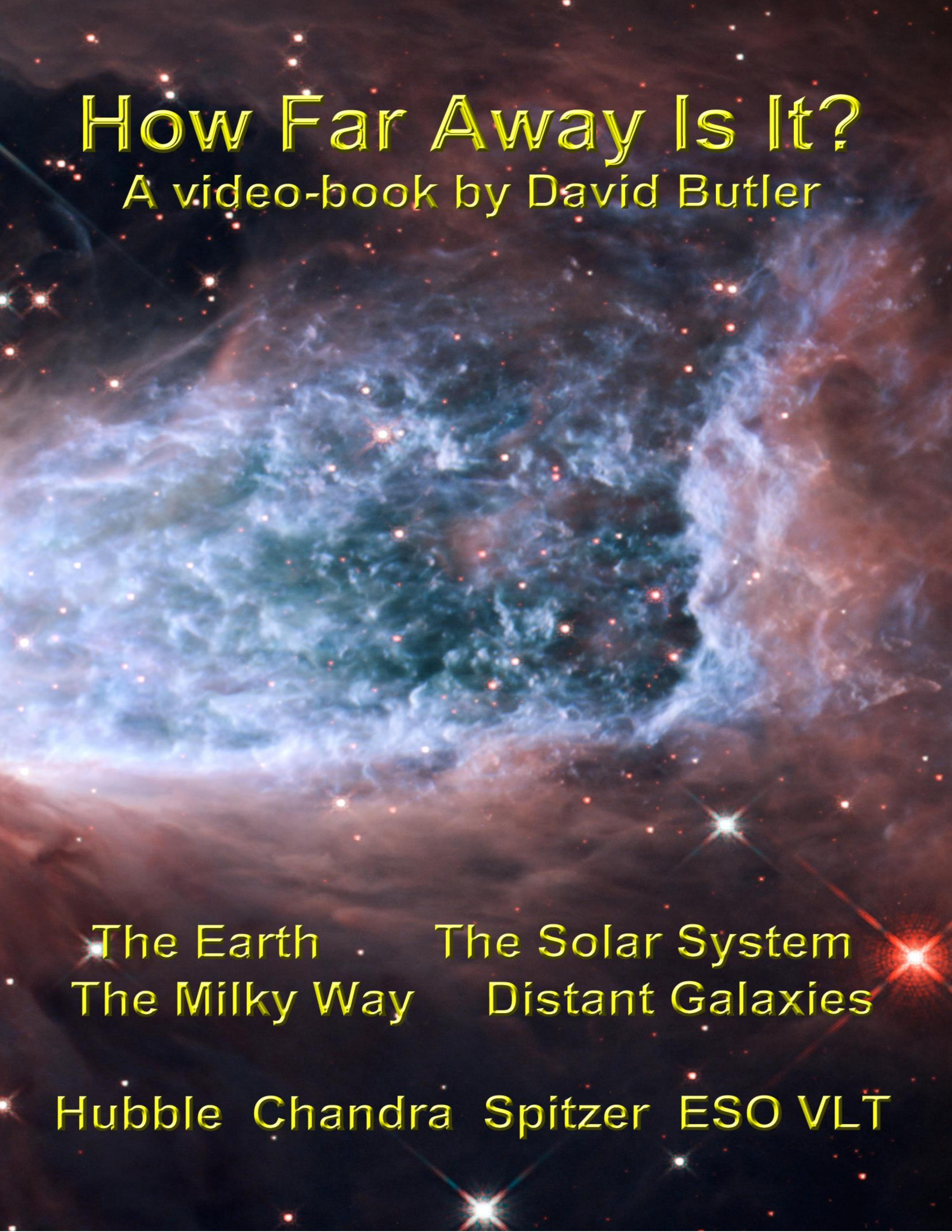


How Far Away Is It?

A video-book by David Butler

The Earth
The Solar System
The Milky Way
Distant Galaxies

Hubble Chandra Spitzer ESO VLT

How Far Away Is It

This is the companion hard copy for the "How Far Away Is It" video book that is available on YouTube. This book contains the full text for each of the 17 "How Far Away Is It" video segments. It also includes notes on additional information and on the musical selections associated with each segment. The vast majority of the celestial object photographs and associated text come from the Hubble Space Telescope website. A full list of sources is included in the Credits segment.

http://howfarawayisit.com

Dedication:

This work is dedicated to my two sons Michael and Sean, and to my current and future grandchildren, Shannon, Tristan, Ashleigh, Caitlyn and possibly others. I trust my sons will bring this video book to their children's attention when they are old enough to understand.

Acknowledgements:

Thanks to my wife Elizabeth Butler for her patience and reviews. I also want to thank Jon Terrell, a science teacher at Mission Hills High School in San Marcos, California. He helped me make it right for high school science students. And I am indebted to Jonathan Onstead for his outstanding editing skills. He pitched in on every single segment in this video book. Thank you Jonathan.

Table of Contents

Preface

Introduction

Hello, my name is David Butler, and I created this video book. I'd like to tell you a little bit about the book and a little bit about myself.

About me

I've recently retired after a 40-year career in computer software development, where I helped build operating systems, parallel operating systems, and massively parallel database systems that represent a foundation for today's social media and the internet.

It's been a very satisfying career. But my education was math and physics culminating in a masters degree from Oxford University studying the mathematical foundations of Quantum Mechanics out of the Math Institute attached to St. Catherine's College. So I've always been very interested in science, physics, astronomy, cosmology.

But I never had a lot of time to pay attention to it during my career. But now I have the time. And I did some research to try and come up to speed on what we've learned in the 40 years I was in the computer business. I was amazed by how much we've learned.

About the Video Book

And I was particularly taken by the photographs and the knowledge accumulated by the Hubble Space Telescope over the last 20 years. And not just Hubble – Chandra, Spitzer, the large array ground-based radars.

So I made this video book to bring the people I care about up to date on what we know about the Cosmos and how far away things are; how big the earth is; how high the atmosphere goes; the Moon; how far away are the planets; the Sun; and how do we know how far away these things are. The entire Solar System; and then a chapter on the Milky Way where we'll cover Cepheid stars; the local group; planetary nebula; supernova; the black hole at the center. Then, in the final chapter, we'll go into all the other galaxies, including a section on colliding galaxies where we'll see galaxies as far back as almost the beginning of the Big Bang.

But this isn't a repeat of what Carl Sagan or Brian Cox have done with their wonderful work with "Cosmos" series and "Wonders of the Universe". I'm taking a slice of physics and astronomy, and just talking about distances and how we know how far away things are.

At the End

We'll come back at the end when we go over the credits and I'll show you where I got this information, and where you might go to find more information if you've got a mind to dig deeper into any of these subjects.

I hope you enjoy it. I trust you'll find it informative. Thank you.

> **[Music:** *Johann Sebastian Bach's - Air 'on the G String'. The original orchestral suite was written by Bach for his patron Prince Leopold of Anhalt some time between the years 1717 and 1723. The title comes from violinist August Wilhelmj's late 19th century arrangement of the piece for violin and piano. Wilhelm was able to play the piece on only one string of his violin, the G string.***]**

The Earth

{Abstract *– In this first segment of our video book, we introduce the most basic distance measurement techniques, and illustrate their use in my back yard. These include direct measurement and triangulation. We introduce minutes and seconds of arch in a degree, and describe a theodolite. We then triangulate the Grand Canyon, Mt. Everest and more. We then introduce lightning as an example where some basic scientific understand about observed phenomena is needed to help determine how far away it is. We discuss what lightning and thunder are, and the speed of sound in air to calculate how far away a lightning strike is. Next, we cover "going there" as a technique for determining distance, using our atmosphere as the prime example. From balloons to the space station, we cover the troposphere, stratosphere, mesosphere and thermosphere. Then, we illustrate how geometry can play a key role in determining distance as we cover in detail how Eratosthenes actually calculated the size of the Earth in 200 B.C. We use how many students could fit inside the Earth to highlight just how vast the Earth really is. We conclude our coverage of the Earth with a look at distances to a number of cities using pictures and video taken by the international space station at night. We start close to home and move out to the most distant cities – much like we'll be moving from neighboring celestial objects out the furthest reaches of space in subsequent video book chapters. We then introduce the distance ladder and show how we have just built the foundational rungs in the ladder. We end with a preview of the coming distant ladder rungs and the video book segments organized around them.}*

Introduction

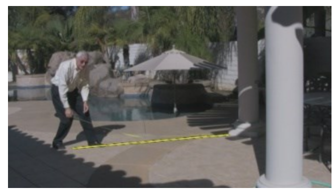
The Earth: It's big, really big. In this section we'll cover how we came to just know how big the earth really is. In so doing, we'll build the first rungs in the distance ladder that will take us across our galaxy. We'll begin our journey to the edges of the visible very close to home.

[Music @00:00 -** Bach, Johann Sebastian: Zion hort die Wachter singen from Cantata No. 140 ('Sleepers Wake!") South German Madrigal Choir, Consortium Musicum / Wolfgang Gonnenwein 1967 EMI Electrola GmbH; from the album "The most relaxing classical album in the world…ever!"**]

Direct Measurement

Here I am in my backyard. This is where we will begin building the ladder that will take us to the stars.

There's a post. If you want to know how far away it is, the simplest thing to do is to measure the distance with something like a tape measure. If we take a look at this one, it's 2 meters (6.56 feet) away.



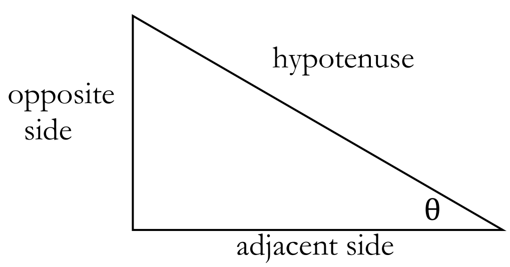
[Note: accuracy of instruments is key**]**

Triangulation

But what do you do if you want to measure something that you can't reach with a tape measure, like the rock on the other side of the water. For that, we do something called triangulation.

Take a point. Measure an angle of 90 degrees. Step off a known amount, say 3 meters (10 feet). Measure the angle from the second spot – 50 degrees. Triangulation gives us the distance – 3.6 meters - to that rock from that first spot.

Rock Triangulation Equation



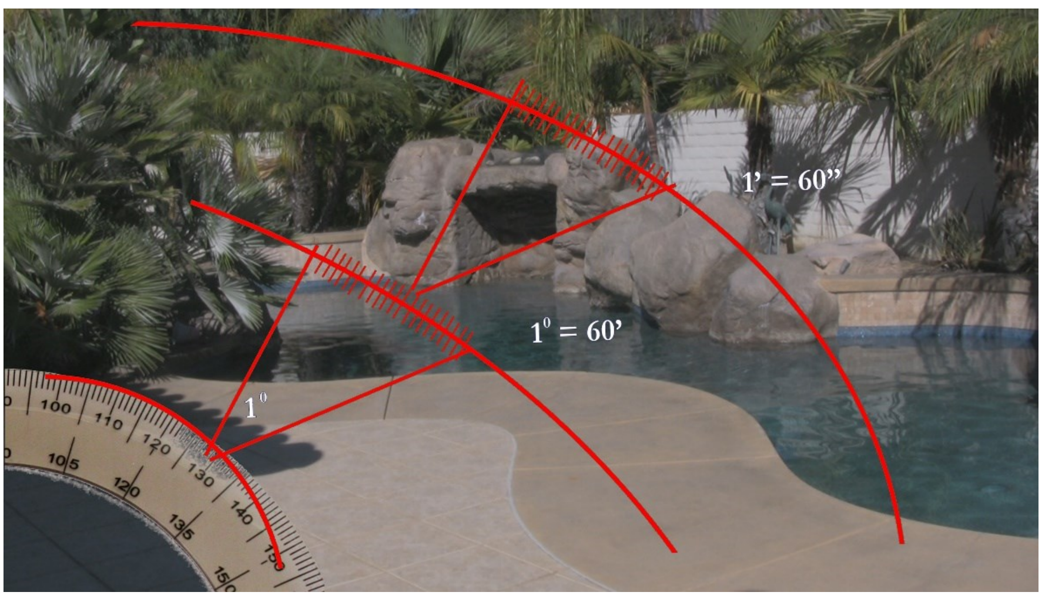
tangent (θ) = opposite side / adjacent side
opposite side = adjacent side x tangent (θ)
= 3 m x tan(50°)
= 3 x 1.2 = 3.6 meters

That combination of direct measurement and angular measurement – triangulation – with triangulation we can triangulate everything there is on the planet Earth that you can see.

<u>Extended triangulation</u>

> ***[Music:*** *Gabriel Fauré - Pavane Op.50. Garth Morris (flute), New Philharmonia Orchestra / Sir David Willcocks 1968; from the album "The most relaxing classical album in the world…ever!" This music was chosen by our space station astronauts as they watched city lights below them dance across the night.* **]**

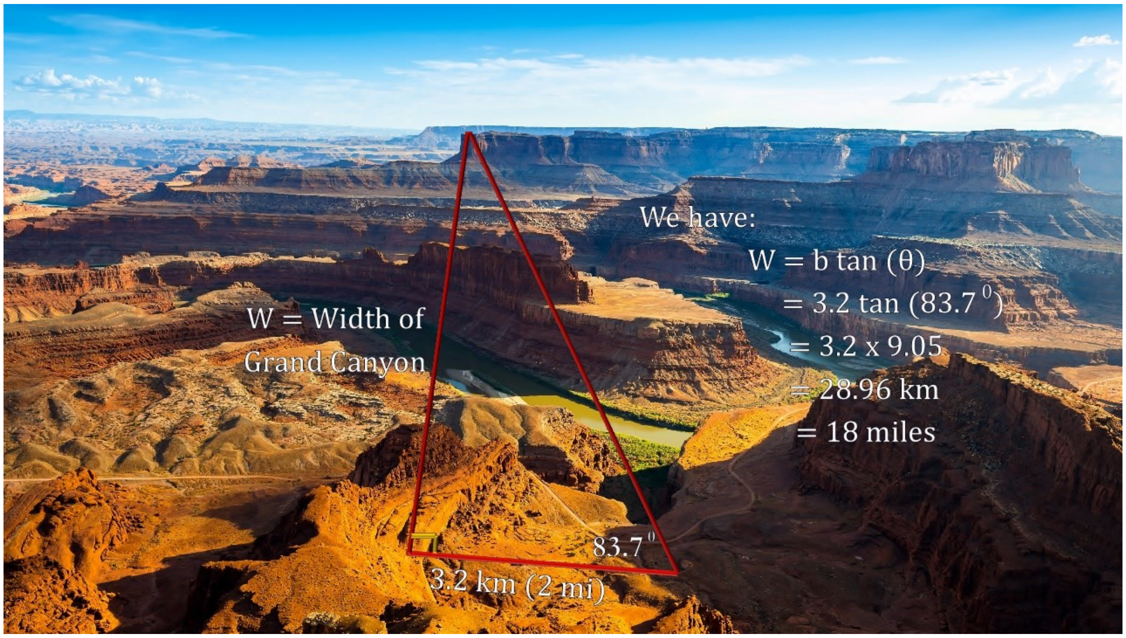
Triangulation is mathematical. The only errors that are introduced are with the accuracy of the angle and baseline measurements. Although tape measures and protractors work OK in a backyard, they are rather crude instruments. They don't scale well to distances beyond the back yard. If we use more accurate instruments than the protractor and tape measure, triangulation can take us a long way.
A protractor can give you an estimated angle to the granularity of a degree. A circle has 360 degrees. For greater accuracy, we break up a degree into 60 arc minutes and each arc minute is broken up into 60 arc seconds.



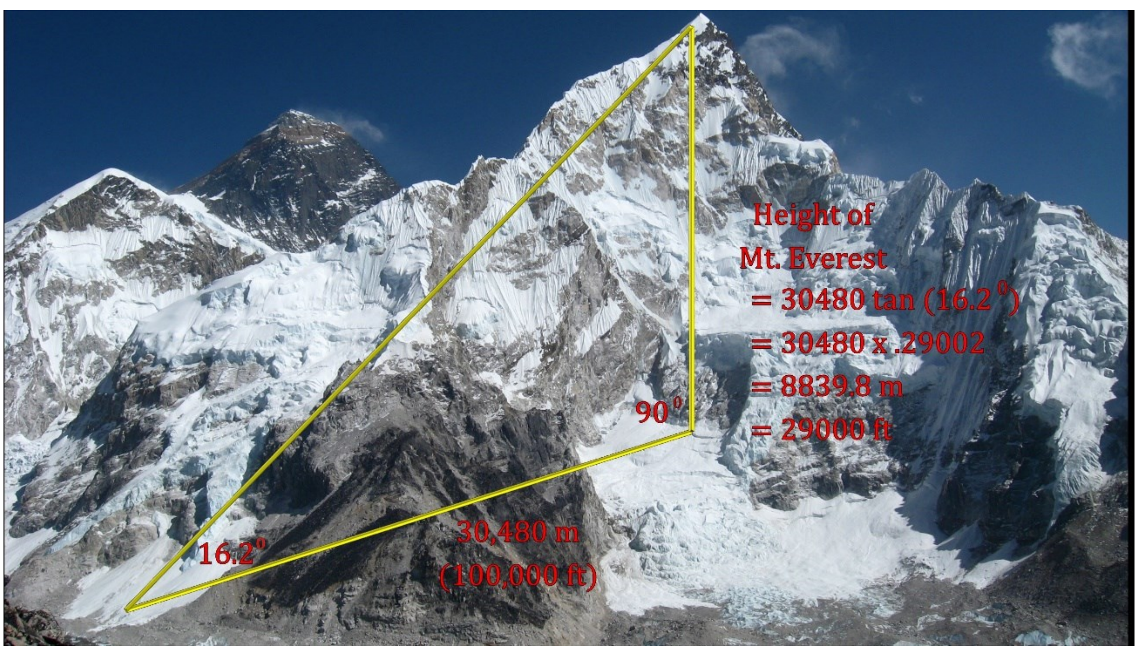
Here we see a theodolite. It's a surveyor's instrument that measures angles in the horizontal and vertical planes down to a second of arc.

Using industrial instruments like these, we can answer "how far away is it" questions like: How wide is the Grand Canyon? and How high is Mt Everest?

In 1902, an extended survey of the Grand Canyon was conducted where 18 primary triangulation stations were marked. The survey found that the Grand Canyon is 446 km (277 miles) long and up to 29 km (18 miles) wide.



In 1856, the Great Trigonometric Survey of India established the first published height of Everest at 8,840 meters (29,002 ft).



[Additional info: Modern methods have it at 8,848 meters (29,029 ft.) the highest mountain on Earth, and the highest point on the Earth's crust.**]**

[Additional info: Surveyors have created networks of triangulations that covered entire countries like France, Great Brittan, and India using spherical trigonometry to account for the curvature of the planet. With these networks, we can triangulate everything that can be seen on our planet. **]**

The only limits on triangulating the distance to an object are:

1) You have to be able to see the object in order to measure angles to it, and
2) You have to be able to measure or calculate the baseline

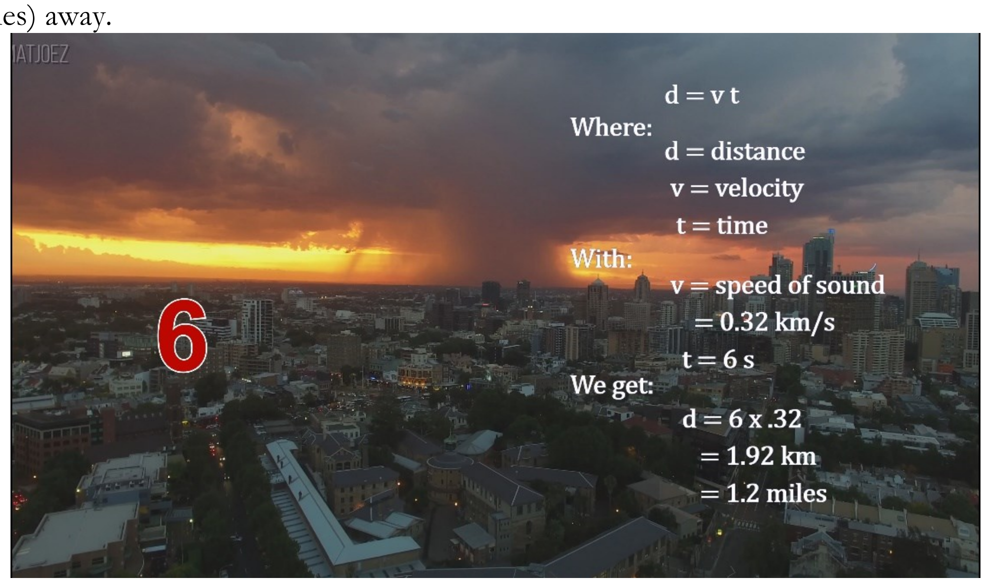
These might not sound like serious limitations. But

- lightning doesn't wait around long enough to take any of these measurements
- and you can't see the top of the sky.

Methods for finding distances to things like these have relevance for the methods that will take us to the planets and the stars, so let's go over them.

Lightning

For some things, you need to know something about the physical processes at play. For example, "How far away is lightning?" To answer this question, it helps to know something about what lightning and sound are. For example, we know that a lightning flash is caused by a massive move of elections across the sky. This creates a vacuum in the air and thunder is the sound of the air collapsing back into the vacuum. We also know that sound is a wave. The speed of sound is variable and depends on the properties of the substance through of which the wave is travelling. In air, the speed of sound is approximately .32 km (.2 miles) per sec. So, all we need to do to see how far away the lightning is, is to start counting the seconds at the flash and multiply the number of seconds by .32 to get the number of kilometers (miles) away it is. Here we have a 6 second delay between the light and the sound, so the lightning is 1.9 km (1.2 miles) away.



As we move up the distance ladder, we'll be using knowledge about stars and light waves in similar ways to our use of lightning and sound waves here.

Atmosphere Distances

For some things, you simply have to go there to find out how far away it is. For example, "How high is the sky?" It's not something you can see, so triangulation won't work. To answer this, you need to go there or send something there and report back how far away it is.

In the beginning, all we could say for sure about the atmosphere was that clouds were closer to the surface of the Earth than the sun, moon, planets and stars. We knew this because clouds always covered up the surface and those objects – never the other way around.

Our knowledge in this area didn't really begin until the late 1700s when high flying balloons came into use. Here's a scientific balloon launch. High altitude balloons have been used for over 70 years for atmospheric exploration. They fly at altitudes in excess of 32 km (20 miles) above the surface of the earth for days on end.

It wasn't until the 1900s that aircraft, rockets, and space craft were put to use to travel high into the atmosphere and figure out just how high it went and how it was structured. It turns out that the atmosphere doesn't have an exact top like a lid would be on a jar. What happens is that the air gets thinner and thinner and eventually merges into and then becomes outer space.

Atmospheric Layers

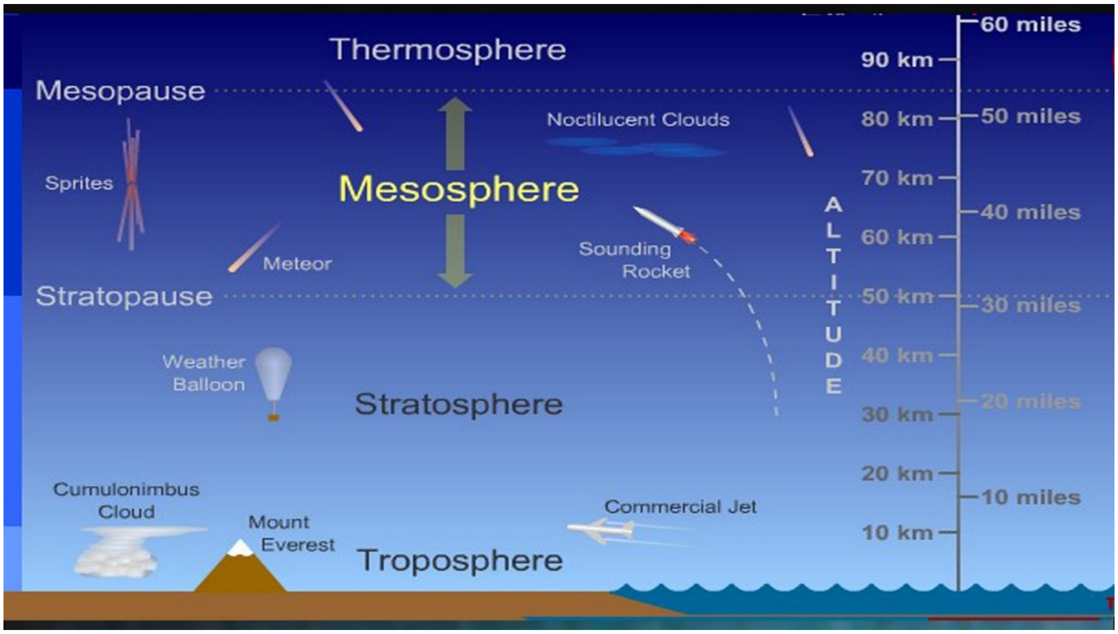
The **troposphere** begins at the surface and extends to around 20 km (12.4 miles). It contains roughly 80% of the mass of the atmosphere. This is where we get all our weather and it is where our passenger jets fly over that weather.

The **stratosphere** extends from the troposphere to about 50 km (32 mi). The balloons we discussed fly in this area.

The **mesosphere** extends from the stratosphere to around 84 km (52 mi). It is the layer where most meteors burn up upon entering the atmosphere.

The **Thermosphere** extends up to 386 km (240 miles) and is considered outer space. The air is so rarefied that an individual molecule travels an average of 800 meters (1/2 mile) between collisions with other molecules. The International Space Station orbits in this layer.

Going there is a technique we can repeat for distances throughout our solar system, but it won't take us to the stars.



Size of the Earth

Now, let's find out "How big is the Earth", using geometry as a key technique.

