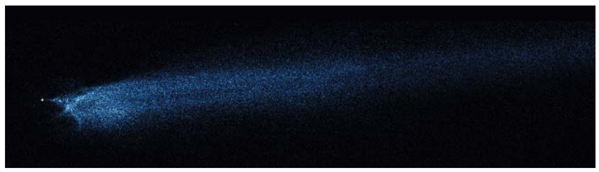
= 12.7 trillion cubic km per asteroid

= 3 trillion cubic miles



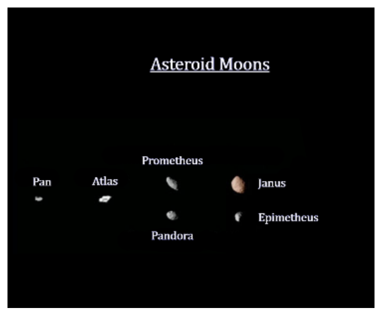
If we went there, it would look quite empty. [Pictures like these are quite misleading.]

So navigating through the belt would be easy, and collisions would be rare. [But they do happen. Here's one photographed recently by Hubble.



]

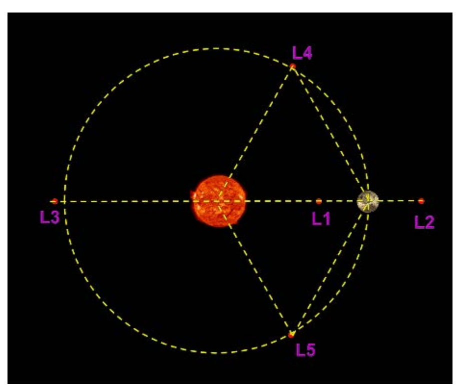
But we do know that lots of asteroid exist outside of the Asteroid Belt. For example, the outer moons of the giant gas planets are all thought to be captured asteroids as are Demos and Phobos the moons of Mars. And asteroids also orbit gravitational points known as Lagrange points.

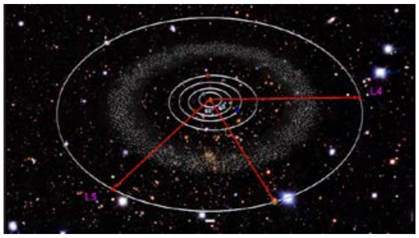


Lagrange Points

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 on the line connecting the two bodies. They are unstable. That means it take a small amount of work to maintain an orbit at or around these points.

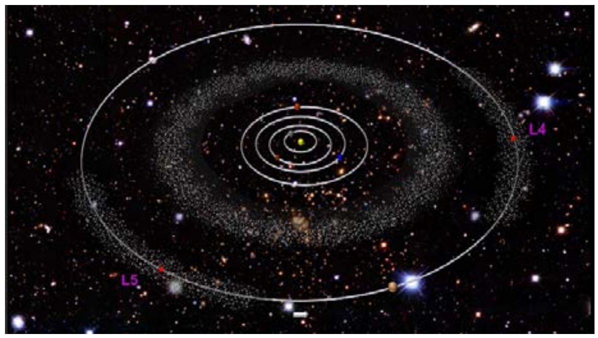
L4 and L5 are on the orbital path of the smaller body. They are found by using equilateral triangles. They are stable and Lagrange claimed that small objects could orbit these Lagrange points.





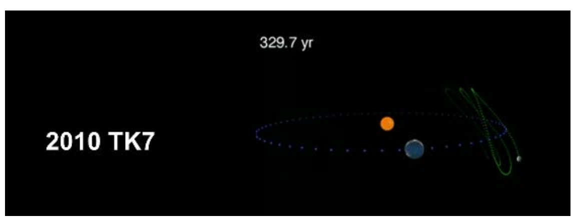
134 years later, between 1906 and 1908, four asteroids were found around Jupiter's L4 and L5 Lagrange points. Asteroids at Lagrange points are called Trojans.

As of May 2017, we know Jupiter has at least 6,515 Trojans. Such objects have also been observed in the orbits of Mars, Neptune and several moons of Saturn.



Earth's Trojan Asteroid

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 shows how the orbit changes over time. Over the next 10 thousand years, it will not approach Earth any closer than 20 million km – that's 50 times further away than the Moon.