In 200 B.C., Eratosthenes actually calculated the size of the Earth and came pretty close! Eratosthenes used Aristotle's ideas that:

1) If the Earth was round, the Sun would appear at different positions to observers at different locations; and

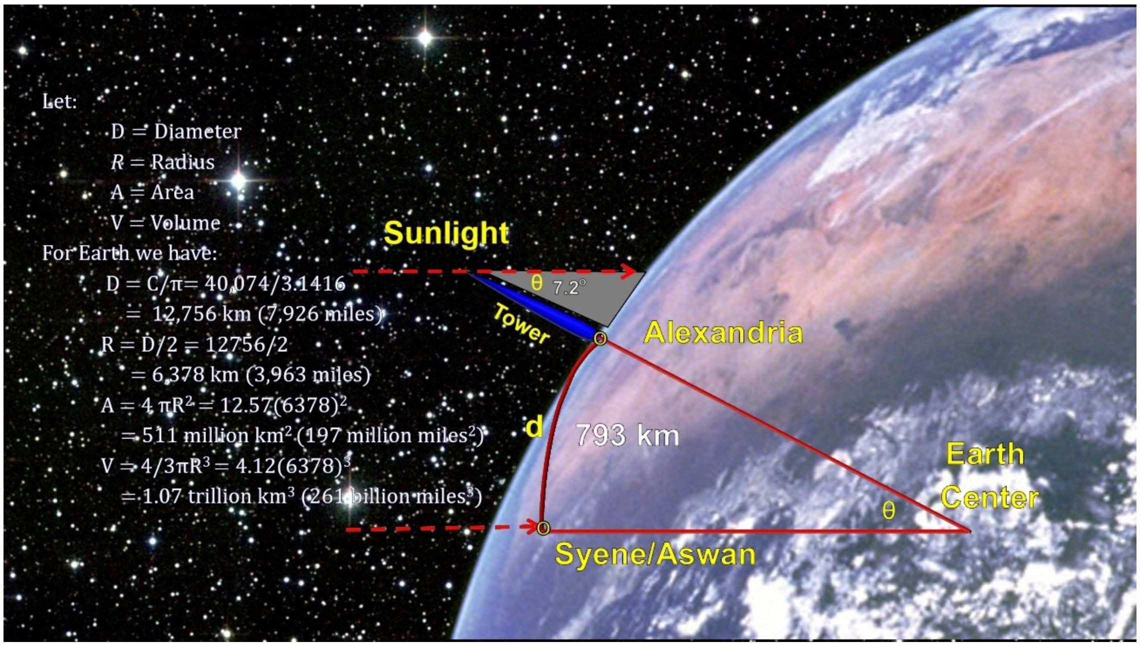
2) If the Sun was very far away, the light rays would be almost parallel between any two locations.

For his two locations, Eratosthenes chose Alexandria and Syene (now Aswan). He knew how far apart these to cities were – 793 km (493 miles) in today's units. Eratosthenes knew that on the first day of summer, the Sun passed directly overhead at Syene.

At midday, of the same day, using a tower in Alexandria, he measured the angular displacement of the Sun from overhead. He found that the angular displacement was 7.2 degrees – that's equivalent to 1/50 of a circle.

Geometry tells us that the angle measured at the tower is the same as the angle between lines connecting the two cities to the center of the Earth. This is because when a straight line crosses parallel lines, it crosses them at the same angles.

So, given that the angle is 1/50th of a circle, the distance between the cities will also be 1/50th of the circumference of the Earth. Thus the circumference can be estimated by multiplying the distance between the two cities, 793 km, by 50, equaling 39,650 km (24,650 miles). The actual number at the equator is 40,074 km (24,901 miles). He was only 1% off.



This is an experiment anyone can do. In fact, in 2005, it was a science project for a number of schools around the country. I'll point you to details in the Credits in case you'd like to try it yourself. **[Go to:** *www.physics2005.org/projects/eratosthenes***]** Once we have the circumference, Geometry gives us the rest. For a spherical Earth:

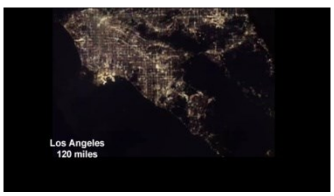
- The diameter D is equal to the circumference divided by π
  - D = C/ π = 40074/3.1416 = 12756 km
- The radius R is half the diameter
  - R = D/2 = 12752/2 = 6378 km
- The surface area A is 4 times the radius squared times π
  - A = 4 π R^2 = 12.57 x 6378^2 = 511 million sq. km
- The volume V is 4/3 the radius cubed times π
  - V = 4/3 π R^3 = 4.12 x 6378^3 = 1.07 trillion cubic km

Needless to say, this is very large! A high school teacher calculated the number of students that could fit inside the Earth. It came to 137,188,690,000,000,000,000 students. This number of students is so large that if you could count one number per second it would take you more than 4 trillion years to count this high. So, you can see, the earth is very large indeed!

<u>Cities at Night from Space</u> **[Music:** *Back to Gabriel Fauré's Pavane*]

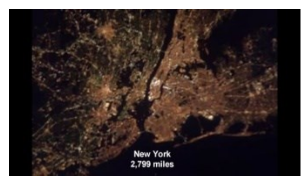
Now that we have a feel for how large our planet Earth is, how high the sky goes, and how we measure and calculate these distances, we'll finish this Chapter with a look at some of our great cities at night from space and identify their distances from our home base - San Diego, California.

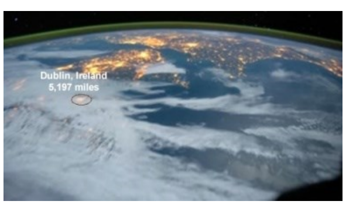
Astronaut Don Pettit went to significant lengths to get high def pictures of the Earth's cities at night from the International Space Station back in 2008. I combined his pictures with the time lapse photos taken by the crew of Expeditions 28 & 29 aboard the Space Station in 2011. The space station orbits 370 km (230 miles) above the earth.



We start with nearby cities. Like nearby stars, these are the most familiar to us. Distances are measured in hundreds of kilometers. Nearby star distances are measured in trillions of kilometers.

As we move east across the North American continent, distances grow to thousands of kilometers. Similarly, distances to far away stars grow to hundreds of trillions of kilometers.





We jump by thousands of kilometers as we cross the voids created by great oceans such as the Atlantic. This reminds me of the galaxy voids in the structures known as superclusters.

Here's one of the furthest cities. From here, because the Earth is round, we start measuring distances to the west. It's interesting to wonder if the same sort of thing could happen if the Universe is curved enough to be closed.

***[Music @14:27 -** Barber, Samuel: Adagio for Strings Op. 11a; The Philadelphia Orchestra / Eugene Ormandy 1984; from the album "The most relaxing classical album in the world…ever!"]*

Distance Ladder Introduction

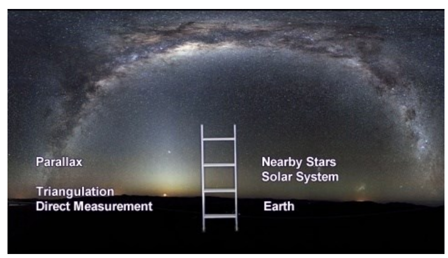
The Distance Ladder is a set of techniques for determining an objects distance. Each step works for a particular situation and distance range and supports the steps above it. This is how we work our way from Earth to the stars and on to the most distant galaxies.

We have just built a solid first rung for our ladder. We can now use the entire diameter of the Earth (12,756 km - 7,926 miles) as our baseline for triangulating off the Earth and into the Solar System.

Here's an overview of the rest of the ladder.

Parallax

Direct measurement doesn't work for figuring out how far away the planets are. For that we use an extension of triangulation called Parallax. If you hold your finger up in front of your eyes, and close one eye at a time, you see a shift in your finger's relative position with respect to distant objects. This is parallax! It can be used to calculate the distance to our Solar System neighbors and nearby stars. All you need for this to work is a more distant star that doesn't move when the target object is viewed from different locations.

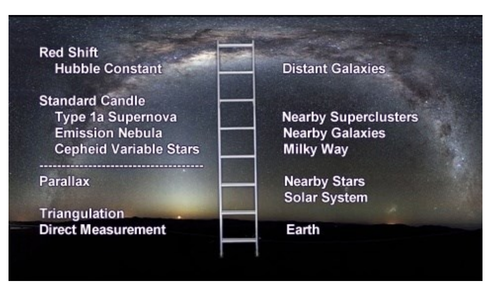


Standard Candles

Parallax accuracy goes down as the distance goes up, and it doesn't work at all for stars and galaxies that don't have more distance objects that remain stationary as the earthbound observer moves. For those objects we use a technique called 'Standard Candles'. Once we know the intrinsic brightness of a star, we can use the simple inverse square rule for the drop-off in apparent brightness as the object is seen on Earth.

Some objects lend themselves to this technique better than others. Some of the most prominent are:

- Cepheid variable stars –
- Emission nebula –
- Type 1a Supernovas –



Red Shift – Hubble Constant

The final rung on the ladder is Red Shift. The most distant galaxies are too far away to see Cepheid starts or Supernova explosions. For these, we owe our thanks to Edwin Hubble who discovered a relationship between the speed that a galaxy is traveling away from us and its distance from us. Based on his evidence for an expanding Universe, the faster a galaxy is receding away from us, the further way it is. We get the receding speed from the red shift in the light from the galaxy. This method works all the way out to near the big bang, around 13 billion light years away.

We'll be building the Cosmic Distance Ladder, rung by rung, as we move through the "How far away is it" video book chapters.

Video Book Preview

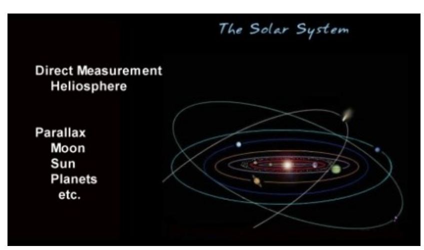
Here's a preview of the "How far away is it" video book chapters.

Earth

In this segment, we used direct measurement, triangulation, and other geometric formulas to calculate 'How far away is it?' for the Earth

Solar System

In the next chapter, we'll use parallax to measure how far away the moon and planets are, and triangulate the distance to the sun. We'll take the direct method to measure the extent of the Sun's Heliosphere. And we'll use geometry to determine how far away comets are.



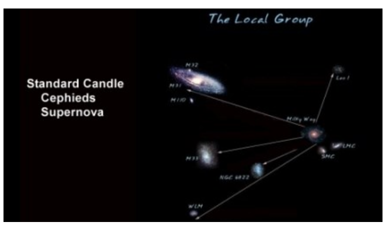
Solar neighborhood

Parallax will take us to the stars in our local neighborhood such as Alpha Centauri and Wolf 359.

Milky Way

Going deeper into the Milky Way, we'll add Cepheids, Supernova, Nebula, Supergiants, and Globular Clusters to work our way across the galaxy.

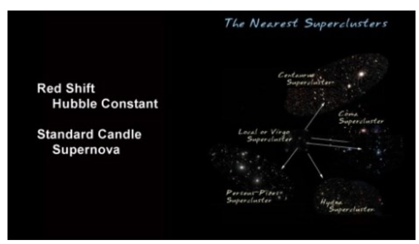
Local Group



A number of these methods drop out as we move into the Local Group of galaxies around us.

Superclusters

As we move further out, only Super Novae can be relied upon. Also, we move into distances where Red Shift begins to work.



For the **furthest reaches of space**, we have only Red Shift.

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.

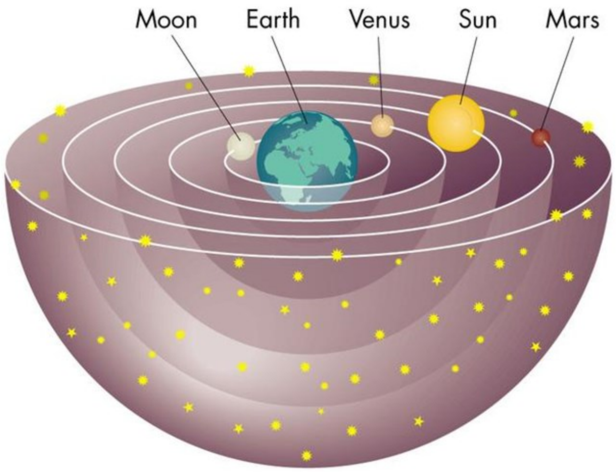
We then turn our attention to the Sun. We triangulate the Sun with Venus to calculate our distance from the Sun – one Astronomical Unit. With distance to the Sun known, we calculate its diameter, surface area and volume; the length of Earth's orbit; the Earth's velocity around the Sun; and with that, 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.}

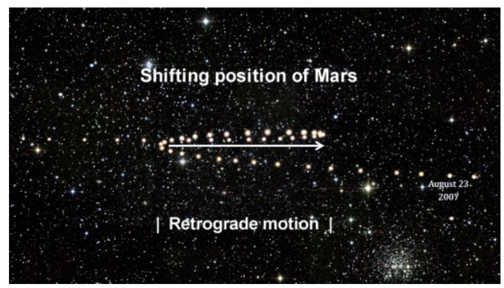
[Music @*00:00* - *Rachmaninov, Sergei: Rhapsody on a Theme of Paganini – Variation 18; Cecile Ousset (Piano), City of Birmingham Symphony Orchestra / Sir Simon Rattle, 1984; from the album "The most relaxing classical album in the world…ever!"***]**

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.

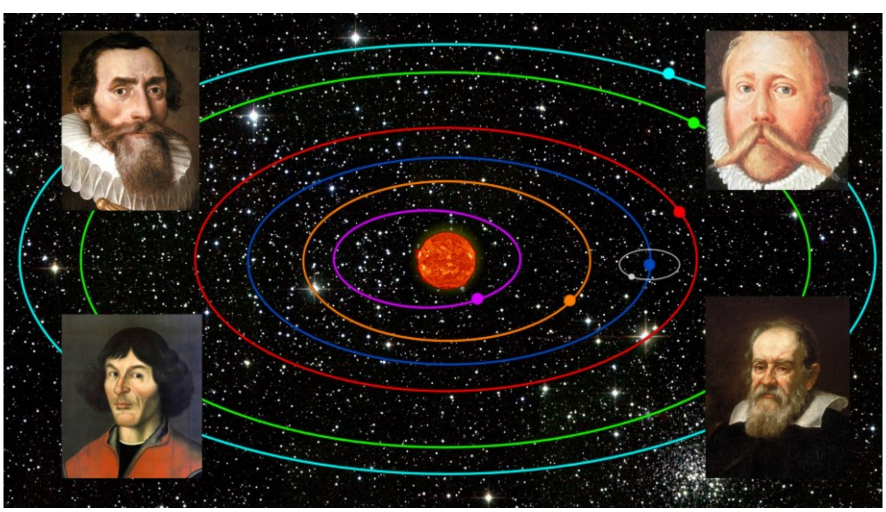


Planets were identified as different from stars because they changed their position over time, whereas the stars were seen to be eternally fixed in place.



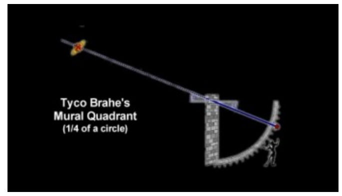
Copernicus

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.

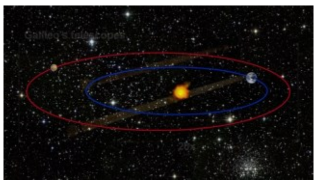


Tycho Brahe

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!

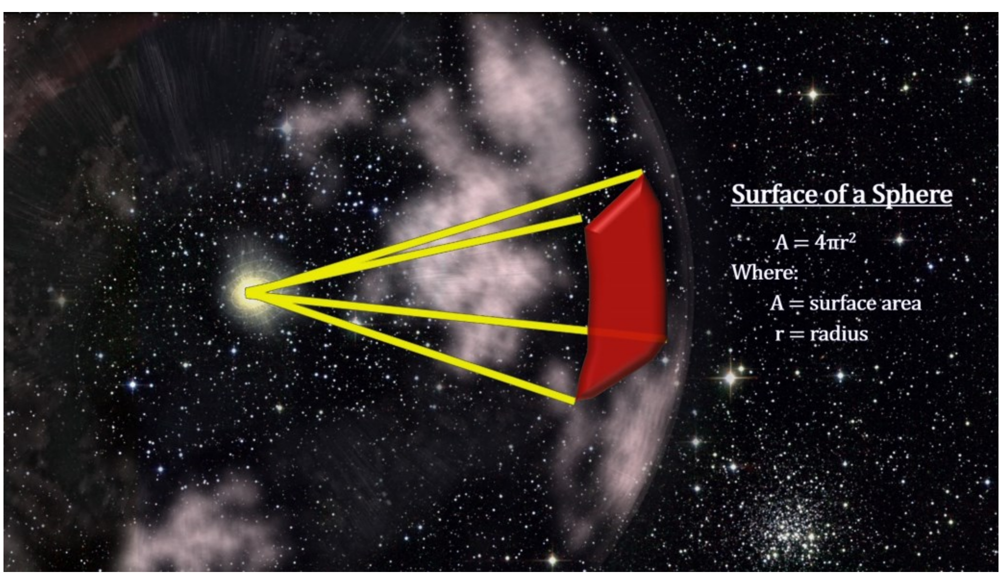
Imagine how it must have felt, when Galileo first saw these moons. All the world believed that everything revolved around the earth, and here you are looking at moons that are orbiting Jupiter and not the Earth!

[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!"**]

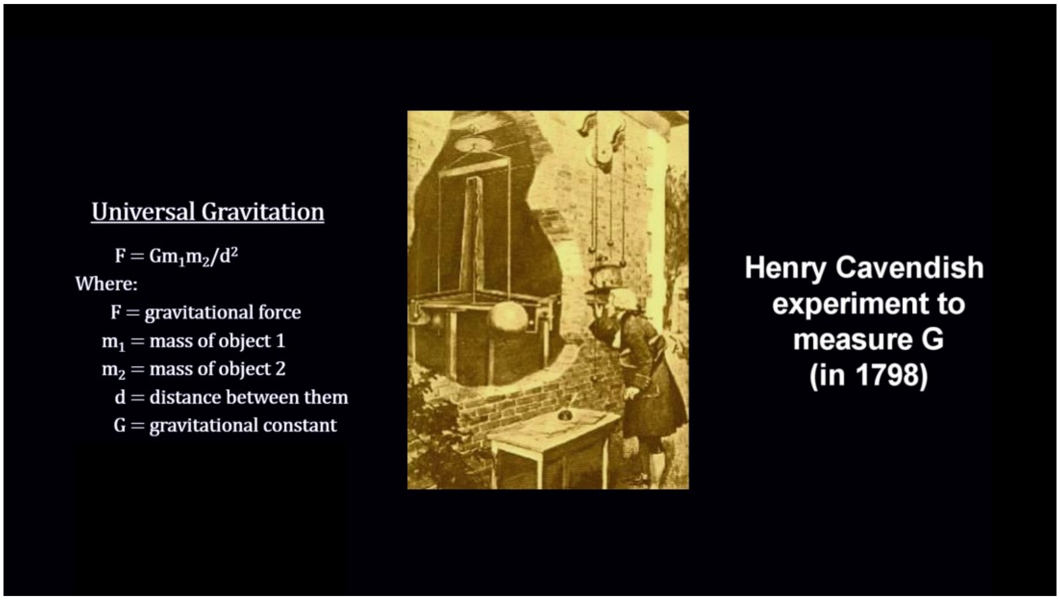
<u>Newton</u>

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.

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.



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.



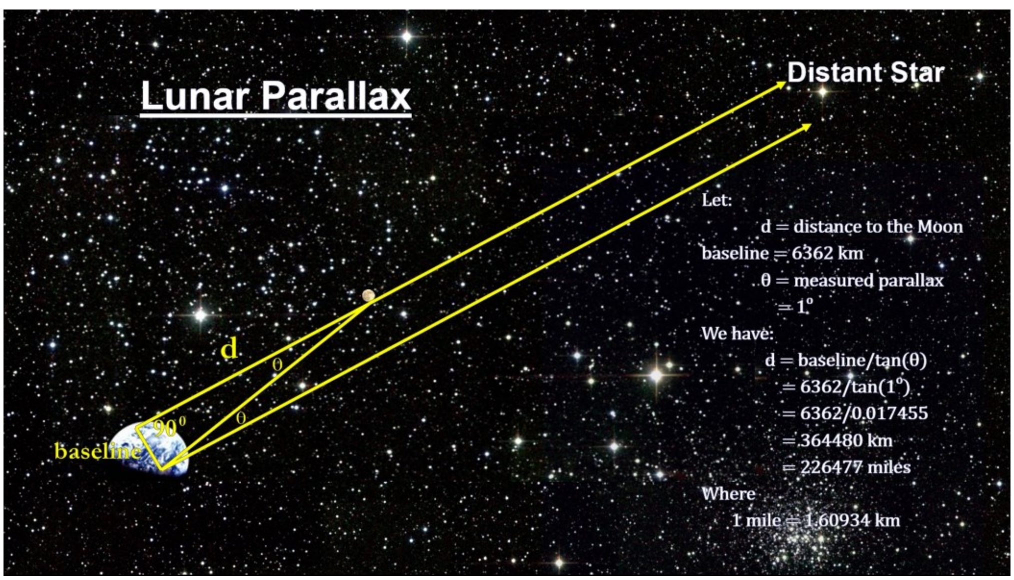
Newton broke Aristotle’s two-thousand-year-old dictum that there are two sets of rules for nature: one set for here on Earth and another set for the havens. With Newton, we came to understand that there is only one set, and it applies everywhere.

[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!"***]**

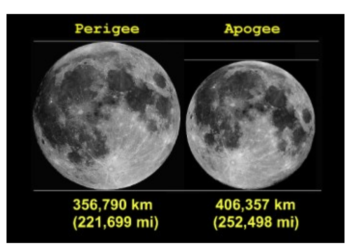
Parallax

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:

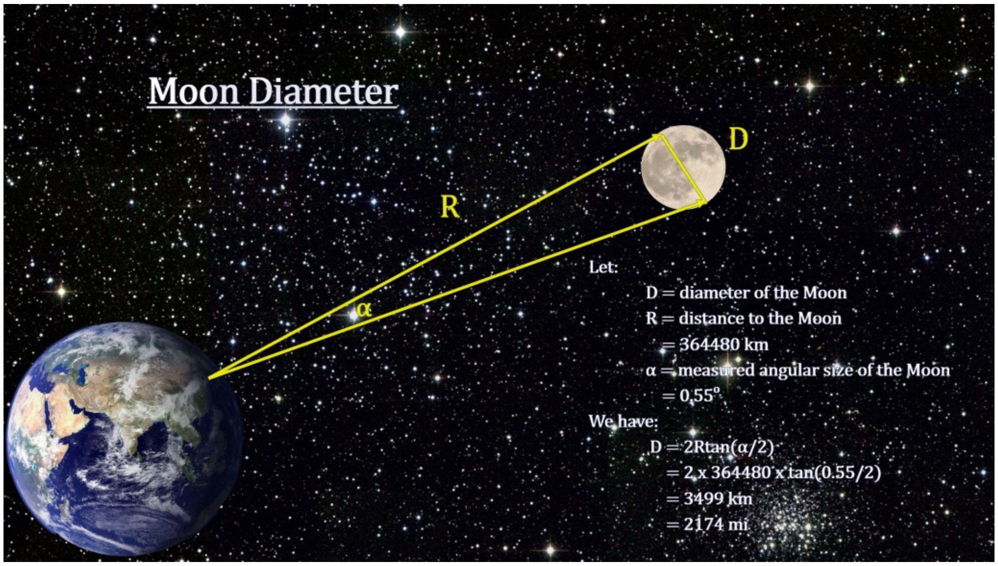
1) Draw a line from a point on the earth to the moon directly overhead.
2) Extend this line to a distant star.
3) From a measured distance across the Earth **[**6362 km = *3953 miles***]**, draw another line to the distant star, and another to the Moon.
4) Measure the angle between these two lines. In 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.



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.



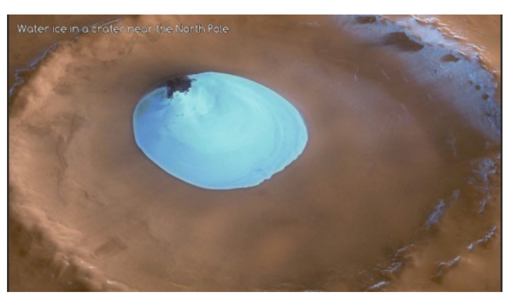
It's important to note that, once you know the distance, there are a number of other things we can learn about an object. For example, given the distance and the angular displacement of the object in the sky, we can calculate its size. Here we see the Moon's diameter is almost 35 hundred km. That's 2,174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

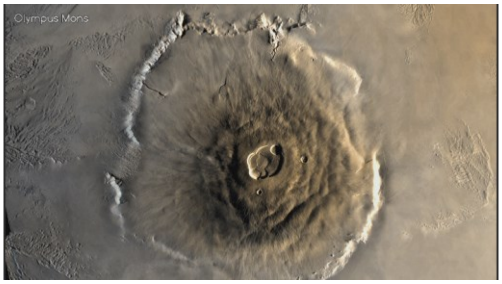


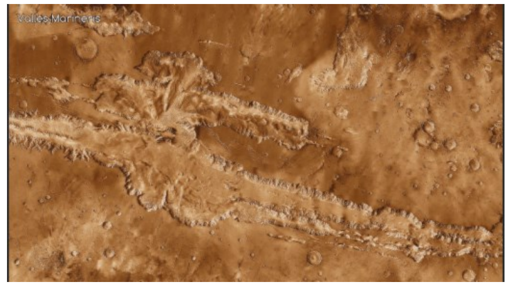
[Additional info:** Today high-precision measurements of the lunar distance are made by measuring the time taken for light to travel between stations on Earth and reflectors on the Moon. These confirm the numbers calculated by Parallax methods. This helps establish Parallax as a key rung on our 'distance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

Distance to Mars

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.

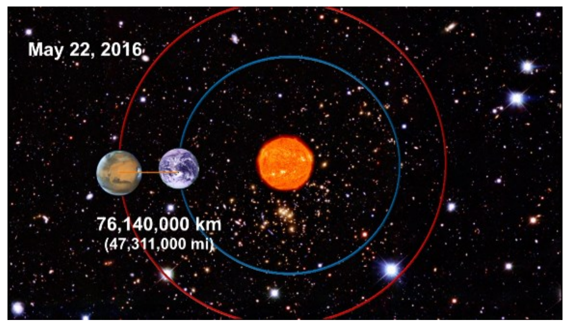




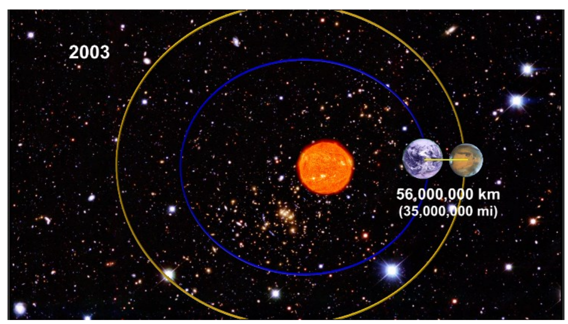


On May 12, 2016, the Hubble Space Telescope captured this image.