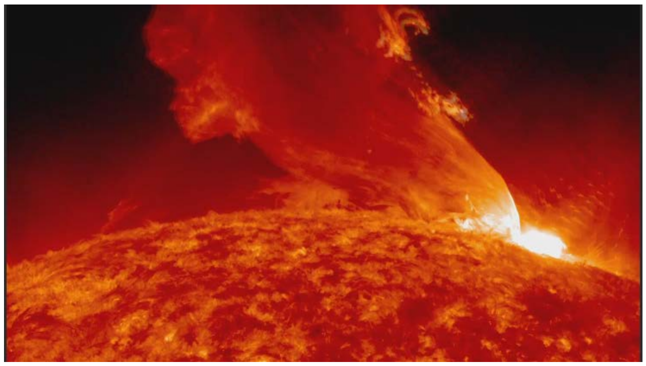


Our Space program takes advantage of these points when we position satellites to observe the Sun. Here we see that L2, where the James Webb Space Telescope will orbit, is 4 times further away from us than the Moon. We'll cover this a bit more in our section on the Heliosphere.

*[**Music @23:26** - Pachelbel, Johann: Cannon in D; Academy of St. Martin in the Fields – Sir Neville Marriner, 1974; from the album "The most relaxing classical album in the world…ever!"]*

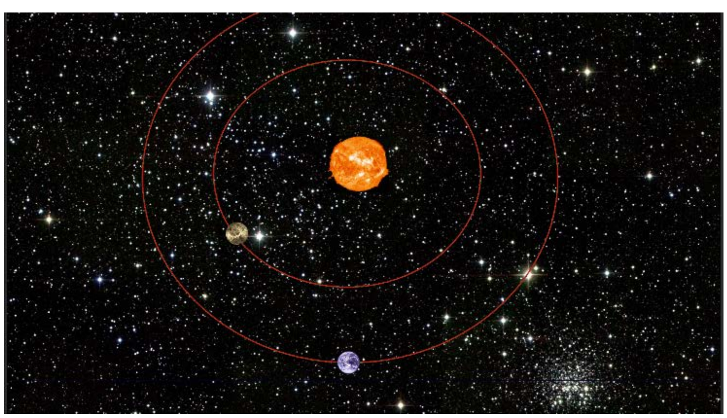
The Sun

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

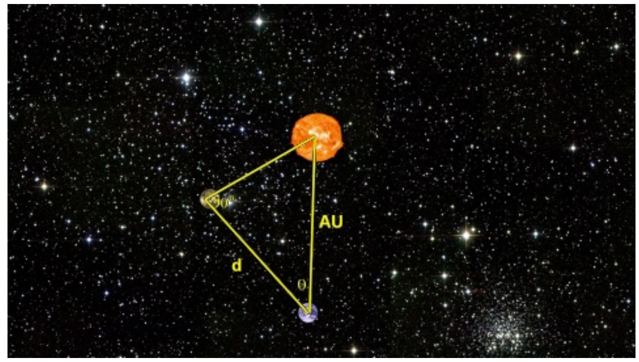


But total eclipses and the passage for Venus across the face of the Sun as viewed from Earth have enabled excellent measurements. Here is a method that uses parallax to find the distance to Venus that in turn enables us to triangulate the distance to the Sun.

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.

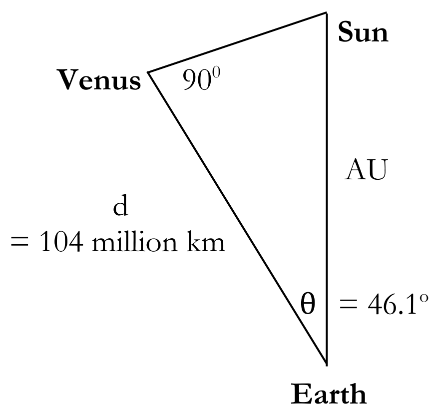


By making observations of Venus in the sky, one can determine the point of greatest elongation. At this point, the distance between the Earth and Venus can be determined via Parallax 104 million km or 64.6 million miles. Also at this point, the line joining Earth and Venus will be tangential to the orbit 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.



The angle at the Earth is easily measured (46.1 degrees). Now, using trigonometry, one can determine the distance AU = 150 million km or 93 million miles.

Earth-Sun-Venus Triangulation Equation



$$\cos(\theta) = \text{adjacent / hypotenuse} = d/AU$$

$$AU = d/\cos(\theta)$$

$$= 104 \text{ million km} / \cos(46.1^o)$$

$$= 150 \text{ million km}$$

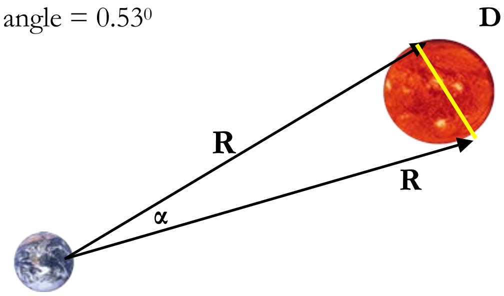
$$= 93 \text{ million miles}$$

[**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 ½ degree. As we did with the Moon, we can calculate the diameter of the Sun at 1.4 million km or 860,000 miles; the surface area at 6.16 trillion square km or 2.3 trillion square miles; and the volume at or 1,440,000 trillion cubic km or 330,000 trillion cubic miles.