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.



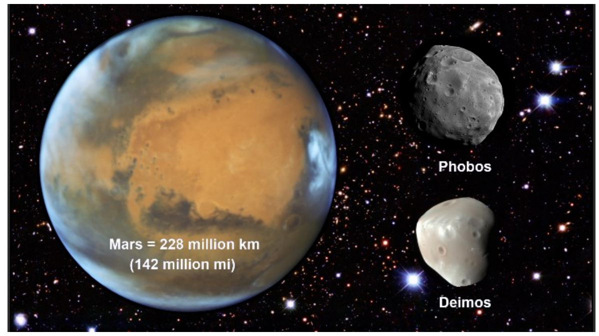
[Music @09:37 -** Vangelis: Conquest of Paradise from the album "1492 - Conquest of Paradise", 1992**]

<u>Planets and Moons</u>

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.

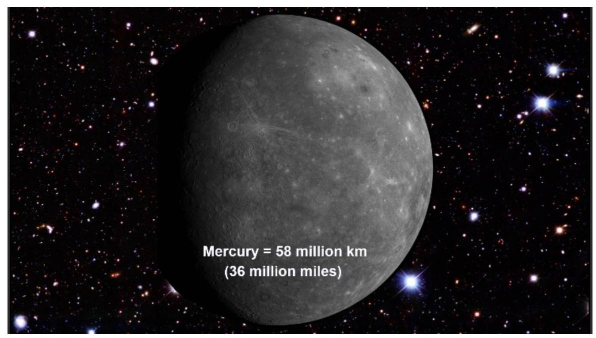
Mars is 1 and a half AU or 228 million km. (That's 142 million miles.)

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.

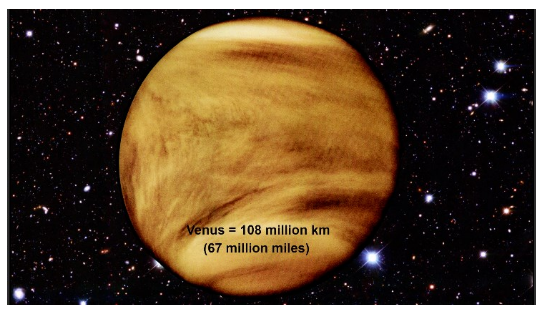


Here are the distances to the other planets in our solar system.

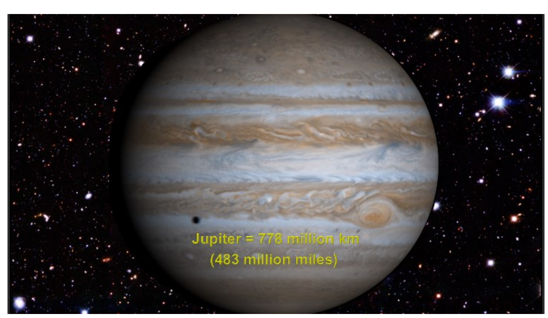
Mercury, a hot cratered rock not much bigger than the moon, is only 58 million km from the sun. (That's 36 million miles.) Its daytime surface temperature is 430 degrees Celsius (that's 800 degrees Fahrenheit). That's hot enough to melt lead. Mercury has no moons.



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.

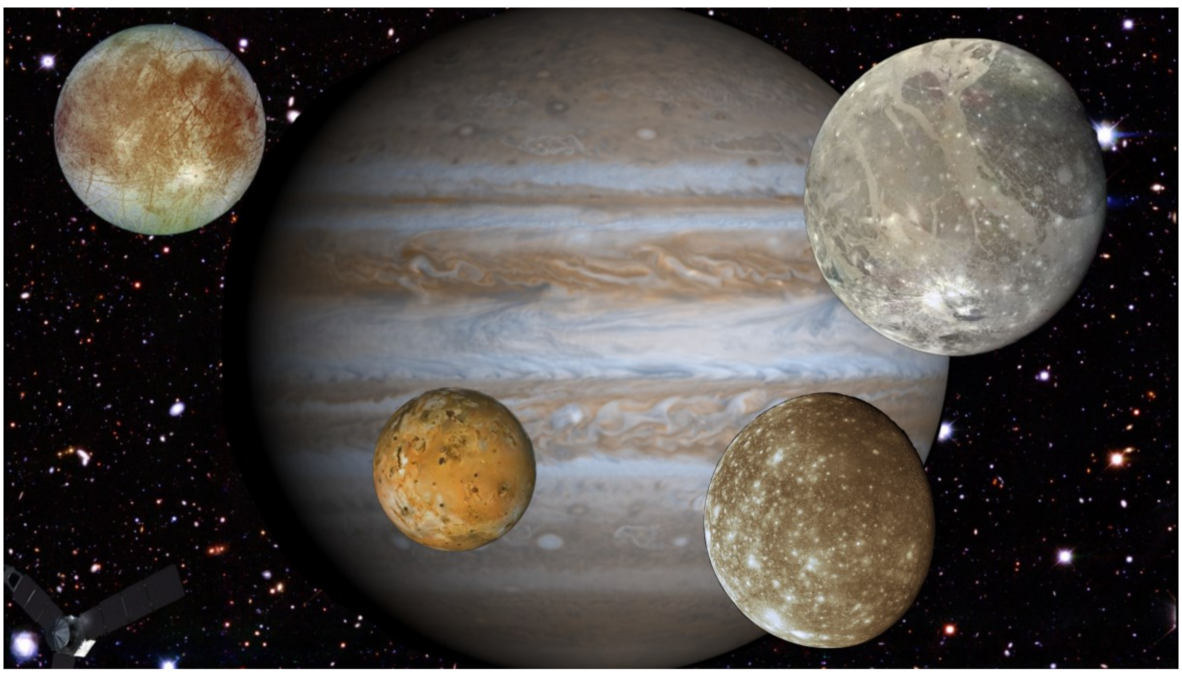


Scientists think Jupiter has at least 69 moons. The most interesting are the four discovered by Galileo – Ganymede, Callisto, Io and Europa. Ganymede is the largest moon in the solar system, and is the only moon known to have its own internally generated magnetic field.

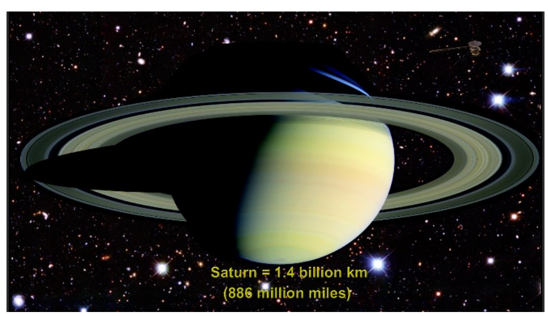
Callisto's surface is extremely heavily cratered and ancient -- a visible record of events from the early history of the solar system.

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.

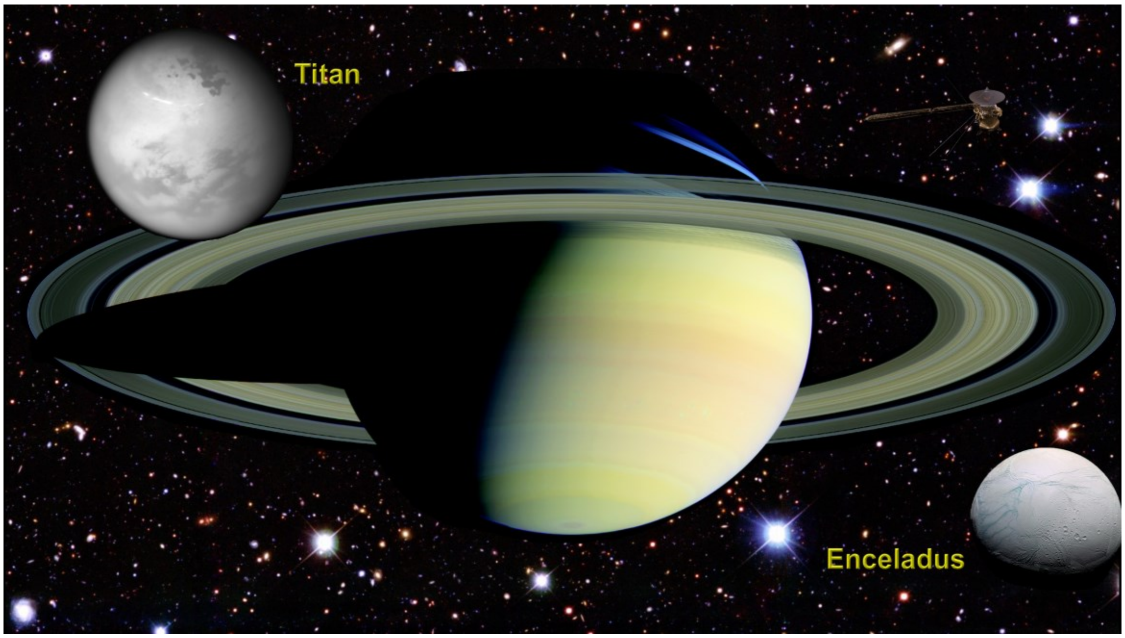
Europa's surface is mostly water ice, and there is evidence that it may be covering an ocean of water. It is thought to have twice as much water as we have here on Earth. This water, along with subterranean volcanoes may have created a zone where life can form.



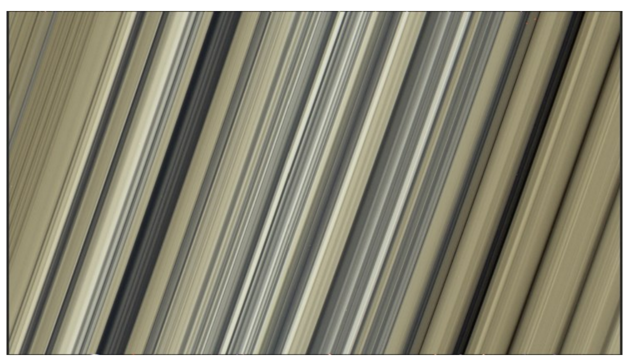
Saturn, with its beautiful rings, is 1.4 billion km from the sun. (That's 886 million miles.) Its mass is 95 times greater than the Earth. The Cassini probe has been taking pictures of the planet, its rings and moons for 13 years.



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.



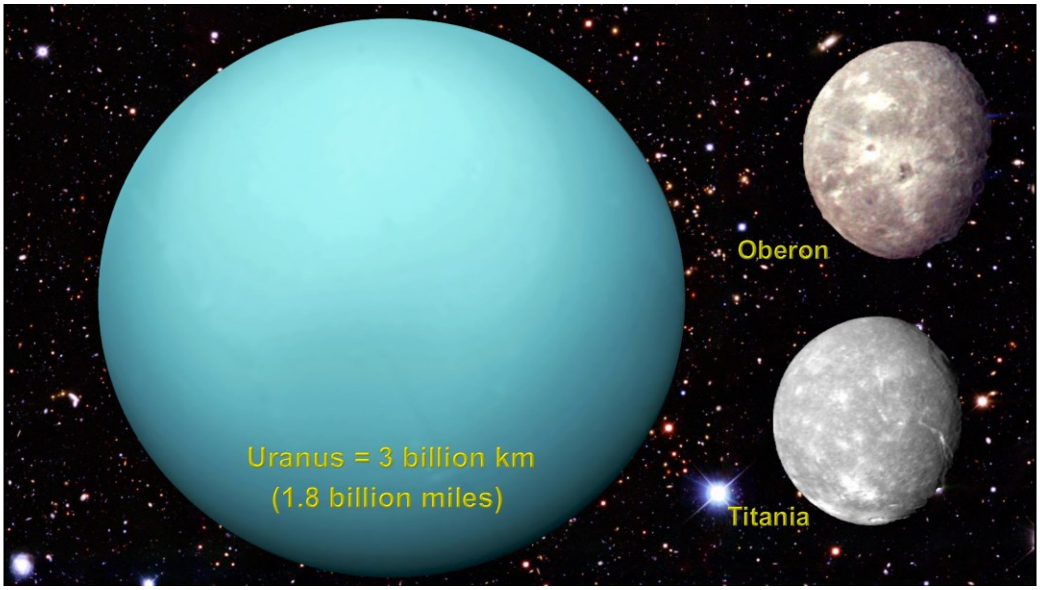
Saturn's rings are absolutely beautiful. There are billions of ring particles in the entire ring system ranging in size from tiny, dust-sized icy grains to a few particles as large as mountains. It's about one kilometer (3,200 feet) thick, and they range out to 282,000 km (175,000 miles) from the center 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.



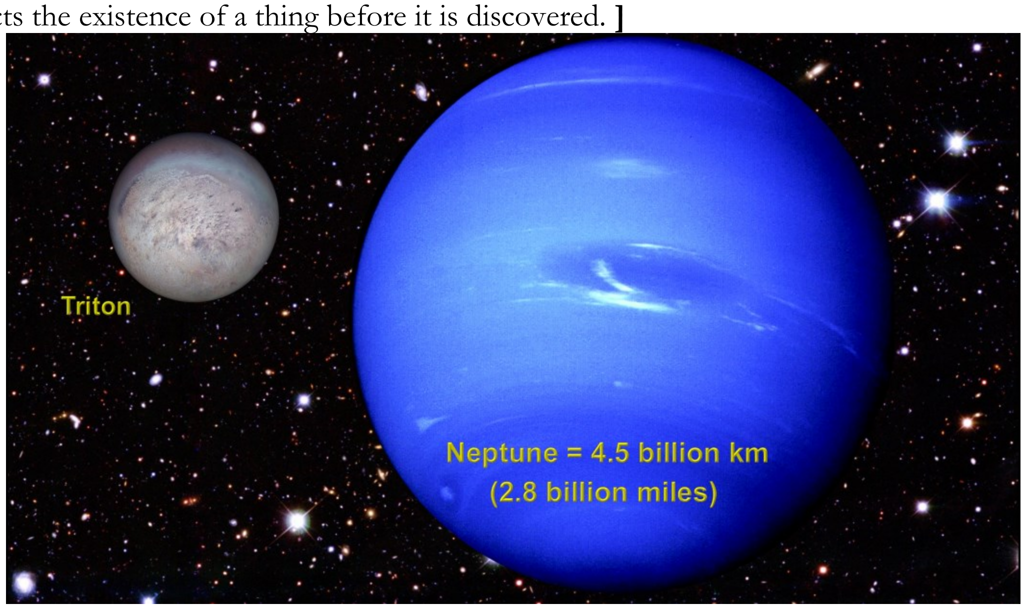
[Two tiny moons orbit in gaps Encke and Keeler in the rings and keep the gaps open. The origin of the rings of Saturn have puzzled astronomers since Galileo Galilei discovered them with his telescope in 1610. One guess is that they are pieces of comets, asteroids or a shattered moon that broke up before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

Cassini ended its mission on September 17^{th}, 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

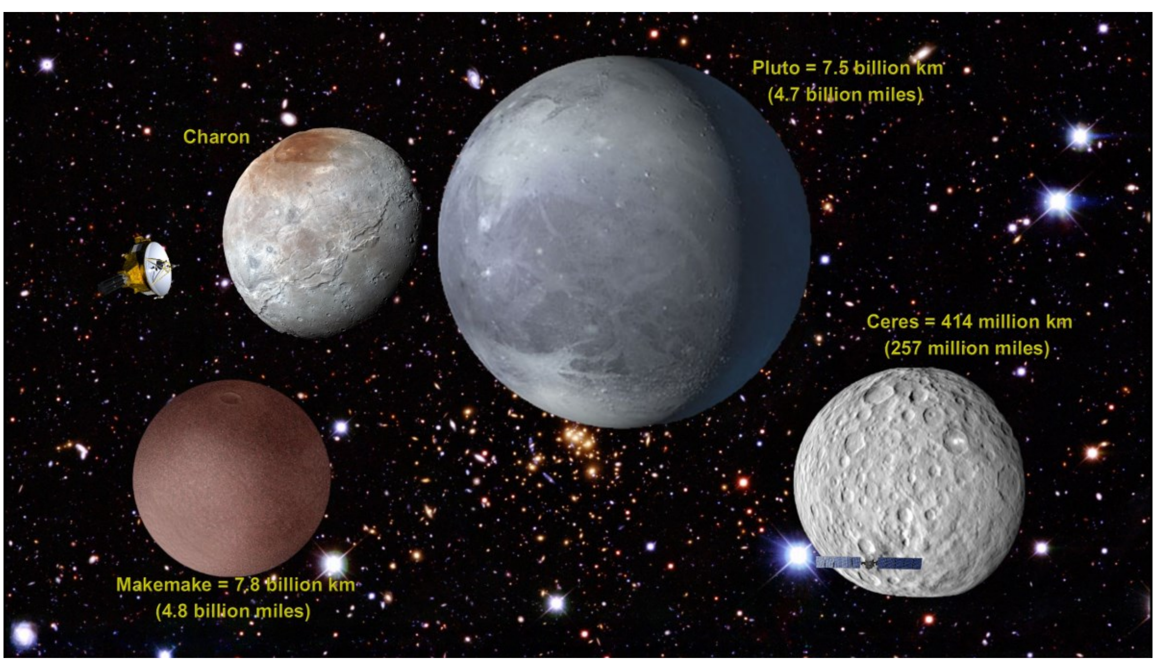
In addition to the eight main plants in our solar system, there are a number of large bodies too small to clear the debris in their orbit. These are called minor or dwarf planets. We know of five, but there could be dozens more. Here are three of them.

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.

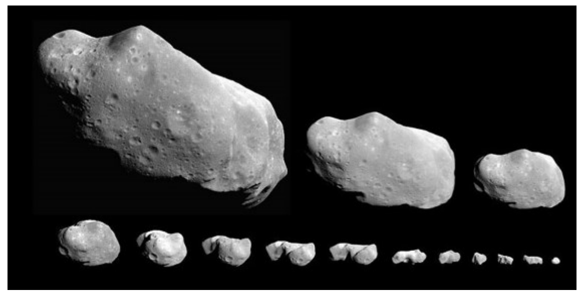
Makemake was discovered in 2005, by a team at the Palomar Observatory. It is in the Kuiper Belt at 7.8 billion km (that's 4.8 billion miles) from the Sun. It is thought that Makemake's reddish-brown color comes from a layer of methane at its surface.



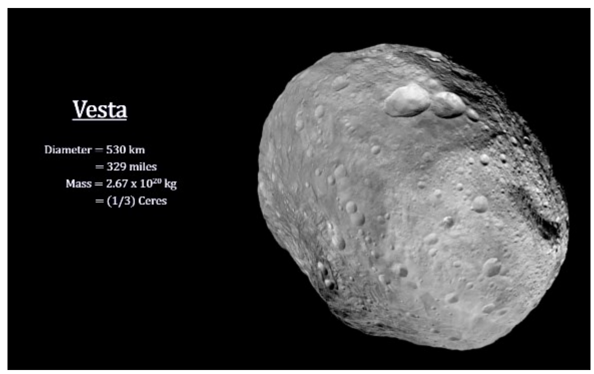
[Music @18:44 -** Massenet, Jules: Meditation from 'Thais'; Hans Kalafusz (violin), Stuttgart Radio Symphony Orchestra / Sir Neville Marriner, 1987 EMI Electrola GmbH - from the album "The most relaxing classical album in the world…ever!"**]

Asteroids

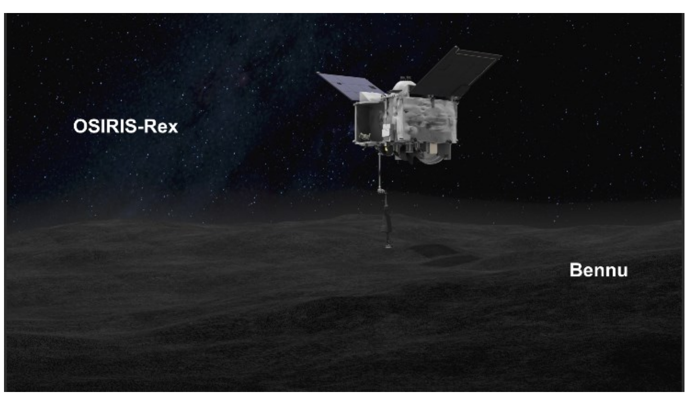
Asteroids are relatively small rocky worlds that revolve in elliptical orbits around the sun. There are billions of them in the Solar System, ranging in size from a few meters across to the size of dwarf planets.



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.

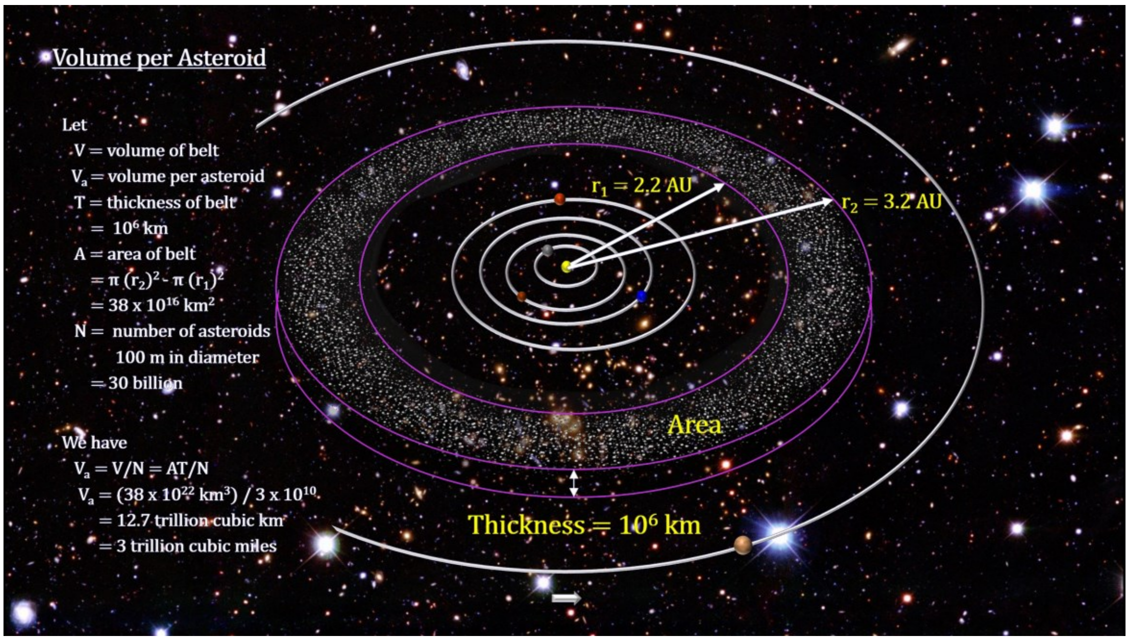


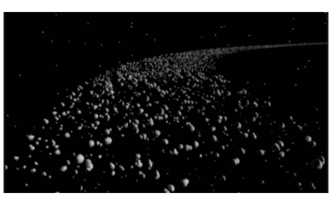
Asteroids have stayed mostly unchanged for billions of years, so research into them could reveal a great deal about the early solar system. To that end, a probe called OSIRIS-Rex launched in September 2016 will travel to a near-Earth asteroid called Bennu and bring a small sample back to Earth for study.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



Asteroid Belt

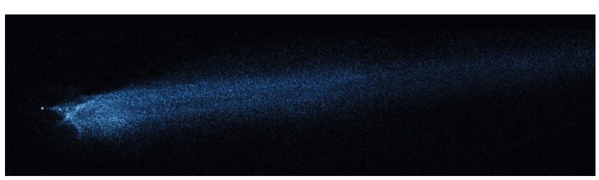
Most asteroids lie in a vast ring between the orbits of Mars and Jupiter called the Asteroid Belt. It ranges from 2.2 astronomical units to 3.2 astronomical units from the Sun and is around a million km thick. It's estimated to contain around 30 billion asteroids larger than 100 meters across. But the 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.



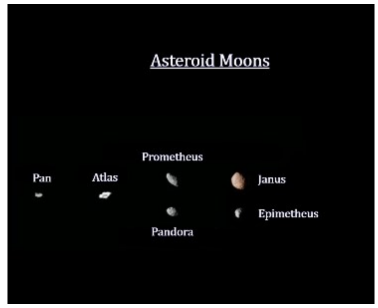


If we went there, it would look quite empty. [Pictures like these are quite misleading.]

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

]

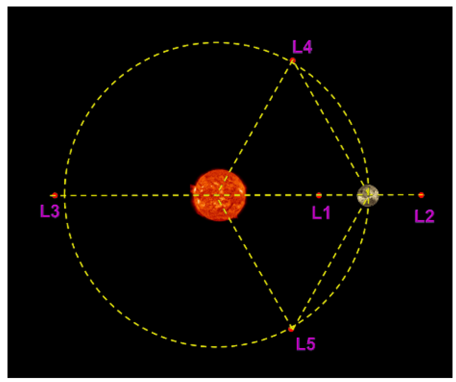
But we do know that lots of asteroid exist outside of the Asteroid Belt. For example, the outer moons of the giant gas planets are all thought to be captured asteroids as are Demos and Phobos the moons of Mars. And asteroids also orbit gravitational points known as Lagrange points.

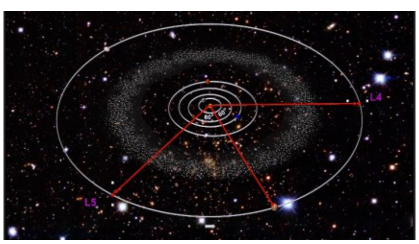


Lagrange Points

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.

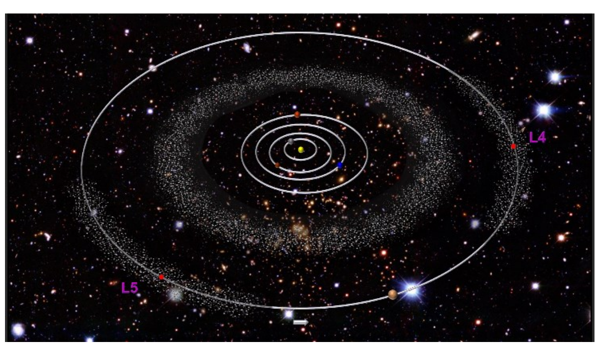
L4 and L5 are on the orbital path of the smaller body. They are found by using equilateral triangles. They are stable and Lagrange claimed that small objects could orbit these Lagrange points.





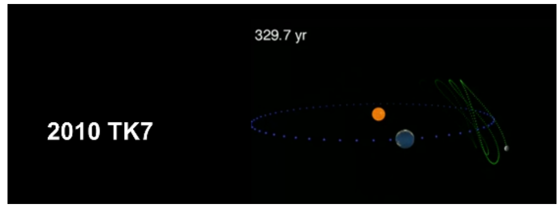
134 years later, between 1906 and 1908, four asteroids were found around Jupiter's L4 and L5 Lagrange points. Asteroids at Lagrange points are called Trojans.

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.

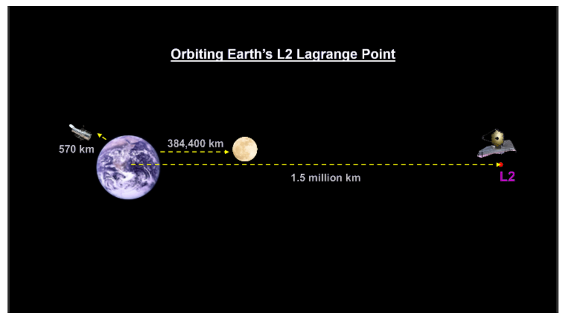


Earth's Trojan Asteroid

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.



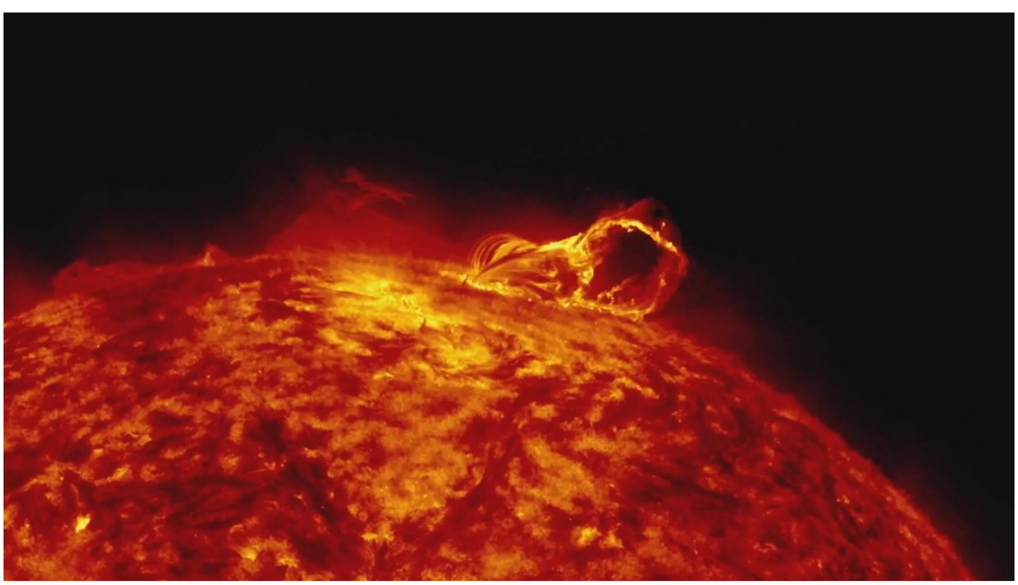
Our Space program takes advantage of these points when we position satellites to observe the Sun. Here we see that L2, where the James Webb Space Telescope will orbit, is 4 times further away from us than the Moon. We'll cover this a bit more in our section on the Heliosphere.



[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!"**]

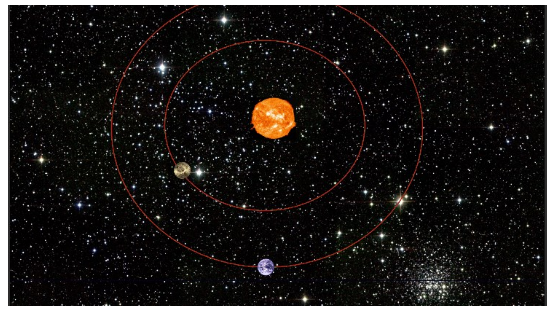
The Sun

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.

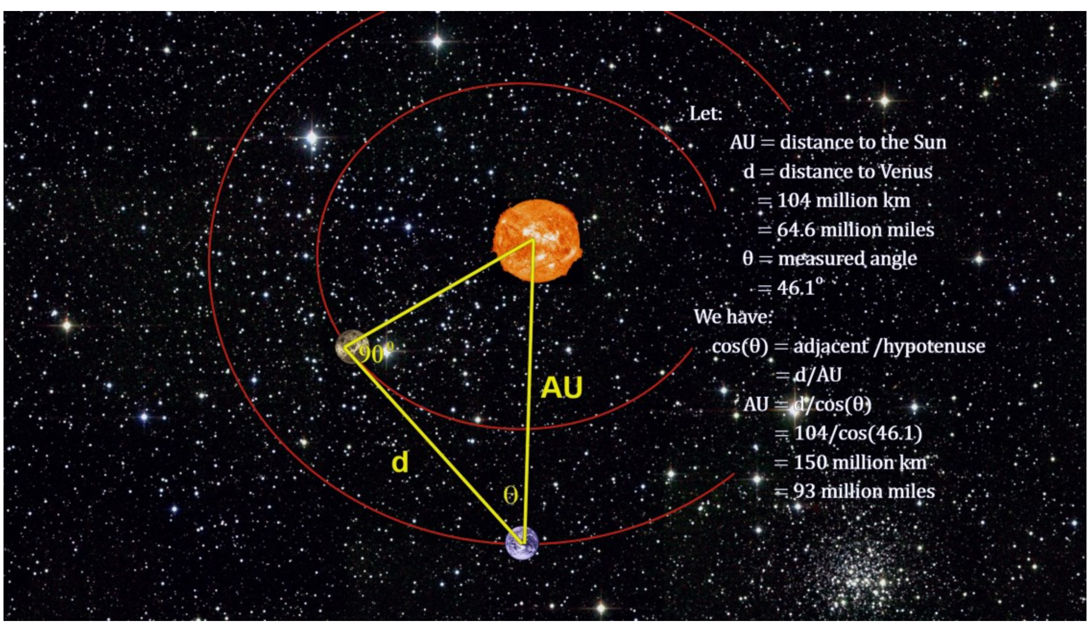


But total eclipses and the passage for Venus across the face of the Sun as viewed from Earth have enabled excellent measurements. Here is a method that uses parallax to find the distance to Venus that in turn enables us to triangulate the distance to the Sun.

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.

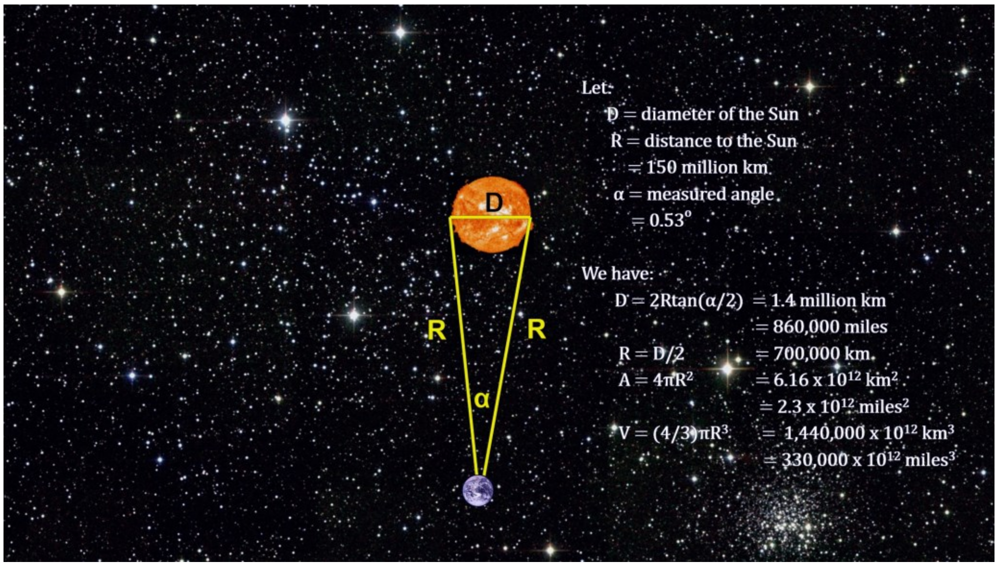


By making observations of Venus in the sky, one can determine the point of greatest elongation. At this point, the distance between the Earth and Venus can be determined via Parallax 104 million km or 64.6 million miles. Also, at this point, the line joining Earth and Venus will be tangential to the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

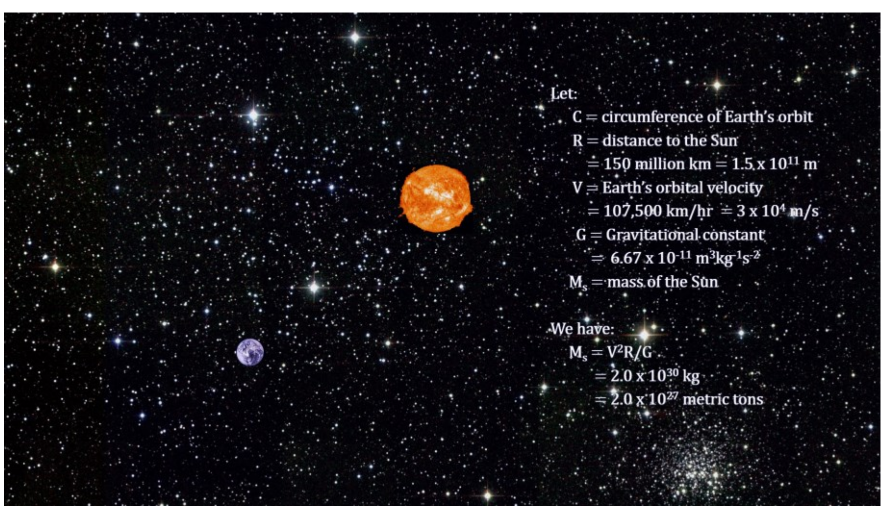


[Additional info: Parallax measurements of the distance to Venus have been verified by radar measurements, where a radio wave is transmitted from Earth bounces off Venus and comes back to Earth. By measuring the time taken for the pulse to come back, the distance can be calculated as radio waves travel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



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



<u>Speed of Light</u> **[Music:** Pachelbel - Canon in D**]**

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

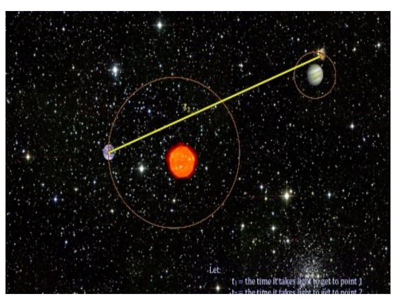
Until early in the 18th century, it was generally believed that the speed of light was infinite. This view was held by Aristotle in ancient Greece, and vigorously argued by the French philosopher Descartes and agreed to by almost all the major thinkers over the two thousand years that separated them.

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

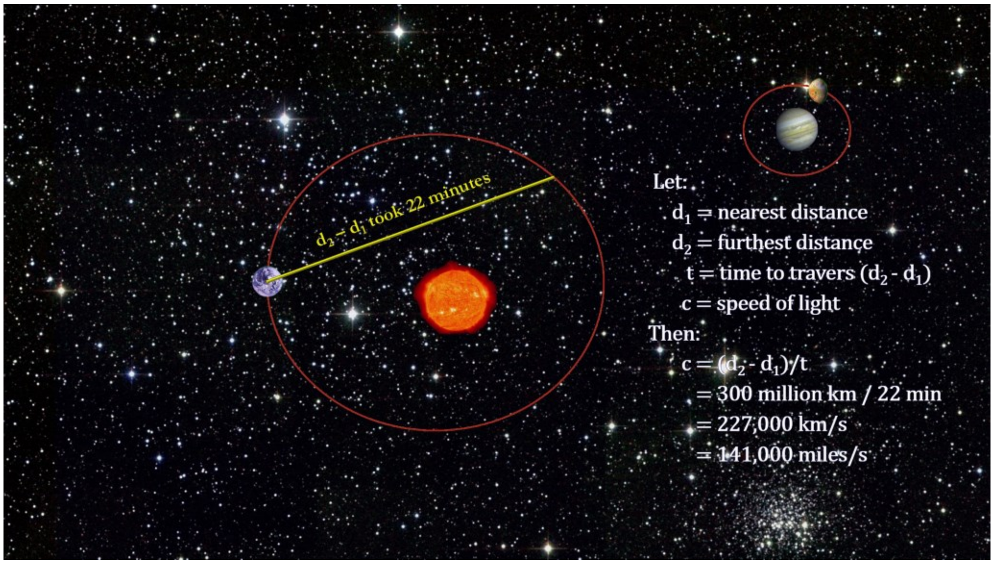
Timing these eclipses over many years, Roemer noticed something peculiar. The time interval between successive eclipses became steadily shorter as the Earth in its orbit moved toward Jupiter and became steadily longer as the Earth moved away from Jupiter.



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.

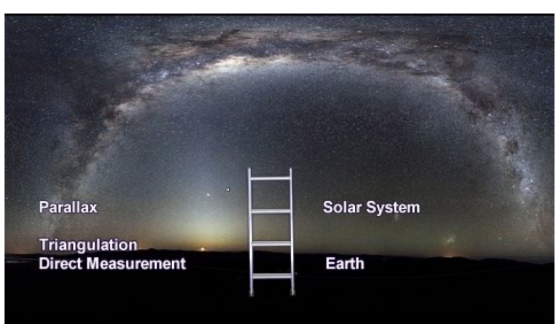


So, to answer our question about how long it takes light from the Sun to reach the Earth, we simply divide the 150 million km to the Sun by 300,000 km per second to get 500 seconds = 8.3 minutes.

[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.



Comets and the Heliosphere

*{**Abstract** – In this segment of our video book, we cover the Sentinels of the Heliosphere fleet; the distance to the edge of our Sun's solar wind; the Aurora Borealis, Comets, the Kuiper Belt and the Oort Cloud.*

We start by defining the limits of the Sun's influence, including the Termination Shock, Heliopause, Heliosheath, and the Bow Shock. Voyager 1 and Voyager 2 progress is reviewed.

Next, we cover the near-Earth fleet of satellites Hinode, RHESSI, TRACE, and FAST; the Magnetosphere satellites Cluster 1 through 4 plus Geotail; the Sun observers Stereo A and Stereo B; the solar wind observers orbiting Lagrange Point 1 – ACE, Wind, and SOHO; and back to the Magnetosphere with THEMIS A through E; and back again to Voyager 1 and 2. We conclude with a look at the big November 2011 solar storm observed by Stereo.

We then cover the nature of the aurora Borealis and aurora Australis. This includes the Bohr atomic model where we explain the quantum jumps in high altitude Oxygen atoms that create photons.

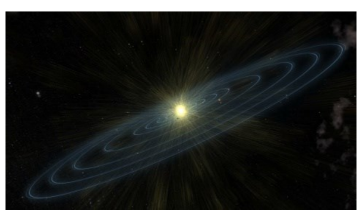
Next, we cover what a comet is and the history of comets including the Great Comet of 1577 studied by Tycho Brahe and the many comets that became Halley's Comet. We then examine comet orbits including the long period comets Siding Spring, Hale-Bopp and Lovejoy 2014, and the short period comets 67P, Encke and Halley's Comet.

These two kinds of comet orbits along with evaporating comets leads us to the Kuiper Belt and Oort Cloud as areas that generate new comets. We end the segment on comets with a look at Shoemaker Levy crashing into Jupiter and the Rosetta Mission to 67P.

We conclude with a review of the Solar System distances we have covered in this and the previous segments.}

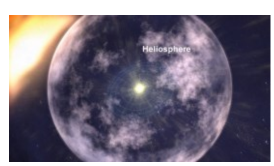
Heliosphere

The sun is moving through the galactic medium like a ship in the ocean. We are just tagging along.



As we discussed earlier, the Sun is a thermonuclear fireball that continually ejects large quantities of highly energetic particles into space. This is the Solar Wind, and it goes out in all directions.

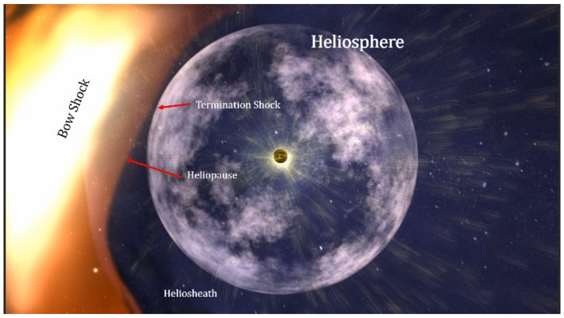
[Music @ 00:00 - *Williams, John: Braveheart End Credits; London Symphony Orchestra from the album "Braveheart - London 1995"***]**



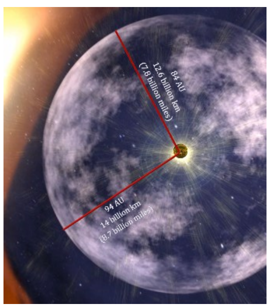
The extent of the solar wind defines the final frontier of the influence of the Sun. It's called the Heliosphere.

The solar wind's strength dies down as it is spread over ever increasing volumes of space **[**the inverse square rule applies once again**]**. As it approaches the strength of the interstellar wind coming from the rest of the Milky Way, its motion slows down abruptly. This is called the Termination Shock.

Beyond this, is a transitional region called the Heliosheath that terminates at the outermost edge of the heliosphere called the Heliopause. And, like ocean water being pushed aside by the bow of a great ship, the Sun, with its solar wind, does the same in the galactic medium. That's why they call the final boundary the Bow Shock. This marks the final extent of the solar wind and defines the outer limits of the Heliosphere.

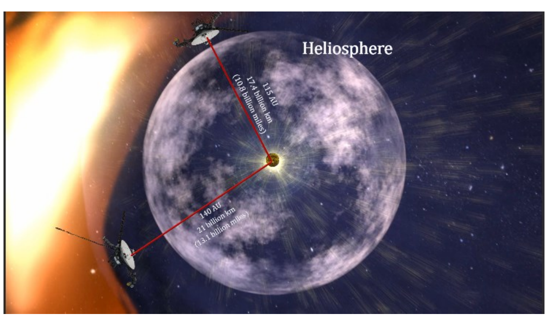


Unlike the other objects in the solar system that can be seen and triangulated to determine how far away they are, the only sure way to find out how far away the Termination and Bow Shocks are, and therefore calculate the full size of the solar system, is to go there, measure which way the wind is blowing, and report back how far you've gone.

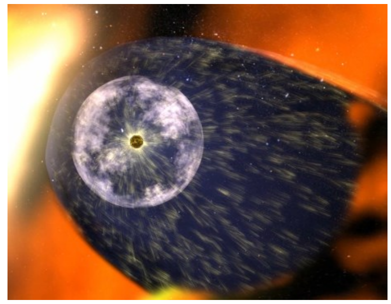


This is exactly what Voyager 1 and Voyager 2 have done. Launched in 1977, both spacecraft have passed through the Termination Shock. Voyager 1 crossed at 94 AU in December 2004. Voyager 2 crossed at 84 AU in August 2007. So, we see that the boundary is not exactly a sphere.

As of October 2017, both Voyagers are deep into the Heliosheath. [After 40 years, their instruments still report on cosmic rays, charged particles, magnetic fields and plasma waves.] When they detect a change in the direction of the wind, we'll know that they have entered interstellar space. They are expected to have enough energy to continue reporting through 2020. So, there is still a chance we'll see it happen.



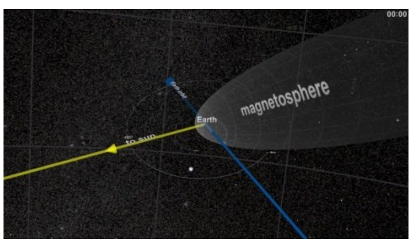
Recent magnetic field data from the Voyager probes, Cassini and IBEX the Interstellar Boundary Explorer mission indicate that the heliosphere may be more rounded than previously thought. If correct, the tail we see here would be replaced by the interstellar medium. Research is ongoing in this area.



Sentinels of the Heliosphere

We now know that the Heliosphere is not exactly a sphere. It is squashed by the galactic wind. At the squashed end, we know it extends to around 11 billion miles from the sun. That's 118 times further than the distance between the Earth and the Sun. It takes light around 16 hours to get from the Sun to the Heliosheath.

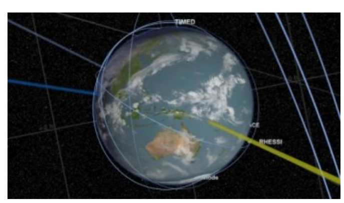
NASA's Goddard Space Flight Center in cooperation with international partners manages a fleet of spacecraft monitoring all aspects of the Heliosphere. This fleet is called the Sentinels of the Heliosphere.



The gray mesh around the Earth is called the Magnetosphere. It is the Earth's magnetic field, pushed back by the Solar Wind. It is critical for life on Earth because it routes charged particles in the wind around the earth instead of letting it bombard us head on. That makes it important for us to understand.

Near-Earth Fleet

Here's the Near-Earth Fleet. It's monitoring solar activity and orbiting Earth once every 92 minutes.



[Additional info:

Hinode (Sunrise) observes the Sun in multiple wavelengths up to x-rays, and is improving our understanding of the mechanisms that power the solar atmosphere and drive solar eruptions.

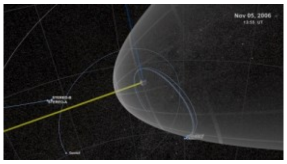
RHESSI : Observes the Sun in x-rays and gamma-rays to explore the basic physics of particle acceleration and explosive energy release in solar flares.

TRACE: Observes the Sun in visible and ultraviolet wavelengths.

TIMED: Studies the upper layers of the Earth's atmosphere: the Thermosphere, Ionosphere, and Mesosphere (40-110 miles up).

FAST: Measures particles and fields in regions where aurora borealis form to study the microphysics of space plasma and the accelerated particles that cause the aurora.]

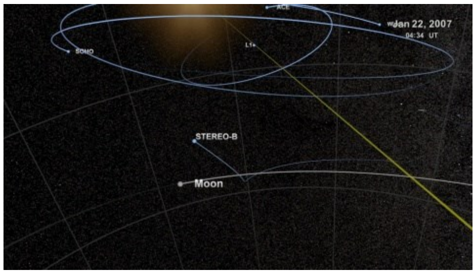
Geospace Fleet



Now we are taking a look at the Geospace Fleet that orbits deep into and around the Magnitosphere.

Cluster is a group of four satellites that fly in formation to measure the three-dimensional boundaries of the Magnitosphere as it interacts with the Solar Wind.

Geotail conducts measurements of electrons and ions in the Earth's magnetotail – the Magnitosphere pushed back by the solar wind.

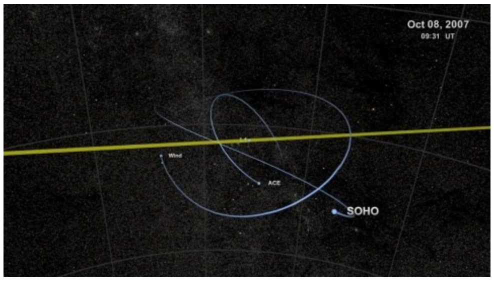


STEREO-A and B observe the Sun, with imagers and particle detectors, off the Earth-Sun line, providing a three-dimensional view of solar activity. Watch how they used the moon to set themselves apart at the best distance to view the Heliosphere.

L1 Fleet

Here we see the L1 Fleet: - orbiting the Lagrange Point 1 between the Earth and the Sun. L1 is the point between the Earth and the Sun where the gravitational pull is approximately equal in both directions.

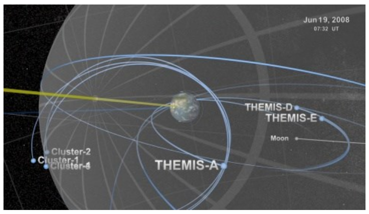
Spacecraft can orbit this location for continuous coverage of the Sun. (You may remember the Trojan Asteroids of Earth, Jupiter and Neptune that orbit other Lagrange Points that we discussed earlier). Out here, there is no Magnetosphere, so a good look at the Solar Wind is possible.



Wind: Measures particle flows and fields in the solar wind.

ACE Advanced Composition Explorer: Measures the composition and characteristics of the solar wind.

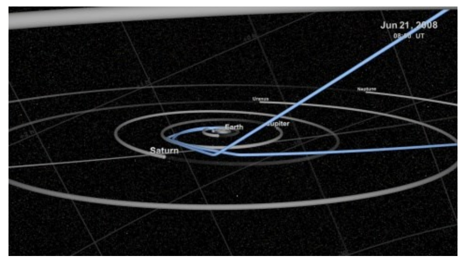
SOHO, is the famous Solar & Heliospheric Observatory studies the Sun from its deep core to the outer corona and the solar wind.



Here we see the THEMIS fleet of five satellites that study how magnetospheric instabilities produce the aurora borealis, also known as substorms.