<u>Sun Diameter</u>

D = Sun diameter
R = distance to the Sun = 150,000,000 km
α = measured angle = 0.53^0



$$D = 2R\tan(\alpha/2) = 1.4 \text{ million km}$$
$$\text{Radius} = R = D/2 = 700{,}000 \text{ km}$$
$$\text{Area} = A = 4\,\pi\,R^2 = 6.16 \times 10^{12}\ \text{km}^2$$
$$\text{Volume} = V = 4/3\,\pi\,R^3 = 1{,}440{,}000 \times 10^{12}\ \text{km}^3$$

The Earth's orbit is very close to circular. So, with the Earth's orbital radius around the Sun being 150 million km, the distance traveled in a year is the circumference of the circle. That's 942 million km or 584 million miles.

[$C = 2\pi R = 6.28 \times 150$ million km = 942 million km or 584 million miles**]**

Dividing by the number of hours in a year, we get the velocity of the Earth around the Sun = 107,500 km/hr or 66,700 miles per hour.

[v = distance/time = 942 million km / ((24 hours/day)x(365 days/year)) = 107,500 km/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 thousand trillion 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 = 107,500 km/hr
R = distance to the Sun = 150,000,000 km
G = the Gravitational constant = $6.67 \times 10^{-11} m^2 s^{-2} kg^{-1}$
M_s = mass of the Sun

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

So, as vast as our planet is, over a million Earths can fit inside the Sun!

Speed of Light

[Music: Pachelbel - Canon in D**]**

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

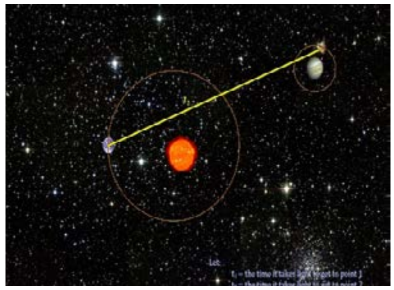
Until early in the 18th century, it was generally believed that the speed of light was infinite. This view was held by Aristotle in ancient Greece, and vigorously argued by the French philosopher Descartes and agreed to by almost all the major thinkers over the two thousand years that separated them.

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.



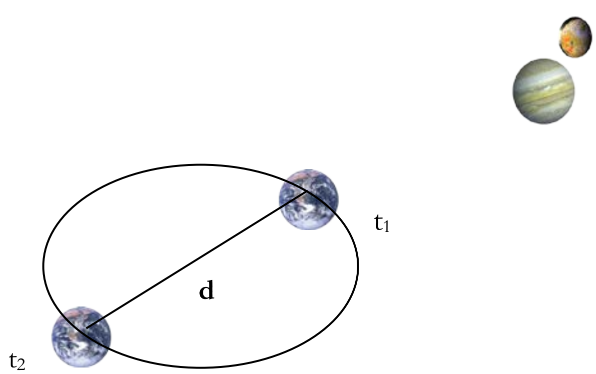
In a brilliant insight, he realized that the time difference must be due to the finite speed of light. That is, light from the Jupiter system has to travel farther to reach the Earth when the two planets are on opposite sides of the Sun than when they are closer together.

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 227,000 km per second or 141,000 miles per second. Not too bad for the instruments of the 18th century. The modern value is 300,000 km per second or 186,000 miles per second as determined by bouncing lazar light off the Moon.

Speed of light

$t_2 - t_1$ = 22 minutes = 1320 seconds
d = 300 million km



Speed of light = c = d/(t_2-t_1)
= 300 million km / 1320 seconds
= 227,000 km/s
= 141,000 miles/s
Modern value = 300,000 km/s
= 186,000 miles/s

So, to answer our question about how long it takes light from the Sun to reach the Earth, we simply divide the 150 million km to the Sun by 300,000 km per second to get 500 seconds = 8.3 minutes.

[You can find the first actual measurement of the speed of light in 1849 by the French physicist Fizeau in the "How fast is it" video book segment on "The speed of light".]

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, 300 million km (that's 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, Kuiper Belt, Ort Cloud and Comets.