Heliopause Fleet

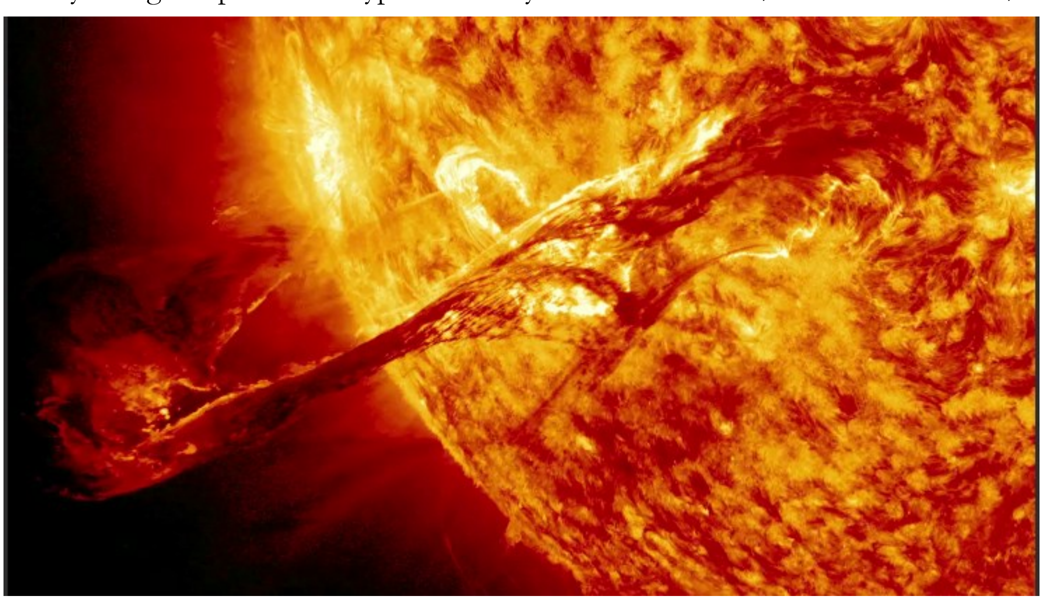
The Heliopause fleet is Voyager 1 and 2. Voyager 1 has traveled the furthest at 140 AU. That's 140 times further away from the sun than we are. It takes light almost 19 and a half hours to reach it.



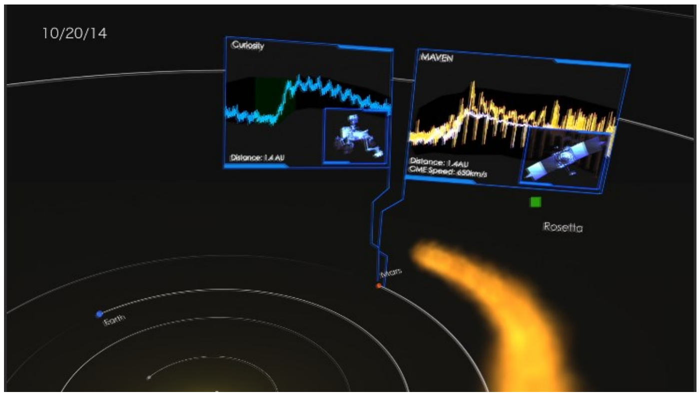
[Music @07:51 -** Debussy, Claude: Petite Suite, L.65 - 1. En bateau; Ernest Ansermet & L'Orchestre de la Suisse Romande; from the album "For the Hopeless Romantic", 2005**]

Solar Storms

Here's a solar storm that erupted on August 21st, 2012. It's like the one on October 14, 2014 that SOHO and other spacecraft tracked across the Solar System. This kind of storm is called a Coronal Mass Ejection (or CME for short). CMEs are billion-ton clouds of solar plasma launched by a single explosion. A typical velocity is around 300 km/s. That's 186 miles/s.



This 2014 CME washed over spacecraft throughout the inner solar system - including Curiosity on Mars and ESA's Rosetta orbiting comet 67P. Measuring these storms enables scientists to predicting a CME's path and strength. This is important because CMEs can disrupt communications and power systems on Earth if we are not prepared.

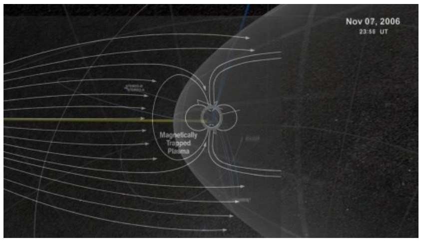


Aurora Borealis

These solar storms with their coronal mass ejections are responsible for the Aurora Borealis or Northern Lights and the Aurora Australis, or the Southern Lights.

Here's a look at the aurora borealis and aurora Australis taken from the space station.

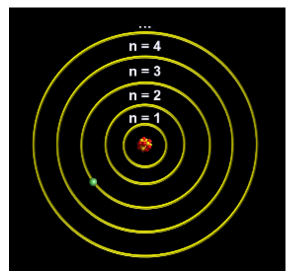
The aurora lights were a mystery for most of man's existence. It wasn't until our modern understanding of the magnetosphere via satellite observations in the second half of the 20th century was combined with Quantum Mechanics developed in the first half of the 20th century that a real understanding was reached.



What happens is that the Magnitosphere routes the solar wind charged particles along the Earth's magnetic field lines to the north and south Polar Regions. There, they collide with oxygen and nitrogen atoms in the Thermosphere.

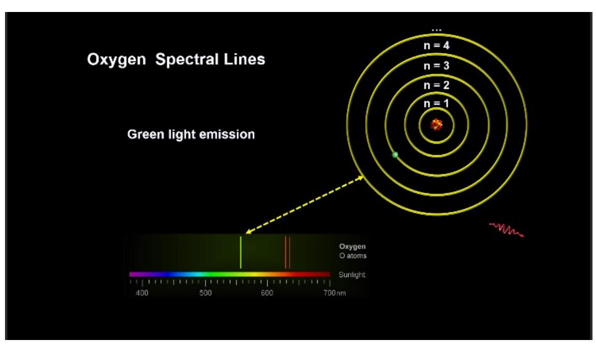
Quantum Mechanics explains how these collisions create light. I'll take a minute to explain this because it's relevant for understanding how a star's light can tell us how far away the star is.

Thanks to the work of Niels Bohr, a Danish physicist, we discovered that electrons attached to atoms occupy quantized discrete energy levels called shells. The further a shell is from the nucleus, the greater the energy level and the larger the quantum number.



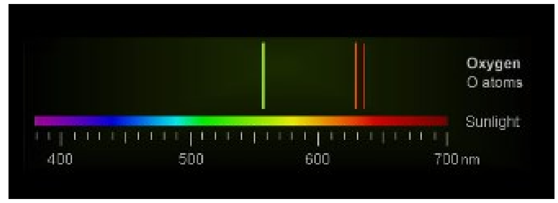
And, thanks to Albert Einstein, we discovered that light was quantized as photons and that they were:

- Created when an electron drops from a higher to a lower energy level, sometimes referred to as taking a quantum leap.
- And absorbed when a photon collides with an atom and drives an electron to a higher energy level.



In the case of the Aurora, the high velocity particles from the solar wind collide with the oxygen and nitrogen atoms in the thermosphere driving electrons in these atoms to higher energy levels. When they drop back down, photons are created.

- For oxygen emissions we get mostly green light – the most common auroras.
- From nitrogen emissions we get mostly blue or red.

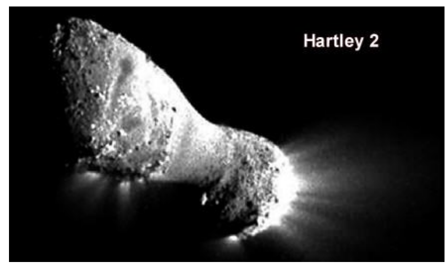


We'll go deeper into quantum mechanics and light at the beginning of our segment on distant stars

[Music @11:51 - *Williams, Vaugan: Fantasia on a Theme by Thomas Tallis; Royal Philharmonic Orchestra; from the album "Britten/Vaughan Williams/Tippett", 1990*]

Comets

A comet is a small Solar System object made of a mixture of frozen water, ammonia and various hydrocarbons, such as methane. When passing close to the Sun, it heats up and begins to outgas and displaying a visible atmosphere or coma, and sometimes a tail – the coma pushed back by the solar wind. You can see the jets in this close up photo of comet Hartley 2.

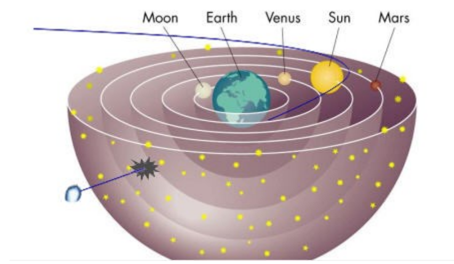


Comet nuclei range from a few hundred meters to tens of kilometers across. The coma and tail are much larger and, if sufficiently bright, may be seen from Earth without a telescope, like this image of Comet ISON.

From ancient Greece to the middle of the 16th century, Comets were thought to be luminous vapors in the earth's atmosphere. Here's a tapestry that illustrates the 1066 comet.

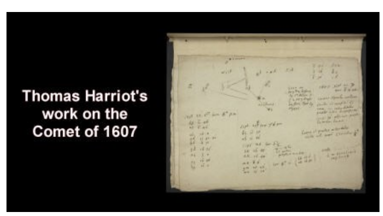
Here's the Great Comet of 1577 as seen over Prague. Tyco Brahe studied this very bright comet that shone in the night sky for 74 days. He found that he could not see any parallax. From his data, he concluded that the comet must be at least six times further away from the Earth than the Moon. This took it out of the earth's atmosphere and started people thinking differently about comets and planets.

Remember that the Ptolemy model had rotating spheres holding each plant in place. Tyco's finding would have comets crashing through these crystal spheres. As you can imagine, this tipped the scales in favor of the Copernican sun centric model and left open the question about just what holds the comets up.



Using the Great Comet of 1680, Edmund Halley worked with Isaac Newton to find out if comets were subject to the same forces as Newton had proposed for the planets. The data showed that the long elliptical paths of the comets fit Newton's theory of gravity perfectly.

In 1705 Halley studied the 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.


COMING END OF WORLD

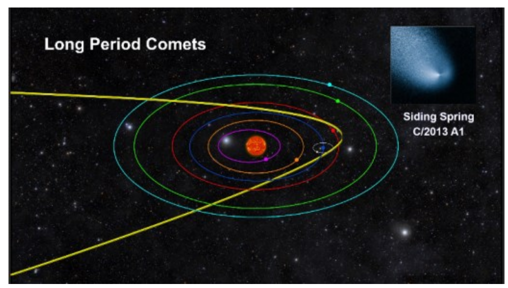
Halley's Comet May Snuff Out Life on the Earth

Here we see the 1910 Halley's Comet. **[Note:** The Earth actually passed through its tail. By 1910, spectroscopy was able to detect the elements in the tails of comets. This produced quite a scare when Haley's comet's tail was found to contain the toxic gas cyanogen.**]**

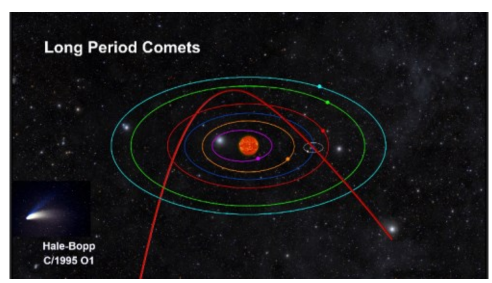
Comet Orbits

Comets come at us from all directions. And we have seen that they have two kinds of orbits: long and short. Long period comets can take thousands of years and have unpredictable orbits. Here are a few of them.

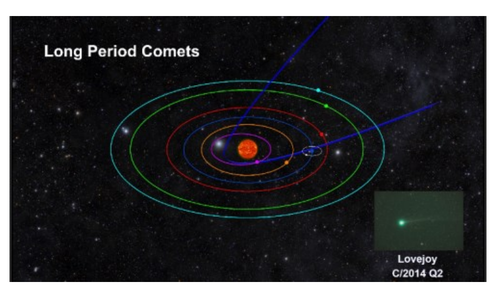
Siding Spring visited us in 2013-2014 and came very close to Mars. Mars orbiters at the time detected hundreds of kilograms per hour of the comet's dust [composed of magnesium, iron, sodium, potassium, mang anese, nickel, chromium and zinc]. It won't be back for millions of years.



Hale-Bopp was one of the brightest comets in decades. It was visible to the naked eye for 18 months. That was twice as long as the previous record held by the Great Comet of 1811. Hale-Bopp is expected back in the year 4385.

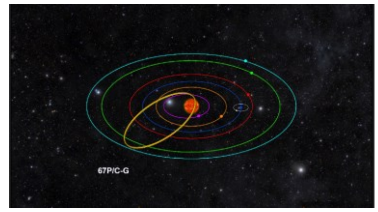


Lovejoy 2014 approached Earth to within half our distance from the Sun. It had travelled inbound for 11 thousand years. It won't return for almost 20 thousand more years.

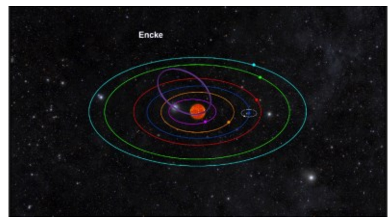


Short period comets (aka periodic comets) take as few as 3 and as long as 200 years. They are also much more predictable.

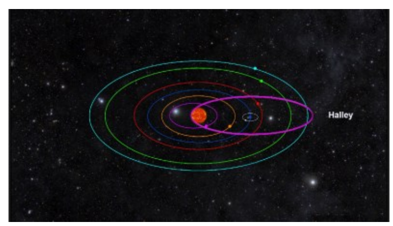
67P has an orbital period of just under 6 and a half years. At the end of this segment, we'll be covering the Rosetta Mission that landed a probe on this comet in 2014.



Encke orbits the sun in just 3.3 years. It is thought to be the originator of several meteor showers here on Earth.



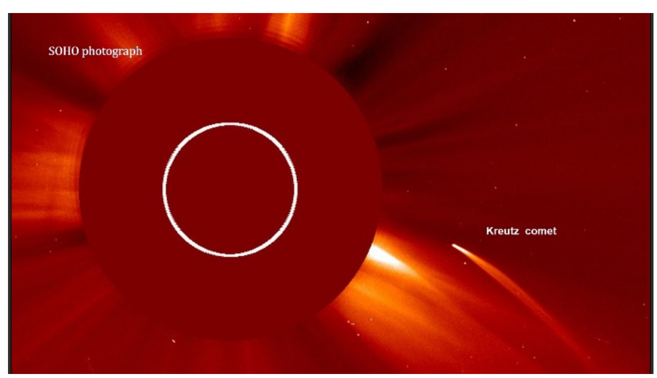
And we have already discussed Halley's Comet. My grandchildren will see it in 2061.



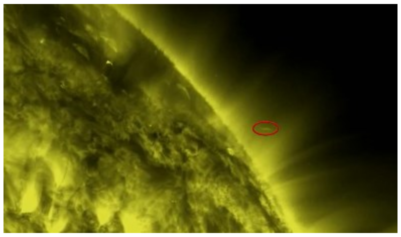
The fact that there are two kinds of orbits (long and short) lead to the idea that comets originate from two different places - with the short period comets coming from the Kuiper Belt and the longer period comets coming from a proposed area called the Oort Cloud.

Kuiper Belt and Oort Cloud

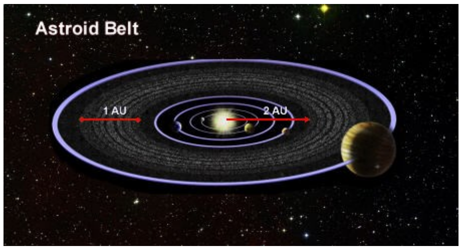
Short period comets visit the Sun so often that they quickly evaporate -- vanishing in only a few hundred thousand years. Here's one (Kreutz) that evaporated in the Sun's corona in July 2011. It was traveling at 644 km/s (that's 400 miles/s).

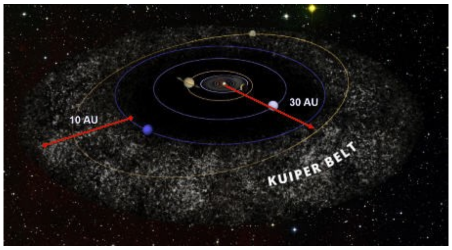


Here we see it in time lapse from the Solar Dynamics Observatory. The comet enters on the right in this video. In this second pass, I've marked it along the way. It starts out with the mass of an aircraft carrier and it's completely evaporated in 20 minutes by the searing heat of the Sun's corona.

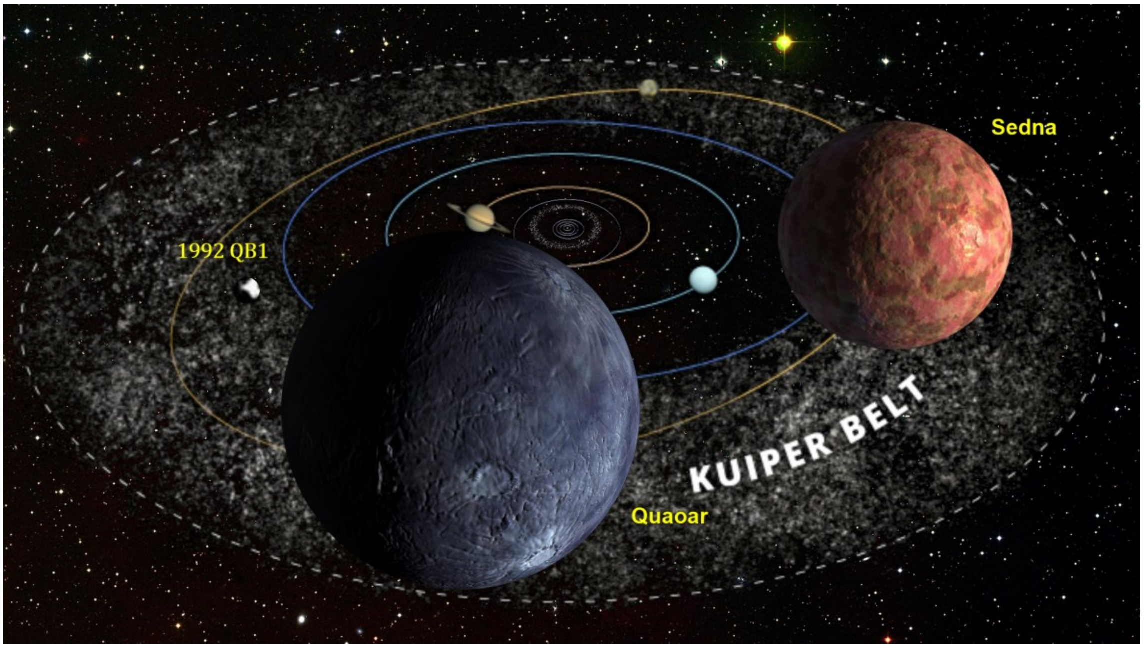


They evaporate so quickly, compared to the age of the solar system, that we shouldn't see any left at all. Yet we routinely track dozens of them every year. In 1951, Gerard Kuiper proposed that there must be a belt of icy bodies orbiting beyond Neptune that is a source for new comets. It is much further away, much larger and far less dense than the Asteroid Belt. It starts at 30 AU from the sun and is 20 AU wide.



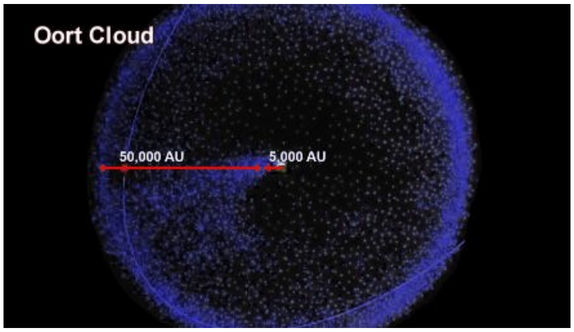


1992QB1 was the first Kuiper Belt Object (KBO for short) found. In 2002, a large KBO hundreds of kilometers in diameter named Quaoar was found. [This object was photographed in 1980, but was not noticed in those images.] In 2004, KBO Sedna (2003VB12) was discovered. And we have seen that Pluto and Makemake are dwarf planet KBOs. It is estimated that the Kuiper Belt contains a 100 million comets.



Oort Cloud

In 1950, in order to explain long period orbits, the Dutch astronomer Jan Oort proposed the existence of a cloud of comets between 5,000 and 55,000 astronomical units from the sun.



Other estimates have it going out much further. All estimates put the Oort cloud well outside the Heliosphere. Oort estimated that this reservoir contained 100 billion comets. Siding Spring, Hale-Bopp, and Lovejoy 2014 are three of them.

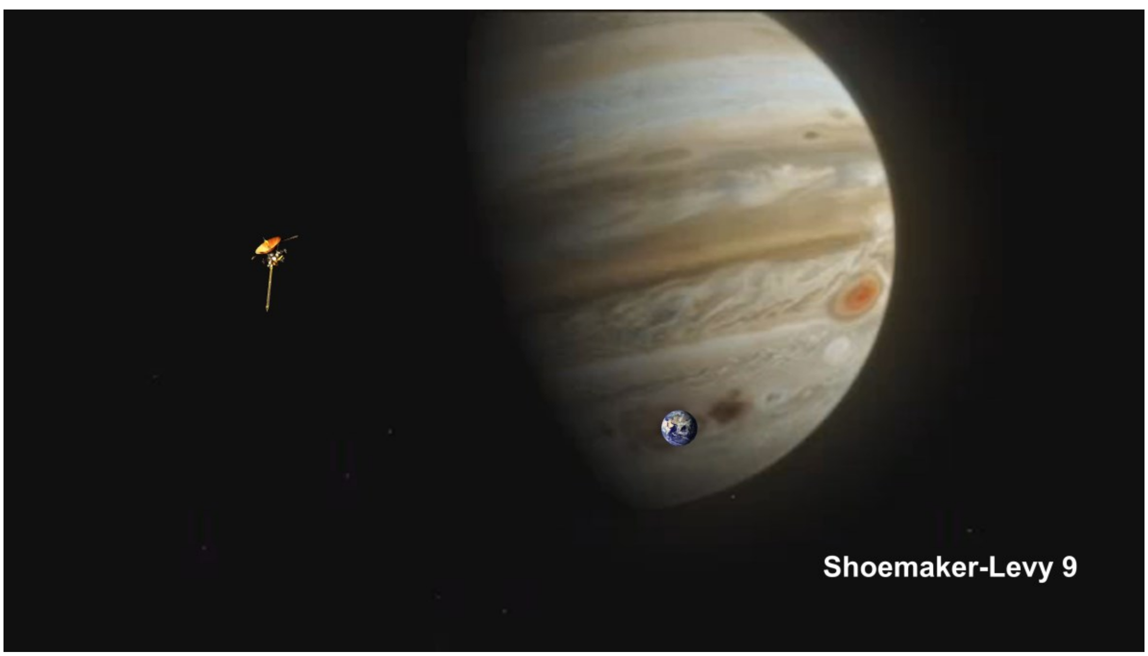
No space probe has yet been sent to the area of the Oort cloud. Voyager 1, in the Heliosheath is traveling at 1.6 million km per day (that's a million miles per day). It will take over 1,200 years just to reach the Oort Cloud, and over 12 thousand years to pass through it. So, its existence will remain a theory for some time to come.

Shoemaker-Levy

We'll end our segment on comets with a look at two of them that changed our thinking and our capabilities when it comes to these objects. In 1994, the comet Shoemaker Levy collided with Jupiter.

The first impact occurred at 20:13 on July 16, when fragment A of the nucleus entered Jupiter's southern hemisphere at a speed of about 60 km/s (that's 37 miles per second). Instruments on the nearby Galileo spacecraft detected a fireball plume that reached a height of almost 3,200 km. (that's 2,000 miles.) Remember that our atmosphere extends only a few hundred km above us.

Observers soon saw a huge dark spot after the first impact – 6,000 km wide (3,700 miles). Over the next 6 days, 21 distinct impacts were observed, with the largest coming on July 18. This impact created a giant dark spot larger than the Earth. Jupiter absorbed them all. The changes to the planet were dramatic but disappeared after a few months. But if Shoemaker Levy had hit the Earth instead of Jupiter, it would have wiped us out.



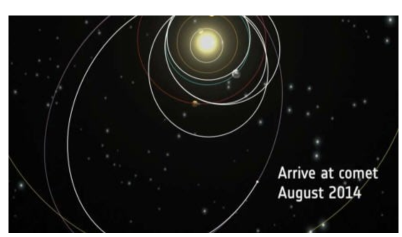
This highlighted for everyone the importance of understanding comets (and asteroids) and how to change their trajectory should we ever find one heading our way. Progress in this area has been made.

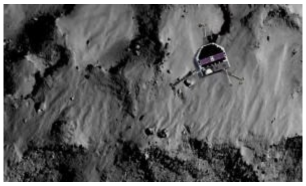
Rosetta Mission to Comet 67P/Churyumov-Gerasimenko

Here's a close up look at comet 67P/CG. Its overall length is 5 km. And the larger of its two lobes is 4.1 km wide. That might not sound like much, but here' what an object this size would look like if we placed it over a city like Toronto, Canada.

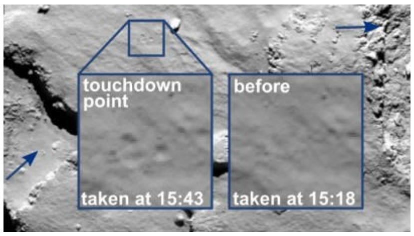
The European Space Agency launched the spacecraft Rosetta in 2004. Its mission was to rendezvous with comet 67P; deploy a lander called Philae to its surface; and escort the comet as it orbits the Sun.

Ten years later, on August 6th, 2014, after getting several gravity assisted velocity busts, and traveling 6.4 billion kilometers, *Rosetta* rendezvoused with 67P.

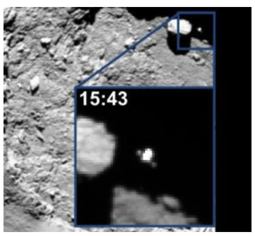




Philae landed on the surface on November 12th, becoming the first spacecraft to land on a comet. Here we see the lander's big bounce off the comet with these pictures captured by

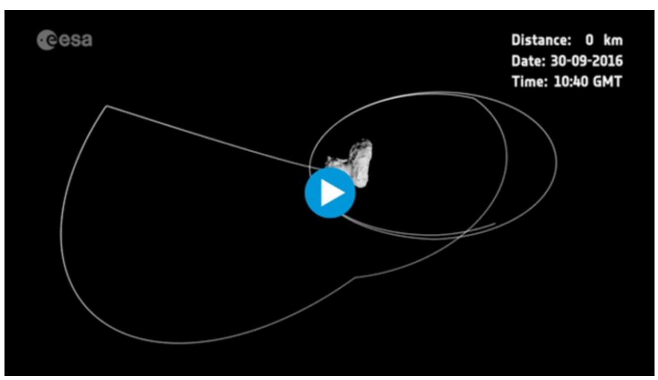


its orbiting mother ship. This is where it first landed. You can see the before and after pictures where Philae made its mark. But the harpoons that were meant to anchor it to the comet did not deploy.

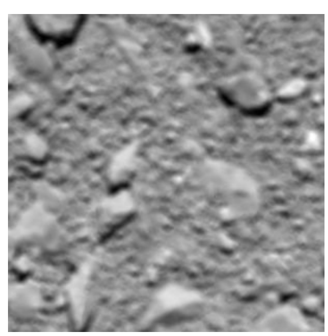


It ended in the shade and has lost its power. But Rosetta continued to transmit for another two years before its power ran out as well.

At that point, in September 2016, the Rosetta mission concluded with a controlled impact onto the comet. Here's the collision course into the comet from an altitude of around 19 km.

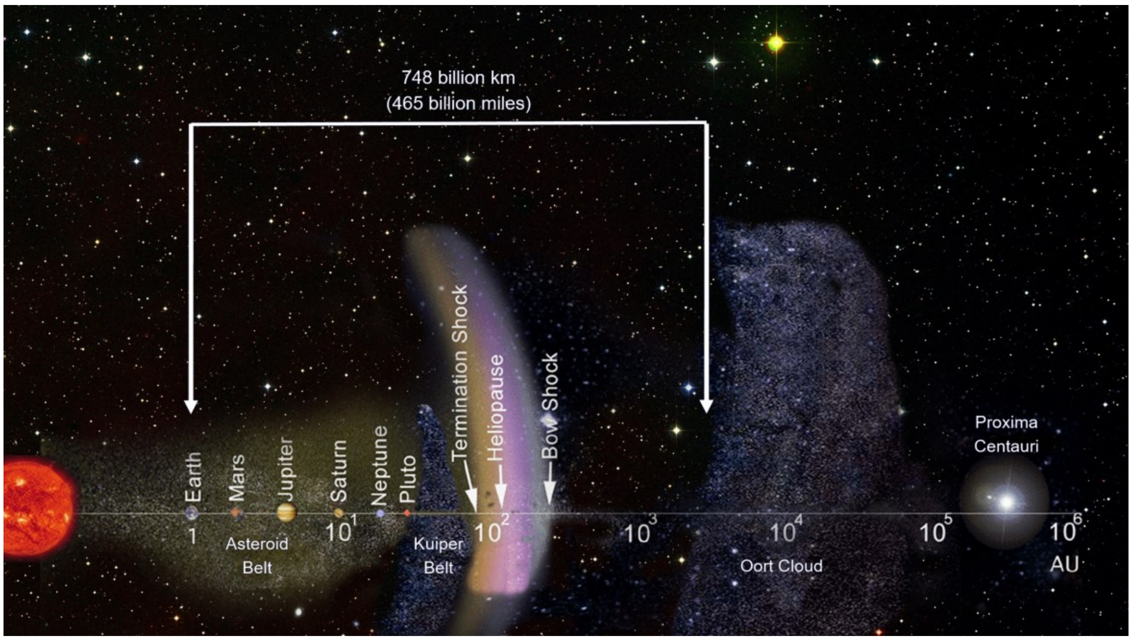


Rosetta targeted a region on the small lobe of the comet, close to a region of active pits. Pits are of particular interest because they play an important role in a comet's activity. Transmissions continued up to the moment of impact. The comet is now beyond the orbit of Jupiter and heading for the Kuiper Belt. It will return with Rosetta's wreckage on board in 2021.



Solar System Distances

Now that we have a feel for the size of the Heliosphere, the Kuiper Belt and the Oort Cloud, let's review how far away the main objects in our Solar System are.



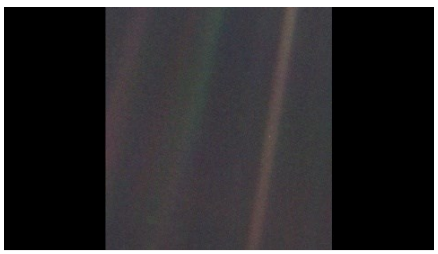
- The Sun is 150 million km (93 million miles) away and a millions earths could fit inside it.
- Mars' orbit is half again as far away as that at 78 million km (48 million miles) from ours.
- Jupiter, the largest planet in the Solar System is 5.2 times further away from the sun than the Earth is. That puts its orbit 772 million km (480 million miles) away from ours.
- The Asteroid Belt fits between Mars' and Jupiter's orbit.
- Pluto's orbit in the Kuiper Belt is 5.6 billion km (3 and a half billion miles) away.
- We have seen that the Kuiper Belt goes from 4 and a half billion km (2.8 billion miles) out to 7 and a half billion km (4.3 billion miles).
- The Termination Shock is 18 billion km (11 Billion miles) away.
- And the Bow Shock is thought to be 19 billion km (12 billion miles) away.
- We have just seen that the Oort Cloud starts much further away than that at 748 billion km (465 billon miles) and extends out to 8.2 trillion km (5.1 trillion miles) or more.

We have used direct measurement by going there, triangulation, and planetary parallax to calculate these Solar System Distances. In our next segment on Nearby Stars, we'll advance our cosmic distance ladder to cover how we know how far away it is to Proxima Centauri, our nearest stellar neighbor.

[Pale Blue Dot

In the first segment, we learned just how vast the Earth is: how high the sky is; how far away the continents are across the great oceans of the world. But now that we've seen the enormous size of the Solar system, we can put Earth's size into this broader perspective.

Back in 1990, Carl Sagan requested that Voyager 1 be turned around to photograph Earth. It was only 4 billion miles away back then. The picture highlights just how small the Earth really is compared to the huge size of the Solar System. Here is the famous clip he created around this photograph. He expresses my feelings to a tee.



[Music: *Vangelis' "Heaven and Hell": This is the music Carl Sagan chose as the theme music for his entire 'Cosmos' series. It is repeated here and in other 'How far away is it' segments.*

"From this distant vantage point, the Earth might not seem of any particular interest. But for us, it's different. Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives.

"The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there – on a mote of dust suspended in a sunbeam. The Earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that in glory and triumph they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the inhabitants of one corner of this pixel on the scarcely distinguishable inhabitants of some other corner.

"How frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds. Our self-importance, the delusion posturings, our imagined that we have some privileged position in the universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity – in all this vastness – there is no hint that help will come from elsewhere to save us from ourselves.

"The Earth is the only world known, so far, to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment, the Earth is where we make our stand.

"It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another and to preserve and cherish the pale blue dot, the only home we've ever known."

—Carl Sagan, *Pale Blue Dot: A Vision of the Human Future in Space, 1997 reprint, pp. xv–xvi*]

Nearby Stars

{Abstract *– In this segment of our video book, we take a look at our stellar neighborhood and how we know how far away these nearby stars are.*

We cover the first stellar parallax measurement form the star Cygni 61. This includes the definition of 'parsec' and 'light year'. We then cover the Alpha Centauri system (Proxima Centauri, Alpha Centauri A & B), and use it to show how we calculate the mass of binary star systems. Then we examine our stellar neighborhood including: Barnard's Star with its Proper Motion, Wolf 359, Lalande 21185, Sirius A & B, 61 Cygni, Altair, Fomalhaut with its planet, and Vega.

A deeper look into what we mean by 'luminosity' is outlined. We point out that it is measured in watts just like a light bulb and that its value over distance from a point source follows the 'inverse square law'. We use our Sun as an example and introduce Einstein's famous "energy = mass time the speed of light squared" formula.

We then cover some more stars including: Pollux, Arcturus, Capella, and Castor. Having reached the limits of ground-based telescopes to measure parallax, we discuss the European Space Agency's (ESA) Hipparcos satellite and the more distant stars it helped fined parallax for including: HD 189733, Aldebaran, Mizar, Spica, Mira, Polaris, and Antares. Along the way, we build the mass vs. luminosity empirical graph.

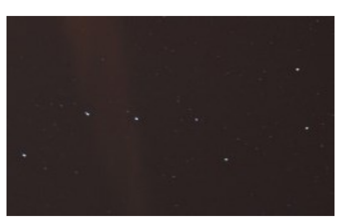
We then cover the new ESA satellite Gaia that is mapping over a billion stars in the Milky Way and nearby galaxies. We follow that with a look at a few stars too far for Hipparcos but well within the range of Gaia: Betelgeuse, CH Cyg, and Rigel.

*We end by pointing out that parallax only takes us to a small percentage of stars in the Milky Way and that we'll need to know more about light to go any further.**}***

Introduction

Twinkle twinkle little star. I imagine that hundreds of thousands of generations have wondered what they are.

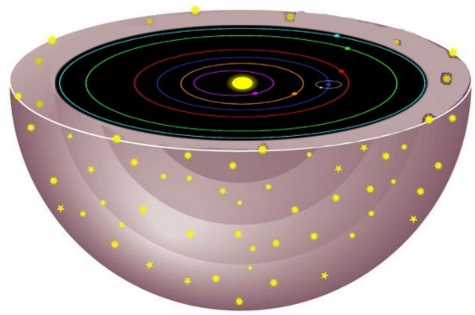
> ***[Music:*** *"Twinkle twinkle little star": This children's music asks the ancient question "what are stars?" This is the very question we will attempt to answer in this video book segment.**]***



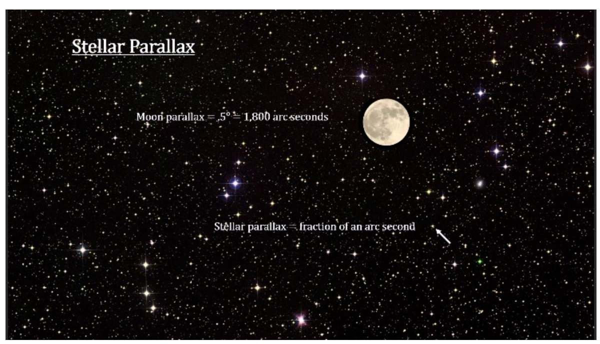
Here I am again in my back yard, looking at the Big Dipper. On a clear dark night, I can see around a thousand stars. For the longest time, it was not known whether stars like these shined by their own light, or whether they were reflecting the Sun's light, as all the planets, moons, comets, and asteroids do. It's only in the last couple of generations that we have finally reached a point where we know what stars are.

[Music @0:31:** Tchaikovsky - Symphony No 6, Pathétique IV Finale. Prague Festival Orchestra; from "Must-Have Adagio Masterpieces"**]

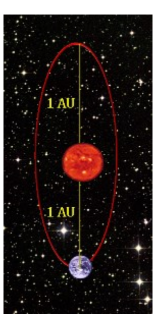
You'll recall that Copernicus first proposed a Sun centric model for the solar system. But you'll note that the outermost celestial sphere did not go away with the Copernican model. Parallax measurements showed us that the Sun was at the center of our planetary system. But no one could find any parallax in the stars – not Tycho Brahe, not Kepler, not Galileo, not even Newton.



The reason it took so long is that stars are so far away, that parallax angles are just too small for the available instruments. Remember that the moon's parallax was ½ of a degree. But star parallax is measured in fractions of an arch second. **[**That's why it took over 300 years of trial and error after Copernicus, before it became possible to measure these small angles.**]**

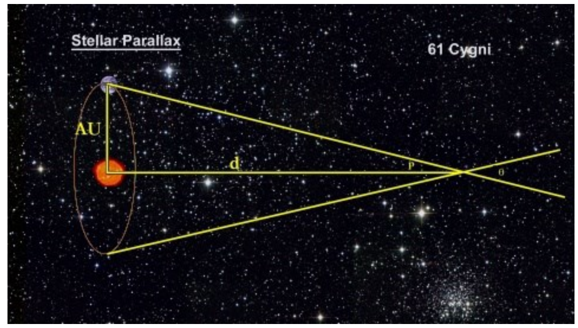


First Stellar Parallax

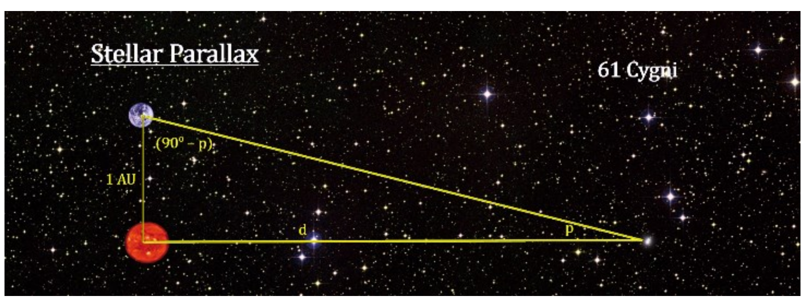


In the 1830s, there was a race to see who could find the first real stellar parallax. The astronomer Fredrich Bessel won. The star was 61 Cygni. Here's how it works. If you recall, the maximum baseline for parallax measurement for planets was the diameter of the Earth. For stellar parallax, we have the diameter of the Earth's orbit around the Sun. That's an increase from around 13 thousand km (or 8 thousand miles) to 300 million km (or 186 million miles). That's 23 thousand times larger.

So, from one side of the earth's orbit (say in July) we take a line to the star, and map the positions of the more distant stars. Six months later in January, we repeat the process. This gives us the angle θ. We define stellar parallax as ½ this angle. This would be the angle at the star with the Earth and the Sun marking the other two corners of a right triangle. The math is the same trigonometry we used for finding distances to the rock in my back yard and to the planets in our solar system.



Of course, this is an oversimplification. Fredrich Bessel mapped 61 Cygni against the distant star background for 28 years observing the star's ellipses that followed the earth's orbit. In 1838, after thousands of measurements and calculations, he made scientific headlines by announcing that the parallax of 61 Cygni was 0.314 arcseconds. That gives us a distance of 98 trillion km – that's 61 trillion miles. [That's over 6 hundred thousand times further from the sun than we are.] Why too far to be reflecting the Sun's light. So, at this point, in the middle of the 19^{th} century, we knew that stars burned with their own light.



Let

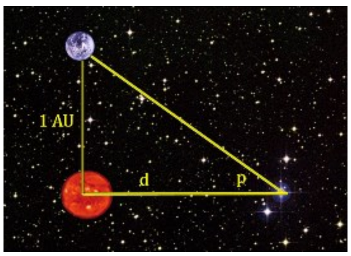
d = distance to 61 Cygni
p = measured parallax
= 0.314"
= 0.0000872 degrees

We have

$$
\begin{aligned}
d &= (1\ \text{AU}) \tan(90^\circ - p) \\
&= (150 \times 10^6\ \text{km}) \tan(90 - 0.0000872) \\
&= (150 \times 10^6)(6.57 \times 10^5)\ \text{km} \\
&= 98.6 \times 10^{12}\ \text{km} \\
&= 61.3 \times 10^{12}\ \text{miles}
\end{aligned}
$$

Parsec

If we were to move in a little closer to a star that had a parallax of exactly 1 second of arc, we'd find it to be 31 trillion km away (that's 19 trillion miles). This distance is called a Parsec. It gets its name from the first syllable of 'parallax' and the first syllable of 'second'. Astronomers like to use it for measuring distances to stars. If you're a Star Trek fan, you'll hear parsecs used a lot in their distance discussions.



Parsec

Let $p = 1$ second of arc
$= 0.000278$ degrees

Then
$$\begin{aligned} d &= (1\ \text{AU}) \tan(90^{o} - p) \\ &= (150 \times 10^{6}\ \text{km}) \tan(90 - 0.000278) \\ &= (150 \times 10^{6})\ (2.06 \times 10^{5})\ \text{km} \\ &= 30.9 \times 10^{12}\ \text{km} \\ &= 19.2 \times 10^{12}\ \text{miles} \\ &= 1\ \text{parsec} \end{aligned}$$

In parsecs

$$d = 1/p$$

Light Year

As we discussed in our segment on the Solar System, light travels at 300,000 km/s (or 186,000 miles per second).

To calculate how far light travels in a year, we multiply this number by the seconds in a minute; the minutes in an hour; the hours in a day; and the number of days in a year. That totals 9.461 trillion km (or 5.88 trillion miles). We call that 1 light year. So, 1 parsec is just over 3 and a quarter light years [equal to 3.26 light years]. I'll use light years throughout this video book, but parsecs will come up from time to time.

Let $c =$ speed of light
$= 300{,}000$ km/s
$= 186{,}000$ miles/s

Then 1 light year $= c \times 60 \times 60 \times 24 \times 365$
$= 9.461$ trillion km
$= 5.88$ trillion miles

And 1 parsec $=$ 3.27 light years

Alpha Centauri System

Let's take a look at some of the stars in our neighborhood - out to around 25 light years. That's about as far as stellar parallax measurements from ground-based telescopes can take us.

Proxima Centauri – p = 0.768 (4.25 light-years)

Proxima Centauri is a dim red star. It is the nearest known star to the Sun and thought to be a third member of the Alpha Centauri system. Here's a recent photo of the star taken by Hubble. Although it looks bright through the eye of Hubble, Proxima Centauri is not visible to the naked eye. Its average luminosity is very low, and it is quite small compared to other stars, at only about an eighth of the mass of the Sun. Astronomers predict that this star will remain for another four trillion years, a thousand times longer than our Sun.

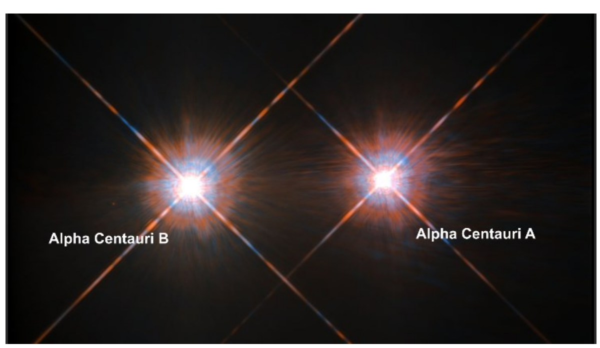
[Note: However, on occasion, its brightness increases. Proxima is what is known as a "flare star", meaning that convection processes within the star's body make it prone to random and dramatic changes in brightness. The convection processes not only trigger brilliant bursts of starlight but, combined with other factors, indicated that Proxima Centauri is in for a very long life.**]**

Alpha Centauri – p = 0.755 (4.37 light-years)

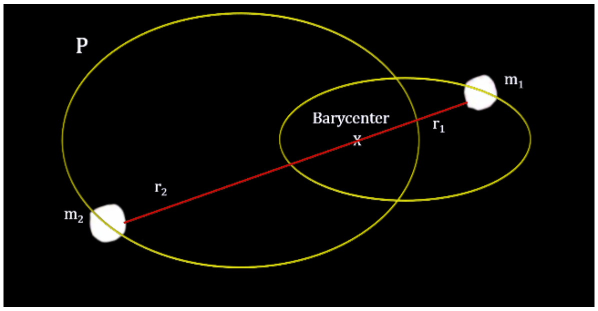
Alpha Centauri A and B form a close binary system that is separated "on average" by a distance slightly greater than the distance between Uranus and the Sun. A, the main star, is bright and yellowish. B is not quite as bright and has an orange tinge.

Mass of a star

Here's a recent photograph of the Alpha Centauri binary system take by Hubble. It turns out that half of all stars are actually binary systems like this one. It is the orbital motion of these kinds of stars that enabled us to measure stellar mass - just like we calculated the mass of the Sun by the motion of the planets around it.



These stars orbit the system's center of gravity (called the barycenter). We can observe the distance between the stars and locate the barycenter as the center of their elliptical motion. We can also observe the length of time it takes to make a full orbit (its Period). This, along with Newton's and Kepler's laws is all we need.



Let

P = orbital period

$r = r_1 + r_2$

$m = m_1 + m_2$

G = gravitational constant

We have

$m = 4\pi^2 r^3/GP^2$

$m_1 = m(r - r_1)/r$

Carful observations of Alpha Centauri, show that the distance between the two stars is just under 24 time the distance from the Earth to the Sun, with A's distance to the barycenter being a little less than half of that. In addition, we see that the orbital period is almost 80 years. This gives us the mass of A at just over the mass of the Sun, and the mass of B at just under the mass of the sun.

For Alpha Centauri

$P = 79.92$ years

$r = 23.7$ AU

$r_1 = 11.2$ AU

$G = 6.67 \times 10^{-11}\ m^3kg^{-1}s^{-2}$

We have

$m = 4\pi^2 r^3/GP^2$

$= 4.17 \times 10^{30}$ kg

$m_1 = m(r - r_1)/r$

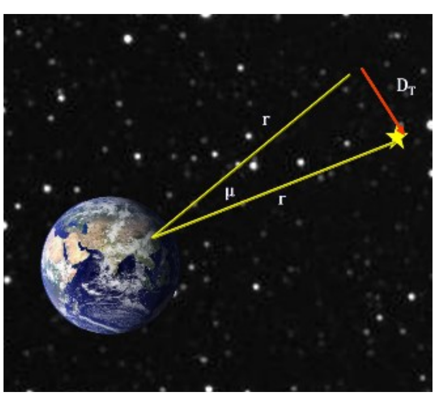
$= 2.2 \times 10^{30}$ kg $= 1.10\ M_{sun}$

$m_2 = m - m_1$

$= 1.97 \times 10^{30}$ kg $= 0.99\ M_{sun}$

Star Motion

For the most part, the position of stars is virtually identical from century to century. But a very small number of relatively nearby stars show dramatic motion across the sky. This is called **Proper Motion**. Its magnitude can be measured using the number of degrees moved and the distance to the star.



Let

μ = proper motion in arcseconds

p = stars parallax

r = distance to star

D_T = tangential distance traveled

V_T = tangential velocity

t = time

We have

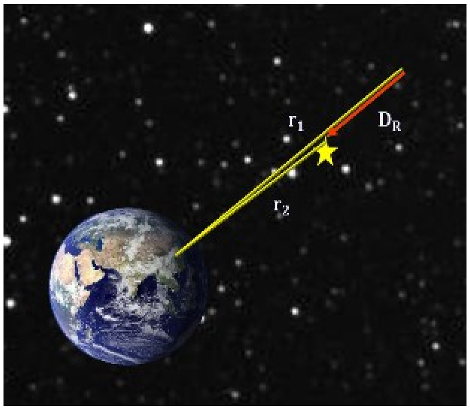
$\mu/360^\circ = D_T/2\pi r$

$D_T = 2\pi r\mu/360^\circ$

$V_T = D_T/t = 2\pi\mu/pt360^\circ$

$V_T = 4.74\ \mu/p$ in km/s

Motion towards us or away from us is called **radial motion**. We define it as positive if the star is moving away and negative if it is moving closer. For nearby stars this motion can be detected by using parallax techniques.



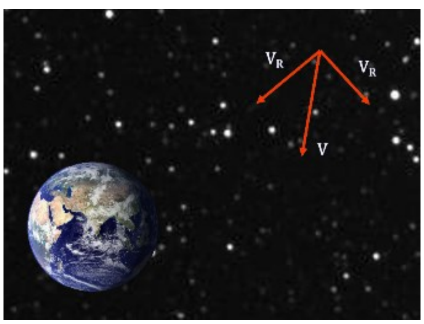
Let

p_1 = stars parallax at time 1
p_2 = stars parallax at time 2
r_1 = distance to star at time 1
r_2 = distance to star at time 2
D_R = radial distance traveled
V_R = radial velocity
t = time

We have

$$D_R = r_2 - r_1 = 1/p_2 - 1/p_1$$
$$V_R = (r_2 - r_1)/t$$

With these two numbers, the total star motion with respect to the sun can be calculated using the Pythagorean Theorem.

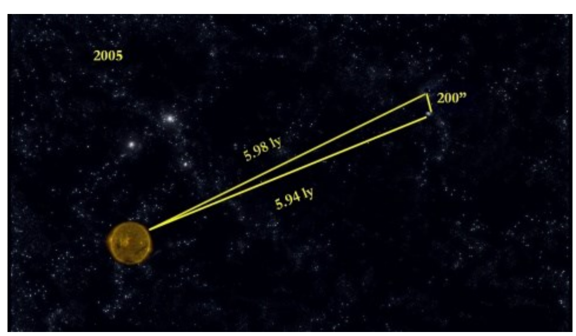


$$V = (V_R{}^2 + V_R{}^2)^{1/2}$$

Barnard’s Star – Parallax = 0.545 (5.94 light years)

For example, here’s Barnard's Star. It’s a dim red star with significant proper and radial motion. It’s moving so fast that it’s called a “runaway” star.

Here’s a look at Barnard’s Star photographed in 1985. Its parallax measurement indicates that its distance is 5.98 light years. In this second photograph, taken 20 years later in 2005, we see that the star has moved 200 arc seconds across the sky. That’s 10” of arch across the sky per year. This is its Proper Motion. Its new distance is 5.94 light years which gives us its radial motion.



Combined, we get the full motion of the star with respect to the Sun. It moves 19.1 billion km each year. (That's 11.9 billion miles). So you can see why it is called a runaway star. In fact, Barnard's Star is approaching us so rapidly that around 11,700 AD, it will be 3.8 light years from the Sun - and that will make **it** the closest star to our own!

Proper Motion

$$\begin{aligned} V_T &= 4.74\ \mu/p \text{ in km/s} \\ &= 4.74 \times 10 / 0.546 \\ &= 86.8 \text{ km/s} \\ &= 2.74 \text{ billion km/year} \end{aligned}$$

Radial Motion

$$\begin{aligned} V_R &= |\, r_1 - r_2 \,| / t \\ &= 0.04 \text{ ly} / 20 \text{ years} \\ &= 18.9 \text{ billion km/year} \end{aligned}$$

Star Motion

$$\begin{aligned} V_{Star} &= (V_T^2 + V_R^2)^{1/2} \\ &= (2.74^2 + 18.9^2)^{1/2} \\ &= 19.1 \text{ billion km/year} \\ &= 11.9 \text{ billion miles/year} \end{aligned}$$

[Music @10:40: *Suppe - Poet and Peasant Overture: Hungarian State Opera Orchestra & Janos Sandor, Janos Sandor, Hungarian State Opera Orchestra; from the album Franz von Suppé: Poet & Peasant***]**

Stellar Neighborhood

Wolf 359 - Parallax = 0.415 (7.86 light years)

Getting back to nearby stars, here's Wolf 359. It is another dim red star. In fact, it's one of the least luminous stars known.

Star Trek fans may recognize Wolf 359 as the scene of a great battle between the Federation and The Borg.

Lalande 21185 - Parallax = 0.393 (8.31 light years)

Lalande 21185 is another dime red star. Recent analysis indicates that it may also be accompanied by at least two orbiting planets. One was confirmed in 2017. The search for planes around other stars (called Exoplanets) is a major focus these days and research is ongoing.

Sirius A & B - Parallax = 0.379 (8.60 light-years)

This Hubble Space Telescope image shows a white Sirius A, the brightest star in our nighttime sky, along with its faint, white tiny stellar companion, Sirius B. The two stars revolve around each other every 50 years.

[Additional info: Astronomers overexposed the image of Sirius A so that the dim Sirius B [tiny dot at lower left] could be seen.**]**

61-Cygni – Parallax = 0.286 (11.4 light years)

Here we have our first parallax star, 61 Cygni again. Modern measurements place the star at 11.36 light-years distant. So Bessel's calculation of 10.4 light years was pretty close. 61 Cygni has another claim to fame in that it was first noted to have a high proper motion as early as 1792, when it got the nickname "Flying Star". To add further to its uniqueness, in 1830 61-Cygni was determined to be a binary star system with two orange stars.

Altair - Parallax = 0.295 (16.7 light-years)

Altair is a bright white star. A recent study revealed that Altair is not spherical, but is flattened at the poles due to a very high rate of rotation.

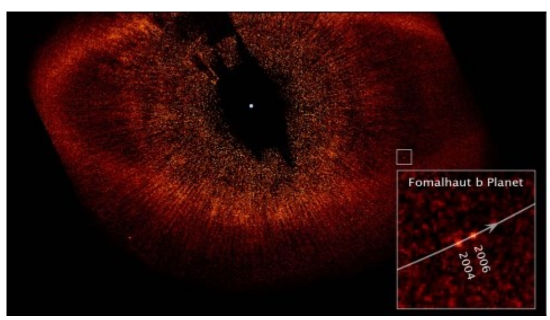
Vega - Parallax = 0.130 (25.0 - light-years)

Vega is a bright white star and one of the most luminous stars in the Sun's neighborhood. It has been extensively studied. It was the first star to be photographed by astronomers in 1850.

It was the northern pole star around 12,000 BC and will be so again around AD 13,727.

Fomalhaut - Parallax = 0.130 (25.1 light-years)

This image of Fomalhaut surrounded by a ring of debris was taken by Hubble.



The white dot in the center of the image marks the star's location. It's a bright white star, but the region around it is black because astronomers used the Advanced Camera's capabilities to block out the star's bright glare so that a dim planet called Fomalhaut b could be seen. The small white box, at the lower right, pinpoints the planet's location.

These observations offer insights into our solar system's formative years, when the planets played a game of demolition derby.

Luminosity

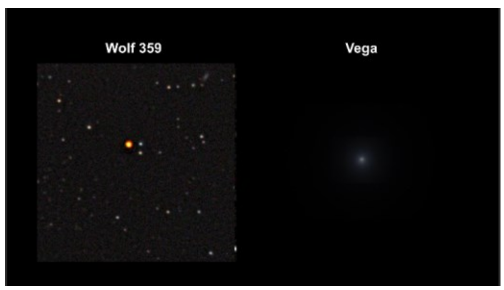
So far, we've identified Wolf 359 as one of the least luminous stars in our neighborhood and Vega as one of the most luminous, but we haven't been explicit as to what we mean by luminous.

Stars have a wide range of apparent brightness as measured here on Earth. The variation in apparent star brightness is caused by two things:

1) Stars have different intrinsic luminosity.

2) Stars are located at different distances from us.

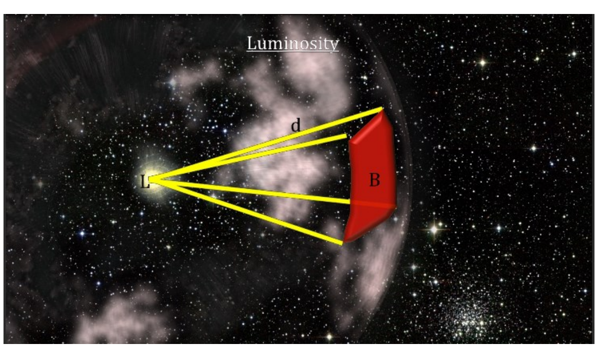
An intrinsically faint, nearby star can appear to be just as bright to us on Earth as an intrinsically luminous, distant star.



Luminosity is what we use to put precise measurements on the idea of brightness. It measures the total amount of electromagnetic energy emitted by a star in watts (just like a light bulb). Apparent brightness is measured in watts/m^2.

> **[Additional info:** For stars, the area we use is the area of the telescope's lens.**]**

Because light from stars spreads out over the surface area of a sphere, we can use the inverse square law to categorize luminosity for all the stars that have parallax distance information.



Let

d = distance to the source
L = luminosity of source in watts
B = brightness in W/m^2

We have

$$L = 4\pi d^2 B$$

Take the Sun for example. The apparent brightness of the Sun, as measured in my back yard, is 1400 watts per square meter. If my backyard solar cells where 100% efficient, that's how much electricity each panel would create. Unfortunately, current technology is only 15% efficient, so I'm only getting around 200 Watts per panel.

Plugging our distance to the sun into the inverse square law, we calculate its total luminosity. Here you can see that the answer is a very big number.

Let

d = distance to the source
L = luminosity of source in watts
B = brightness in W/m²

We have

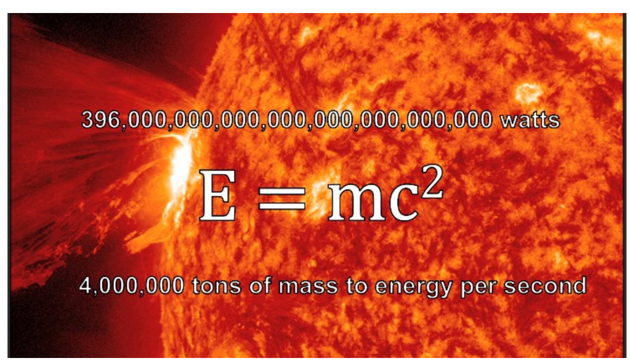
$$L = 4\pi d^2 B$$

Using Einstein's famous $E = mc^2$, or Energy = mass time the speed of light squared we calculate that the Sun is fusing 600 million tons/sec of Hydrogen in to Helium, and in the process converting 400 million tons/sec of matter into energy.

To put this into perspective, this number is equivalent to around 4 billion Hydrogen bombs exploding per second!

[Additional info: Luckily for us, the Sun has enough mass to keep this process going for at least another 4 billion years!**]**

The apparent brightness from stars is a tiny fraction of what we get from the Sun. But modern instruments are very good at measuring it very precisely. The equation to determine the intrinsic luminosity is the same. For Vega, the measured luminosity at 25 light years gives us the luminosity for the star at 40 times the Sun's power.
For the Sun and for Vega, and for all the stars we have seen so far, we know the apparent brightness and distance to the star via parallax. The inverse square law gives us the intrinsic luminosity. If we know the intrinsic luminosity and apparent brightness, the same equation gives us the distance. In other words, if we know the luminosity of a star, we can calculate its distance. This is the basic concept around 'Standard Candles'. We'll discuss this a little more in a few minutes. **]** Astronomers use a more complex set of classifications for calculating brightness called Magnitudes and absolute magnitudes at 10 parsecs. But, for our purposes, we'll stick to Luminosity.



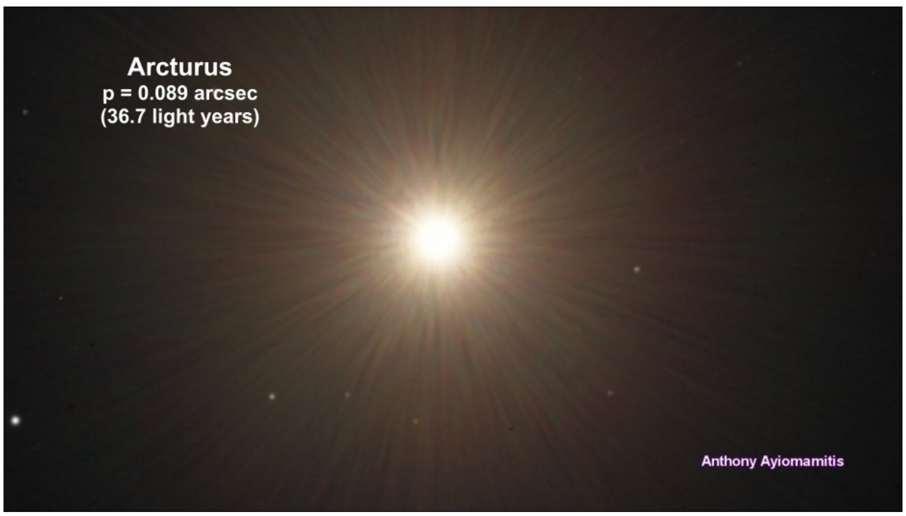
More Neighborhood Stars

Pollux – Parallax = 0.098 – (33.8 light years)

Getting back to stars, here's Pollux, a bright orange star. In 2006, it was confirmed to have an orbiting planet.

Arcturus – Parallax = 0.089 (36.7 light years)

Arcturus is an even brighter orange star. In fact, it is the fourth most luminous star in the Sun's neighborhood.



Capella – Parallax = 0.076 (42.9 light-years)

Capella has a rich yellow color and is the third brightest star in the northern hemisphere, after Arcturus and Vega. Closer examination finds that Capella is actually four stars organized as two binary systems.

[GJ1214 – Parallax = 0.069 (47.5 light-years)

GJ1214 is a dim reddish star. Observations by Hubble in 2009 discovered GJ1214 b, a water-world planet enshrouded by a thick, steamy water rich atmosphere.]

Castor – Parallax = 0.064 (51.0 light years)

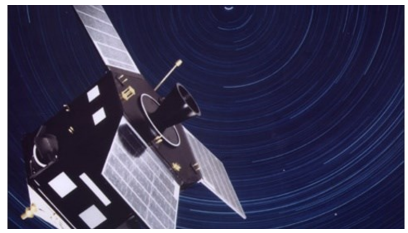
Castor is actually three sets of binary systems with some bright yellow and some dim red stars.

[Music @17:51: *Puccini - Manon Lescaut - Donna non vidi mai - I have never seen a woman like this; Sofia Philharmonic Orchestra; from album "100 Must-Have Opera Karaoke"***]**

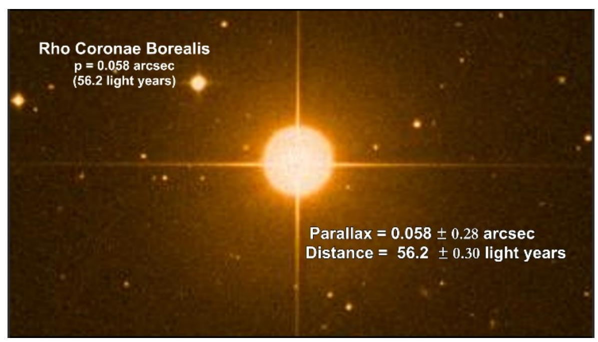
Hipparcos

Since 1838, many astronomers have spent decades measuring star parallaxes, but the work is so painstaking that up until 1989, only a few hundred were measured. That's out of a total population of over 1,500 stars within 60 light years from us.

In 1989, however, the European Space Agency launched a spacecraft called **Hipparcos.** It was specially designed to accurately measure parallaxes without all the interference from the Earth's atmosphere. It did so for over 118,000 stars.



[Astronomers go to considerable lengths to analyze how much error is introduced into their measurements by the instruments they use. You often see distances followed by a plus and minus error amount like this one for Rho Coronae Borealis 56 light years away. Hipparcos is accurate to within 5% to 10% for stars up to 650 light years away. We'll simply list the baseline distance for each celestial object throughout this video book, but applying an error in this range to each of them should be understood.**]**



Let's take a look at a few of these.

A Few More Stars

HD 189733 – Parallax = 0.051 (63.4 light years)

HD 189733 is a binary star system with the primary star being a dim orange star and the secondary star being a dim red star. As we zoom into the star, you can see the Dumbbell planetary Nebula. We'll cover these objects in the next section.

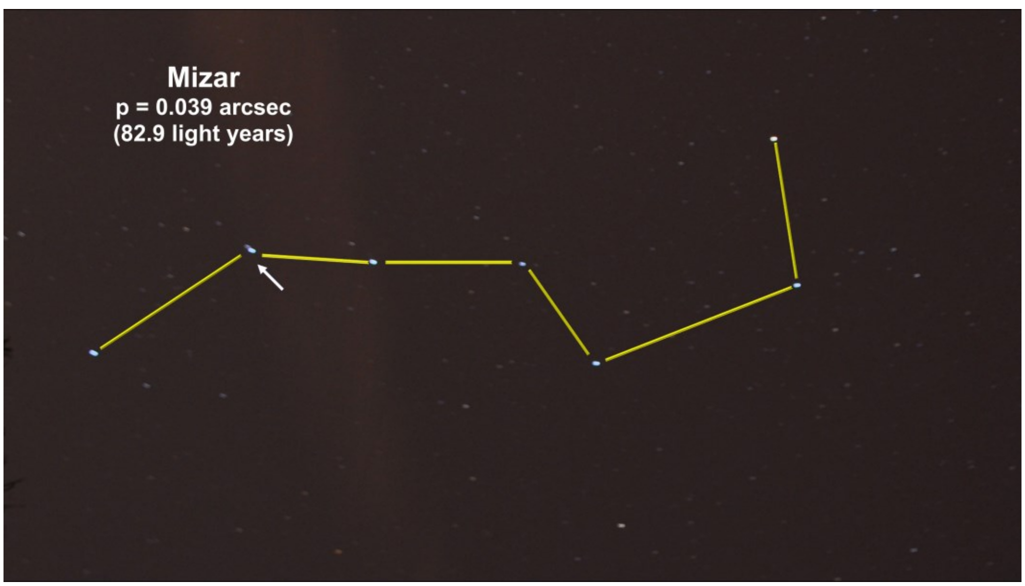
Hubble has made the first detection ever of an organic molecule in the atmosphere of a Jupiter-sized planet orbiting this star. The molecule is methane. Under the right circumstances, methane can play a key role in prebiotic chemistry — the chemical reactions considered necessary to form life as we know it.

Aldebaran – Parallax = 0.050 (65.3 light years)

Aldebaran is a very bright red star. It may have a Brown dwarf companion. A brown dwarf is a star that did not have enough mass to trigger fusion, so it only produces light via conventional means. This makes it very hard to see.

Mizar – Parallax = 0.039 (82.9 light years)

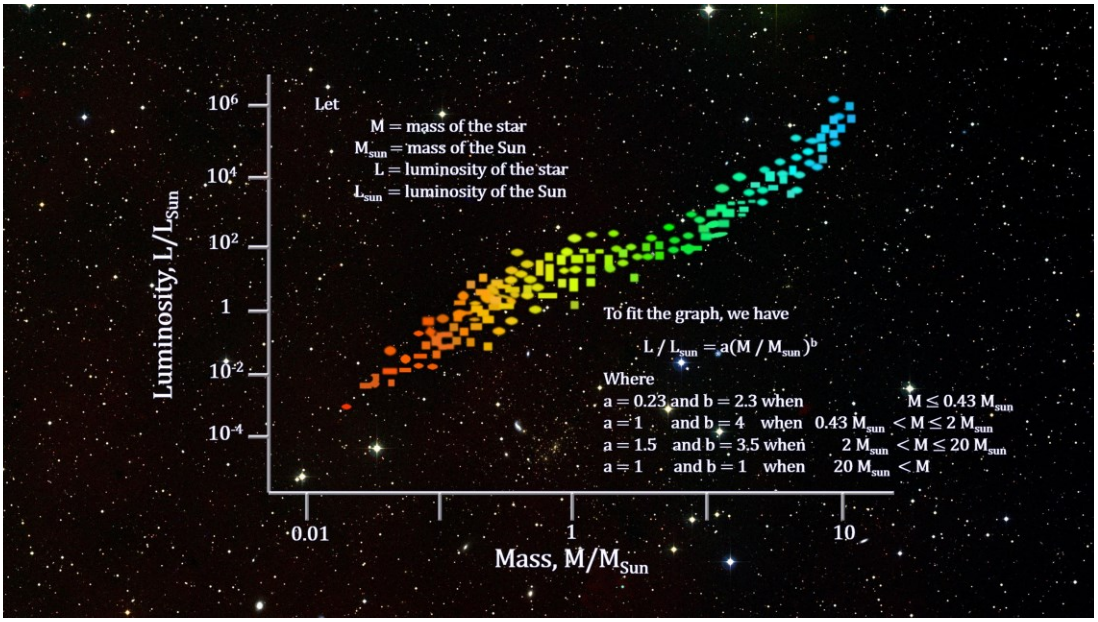
Mizar is a bright white star. It is famous for being the first binary star system discovered. Galileo studied it extensively. These two stars take thousands of years to revolve around each other, so they were not seen to be rotating around each other in those days. It wasn't until the early 1800s, that binary stars rotating around each other were seen. This was the first evidence that gravitational influences existed outside our solar system.



[Music @20:38: *Schubert - The Trout from album "A Calendar of Classics - A 12 CD Set of Romantic Classics for Every Month of The Yea"***]**

Star Mass vs Luminosity

Once the mass of enough binary stars was calculated, it became possible to plot Mass vs. Luminosity on a graph. Here's what they found.



Instead of having any combination of mass and luminosity, we see that stars fall on a line from low-mass / low-luminosity to high-mass / high luminosity. But it is not linear. Each time the mass is doubled, the luminosity goes up 11 times. This relationship seems to work for most stars that aren't too massive.

Note that this is an empirical relationship. We don't start with an equation and plot its graph. We observe events to create the graph and then find an equation that would have created a graph that looks the same or 'fits' what we observed.

Now back to the stars again.

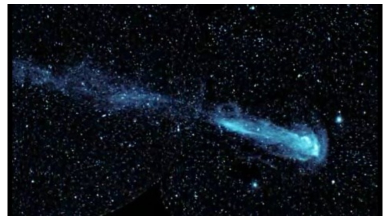
Four More Stars

Spica – Parallax = 0.031 (250 light years)

Spica is a blue star and the 15th brightest star in the nighttime sky. It's a close binary star system whose components orbit each other every four days. They are so close together that they cannot be resolved as individual stars through a telescope.

Mira – Parallax = 0.011 (300 light-years)

Mira is a very high proper motion red star that is shedding an enormous trail of material. The tail stretches a startling 13 light-years across the sky. It has released enough material over the past 30,000 years to seed at least 3,000 Earth-sized planets.



[Additional info: It is zipping along at 468,000 km/hour (291,000 miles per hour). This creates the bow shock, in front of the star. This is similar to the one we saw our Sun creating in our section on the Heliosphere. Mira is also what's called a pulsating variable star. It dims and brightens by a factor of 1,500 every 332 days. Sometimes it is even bright enough to see with the naked eye.**]**

Polaris Parallax = 0.0075 (433 light years)

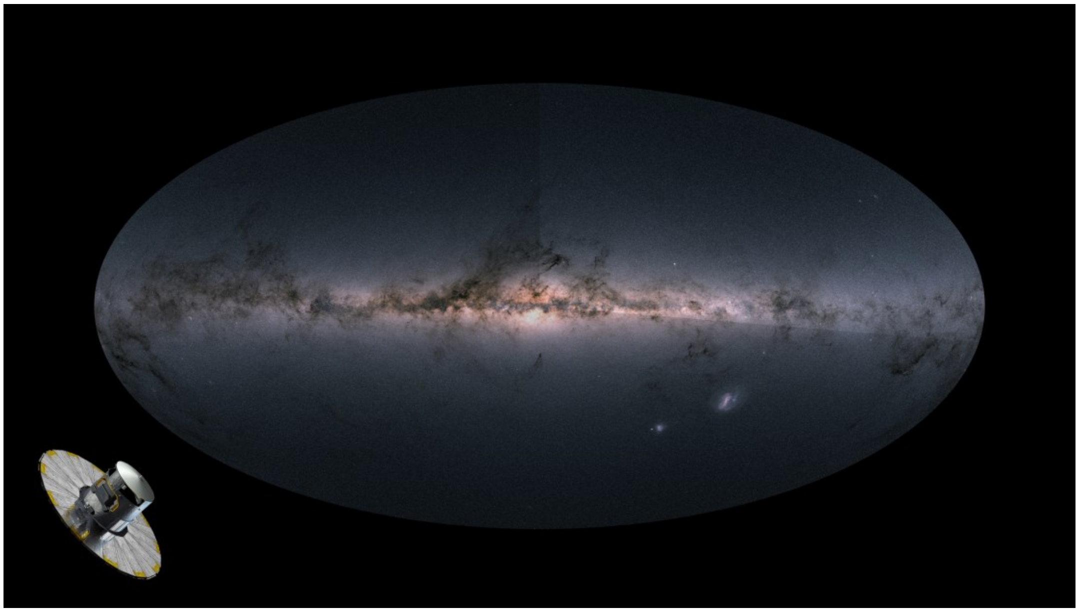
Polaris is our current day 'North Star', for it lies less than 1.0° from the north celestial pole. It is a double star system with one being a supergiant. The supergiant is a classic Cepheid variable star. Cepheids are a critically important kind of star for our distance ladder. I'll talk more about them in a minute when we come to Delta Cephei – the first Cepheid star completely analyzed.

Antares Parallax = 0.0059 (550 light years)

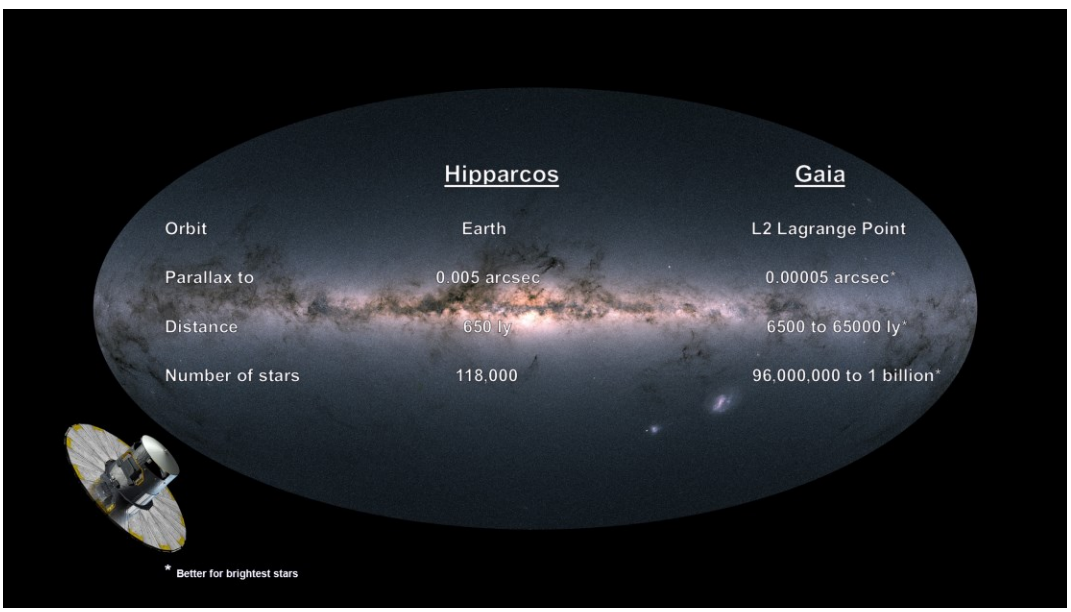
Antares is a bright red star - the sixteenth brightest star in the nighttime sky. The size of Antares has been calculated using its parallax and angular diameter. Its radius is 822 times larger than our Sun's.

Gaia

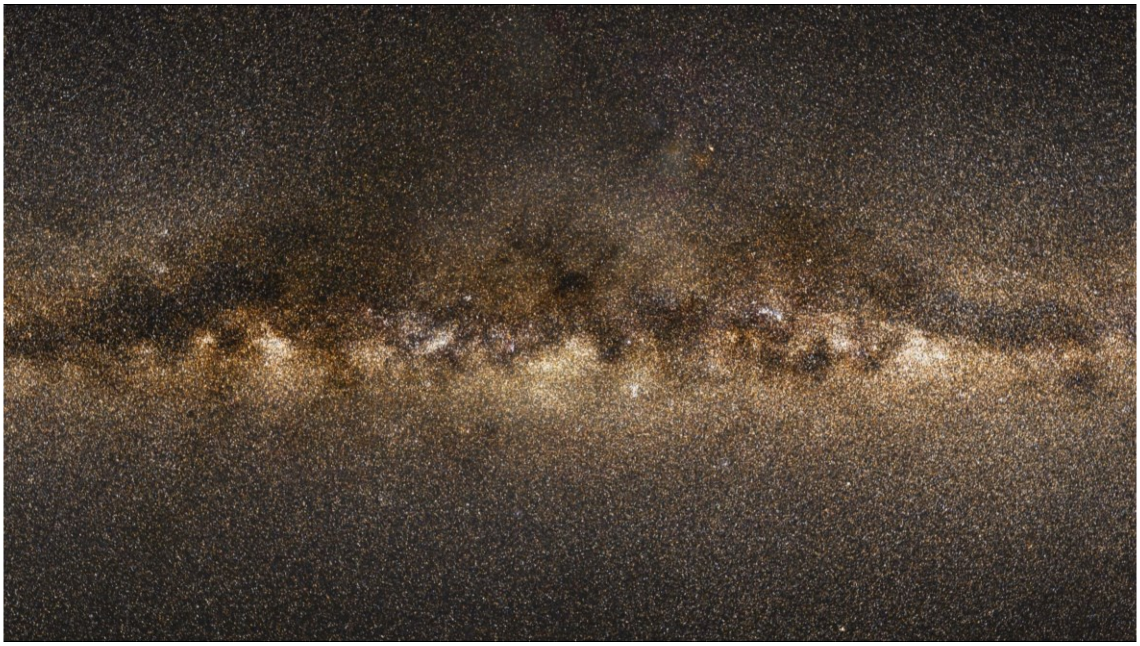
Launched in 2013, Gaia is a European Space Agency mission to create a three-dimensional map of our Galaxy. This map shows the density of stars observed by Gaia in each portion of the sky. Brighter regions indicate denser concentrations of stars, while darker regions correspond to patches of the sky where fewer stars are observed. The color representation is obtained by combining the total amount of light with the amount of blue and red light.



As of April 26, 2018, Gaia has pinned down the brightness and position on the sky of 1.7 billion stars. It has also cataloged the parallax, proper motion and color for 1.3 billion stars, and has relatively accurate distance information on 96 million stars. Hipparcos recorded parallax information for 118,000 stars. Gaia has done thousands of times more. With all this new data, astronomers will be calibrating the parallax run on our distance ladder for years to come.



This view shows both brightness and color information of 96 million stars, selected from the Gaia catalogue by choosing the ones with the most accurate distance determinations. [After a few seconds, the stars start to move according to their true velocity across the sky, or proper motions, as measured by Gaia.] This shows the way the stars will move across the sky during the next 800,000 years.



Now, let's take a look at a few stars too far for Hipparcos, but well within the range of Gaia.

Final Nearby Stars

Betelgeuse – Parallax = 0.0045 (724 light-years)

Betelgeuse is a very rich reddish cool supergiant star. It is also one of the largest and most luminous stars known. If it were at the center of the Solar System, its surface would extend past the orbit of Jupiter.

[Additional info: Betelgeuse is also a runaway observed racing through the interstellar medium at a supersonic speed of 30 km/s (18 miles/sec), creating a bow shock over 4 light-years wide. It's expected to end as a supernova within the next million years.**]**

CH Cyg Parallax = 0.0041 (800 light years)

CH Cyg is a "symbiotic" star system in which a white dwarf feeds from the wind of a companion red giant star.

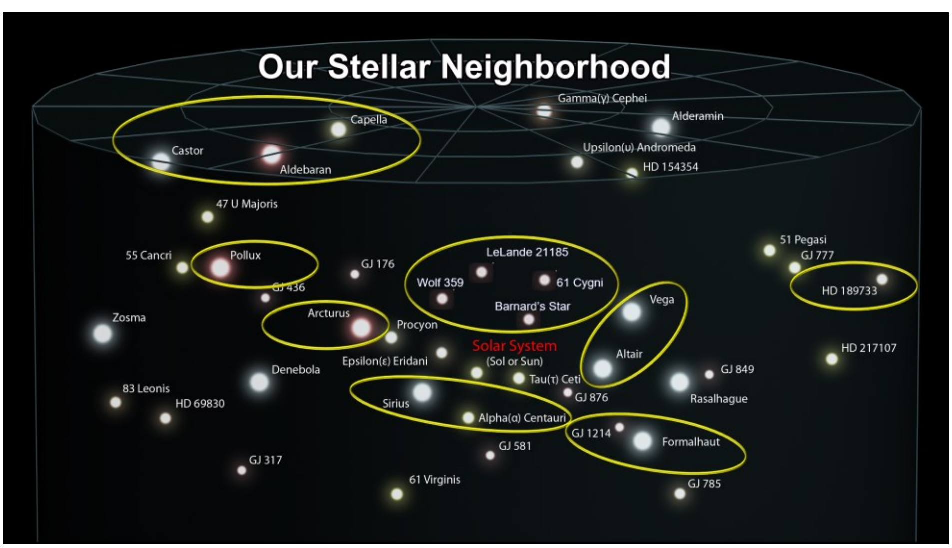
Rigel – Parallax = 0.0038 (860 light years)

Rigel is the sixth brightest star in the sky. Since 1943, this star has served as one of the stable anchor points by which other stars are classified.

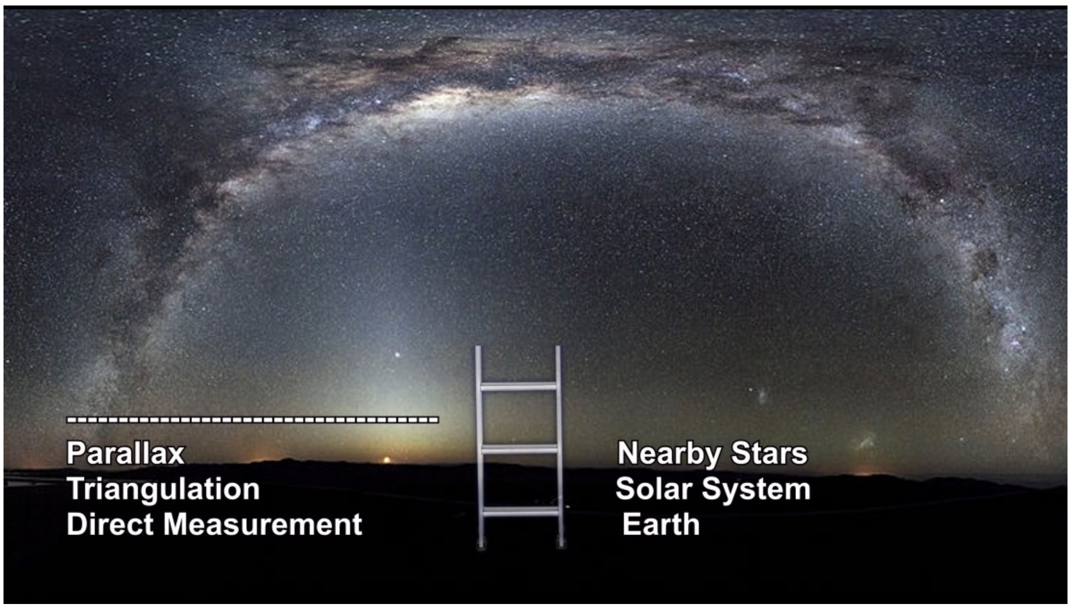
[Additional info: The star is actually a triple star system. The primary star (Rigel A) is a blue-white supergiant around 117,000 times as luminous as our sun. Rigel B is itself a binary system.**]**

Nearby Stars Summary

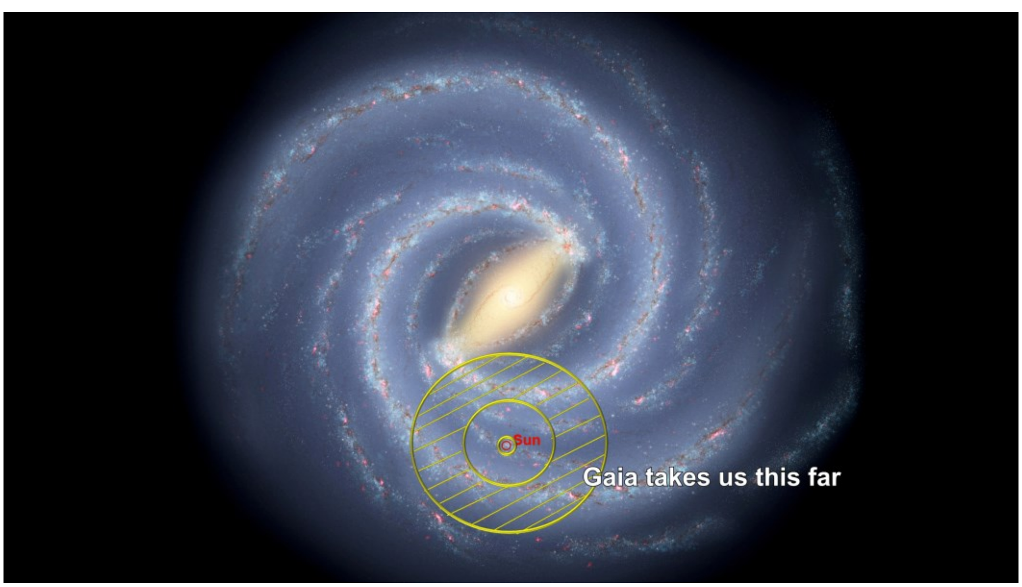
We have now visited a number of stars from our local neighborhood. We started with the nearest stars where parallax measurements from earth bound telescopes were good enough. We then moved out to the further reaches of our neighborhood using Hipparcos based parallax measurements. And we went even further with Gaia.



In our segment on the Solar System, we extended the direct measurement and triangulation to include parallax for the planets. This segment covered how we measured stellar distance, mass, luminosity and motion – all based on parallax techniques – just like we did for the solar system. And thanks to the Hipparcos and Gaia satellites, we know the parallax for hundreds of thousands of stars which are relatively close to the Sun. So we can add stars to the reach of the parallax rung on our cosmic distance ladder.



But, if all we had was parallax, we'd know very little about our galaxy and virtually nothing about the universe beyond. But the only thing we can get from a star is its light.



Distant Stars

*{**Abstract** – In this segment of our video book, we take a close look at light in order to understand the Hertzsprung - Russell diagram.*

We explain that by distant star, we mean a star too far away for parallax distance measurements. We then go into the dual nature of light as both a particle and a wave. Viewing light as a wave, we cover the full electromagnetic spectrum, followed by blackbody radiation. Then using known luminosity from nearby stars, we map star color to temperature and star temperature to luminosity – the basic H-R Diagram.

To give this diagram meaning, we introduce the nature of nuclear fusion and how star color and temperature are related to the mass of the star. This gives us the meaning behind the main diagonal line on the H-R Diagram – it represents the main sequence for stars burning Hydrogen. We follow by describing the end-of-life process for stars that moves them off the main sequence and into the realm of giant and supergiant stars. This gives meaning to the two collections of stars above the main sequence. Finally, we discuss the cataclysmic explosion at the end and how this leaves behind White Dwarfs.

Once the meaning of the H-R Diagram is understood, we use spectral analysis to determine a star's place on the diagram. We use a star's color, temperature and spectral class to determine its place on the horizontal axis. We use spectral absorption lines and Luminosity Classes to determine its place on the vertical axis. This gives us its intrinsic luminosity and thereby its distance.

We then use this new technique for determining distance to distant stars V1331 Cyg, UY Scuti, WR 124, and AG Carinae.

Next cover Delta Cephei a variable luminosity star, and Henrietta Leavitt's work mapping the period of a Cepheid star's luminosity cycle to the star's luminosity. This gave us our first "Standard Candle". RR Lyrae came as the next standard candle variable.

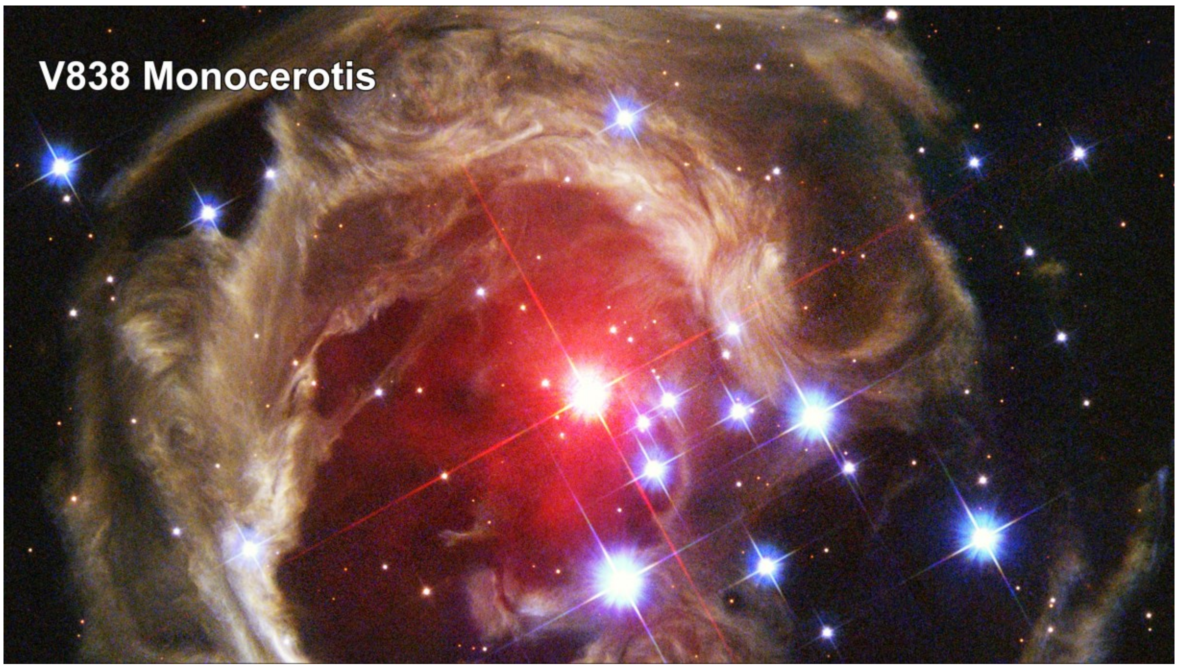
We go on to cover Zeta Geminorum, Eta Aquila, HIP 13044, T Lyrae, SDSS J102915+172927, Mu Cephei, HE 1523-0901, Eta Carinae, V838 Monocerotis, AW Cyg, extra galactic Hypervelocity Star HVS 2v, and HE 0437-5439 a star that is being ejected from the galaxy possibly via a close encounter with the Milky Way's central supermassive black hole.

We conclude with the major new distance ladder rungs: the H-R Diagram, along with Cepheid variables and RR Lyrae variables as "standard candles".}

Introduction

[***Music @00:57*** *Chopin, Frédéric: Prelude from Les Sylphides; from the album "A Calendar of Classics - A 12 CD set of Romantic Classics for every Month of the Year", 2007*]

Welcome to our segment on distant stars. By distant, I mean stars that are so far away that parallax doesn't work anymore. Stars like this one, V838 Monocerotis. In order to know how far away V838 Monocerotis is, we'll need a new way to determine distance.



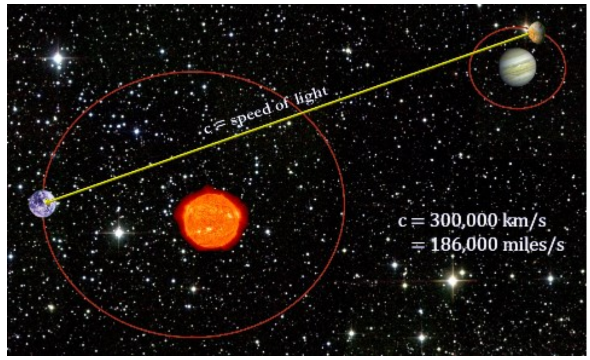
To do that, we'll develop a diagram that maps a star's color to its luminosity. Then we'll study the nature of light that comes from the stars. And with that knowledge, we'll be able to use that diagram to determine the intrinsic luminosity of stars like this one. And with that, we'll know how far away they are.

Starlight

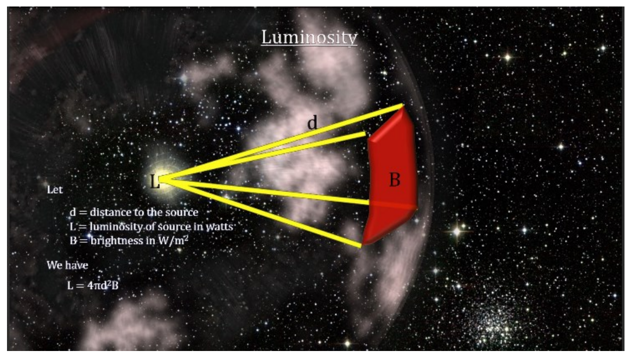
So, let's start with our study of light. We know a few things:

We know that light is electromagnetic radiation created by moving electrons.

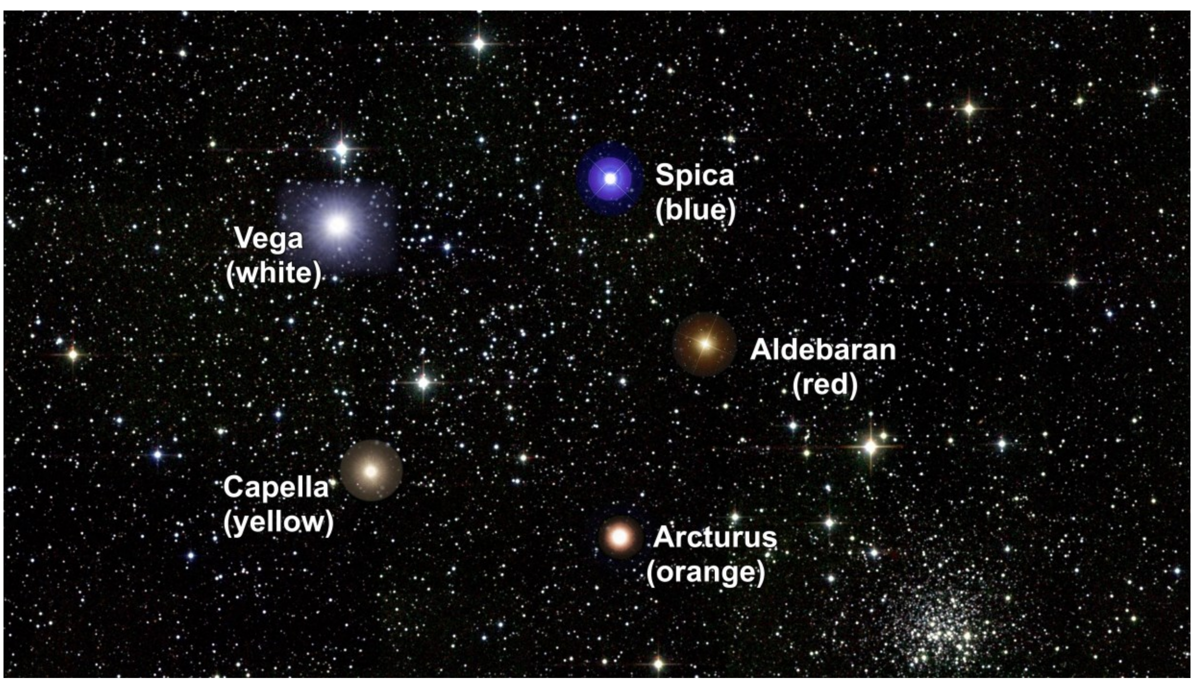
With help from Jupiter's moon Io, we know that light travels across empty space at 300,000 km/s (that's 186,000 miles/second).



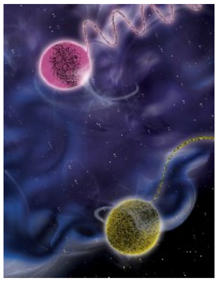
And, as we have seen, stars vary in apparent brightness and knowing the star's distance we can use the inverse square law to find its intrinsic luminosity.



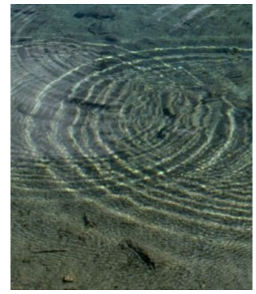
The other thing we know is that stars have different colors. And very interestingly, color tells us a lot more than you might think. But to understand color, we need to know more about light.



Light, as we currently understand it, has a dual nature:



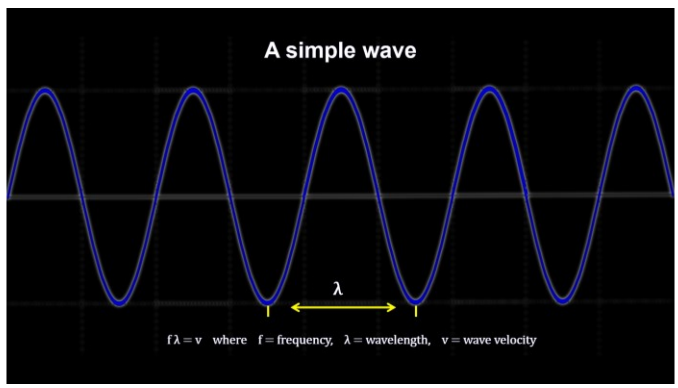
We can view it as a particle or photon. Or we can view it as a wave that can interfere with itself.



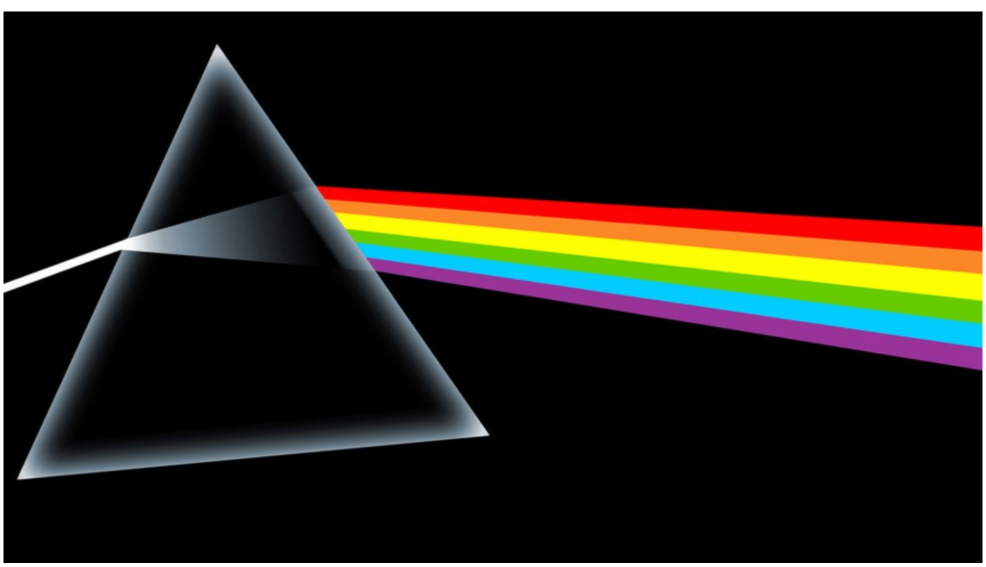
Although we haven't been able to reconcile these two incompatible views with one underlying understanding, what we do know has turned out to be surprisingly sufficient for the distance ladder.

For color, we view light as a wave. Here's a simple wave. It has:

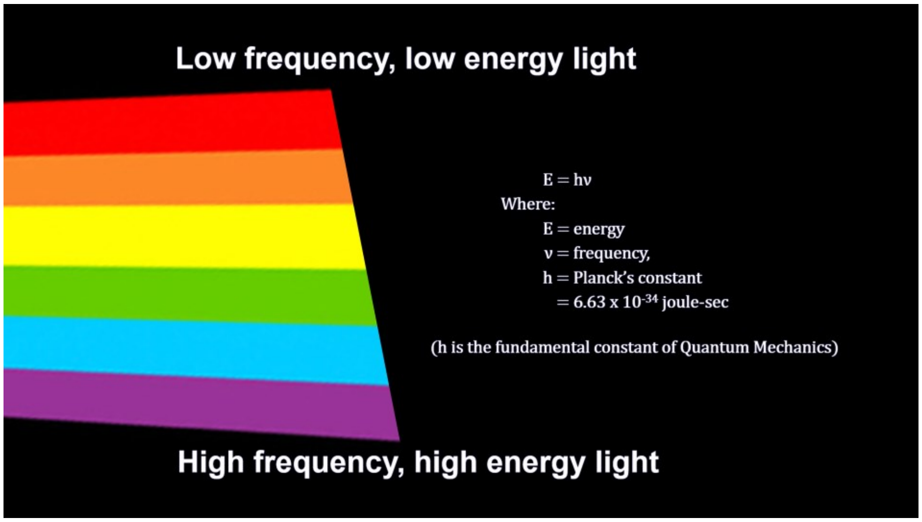
- a repeating cycle
- a wave length;
- and a frequency in cycles/second



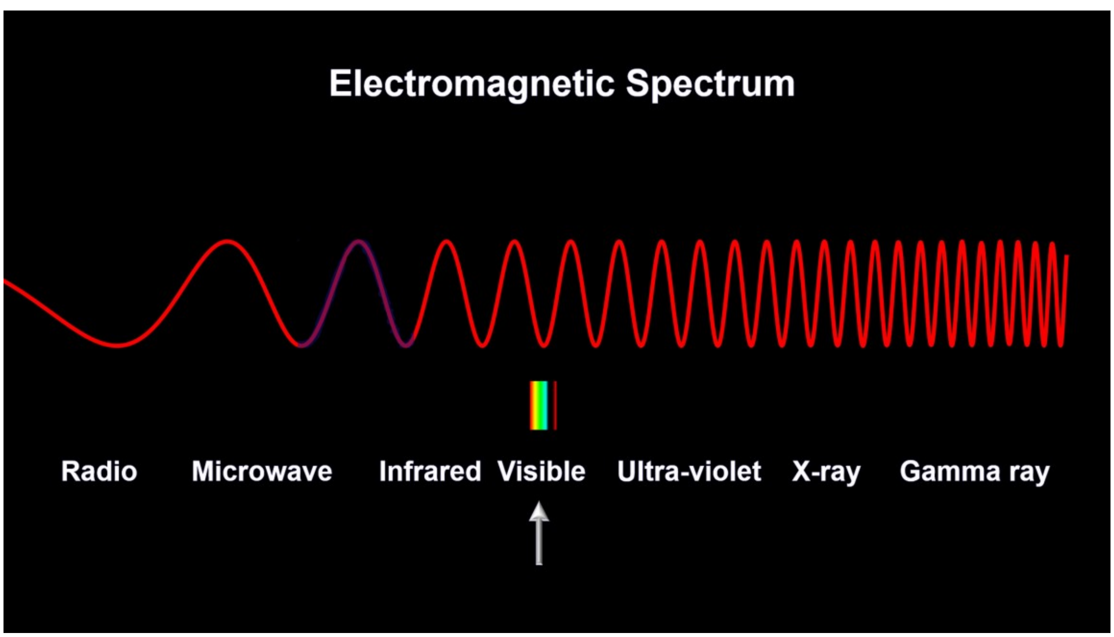
Newton showed that the Sun's light can be dispersed into the colors of the rainbow with a crystal **[**prism**]**. This effect comes from the wave nature of light.



Different colors represent different light frequencies. The higher the frequency or inversely the shorter the wave length, the more it's bent by the crystal. This produces a spectrum of light with blue and violet at the high frequency end, and red at the low frequency end. An important relationship between energy and light is that a light's energy is directly proportional to the frequency. So, when physicists see color, they think energy. Red is low energy light and blue is high energy light. **[**Planck's constant is very very small. It is the fundamental constant of Quantum Mechanics**]**



Here we see the full electromagnetic spectrum with visible light in the middle. with longer wavelengths and smaller frequencies than red light is called *infrared*, and still longer wavelengths are called *radio waves*. Moving up the energy scale, radiation with shorter wavelengths than violet light is called *ultraviolet*; still shorter wavelengths are called *X-rays* and the maximum energy radiation is called *gamma Rays*. Celestial objects shine in radio to infrared, visible light, and ultra-violate to x-rays.



Blackbody Radiation

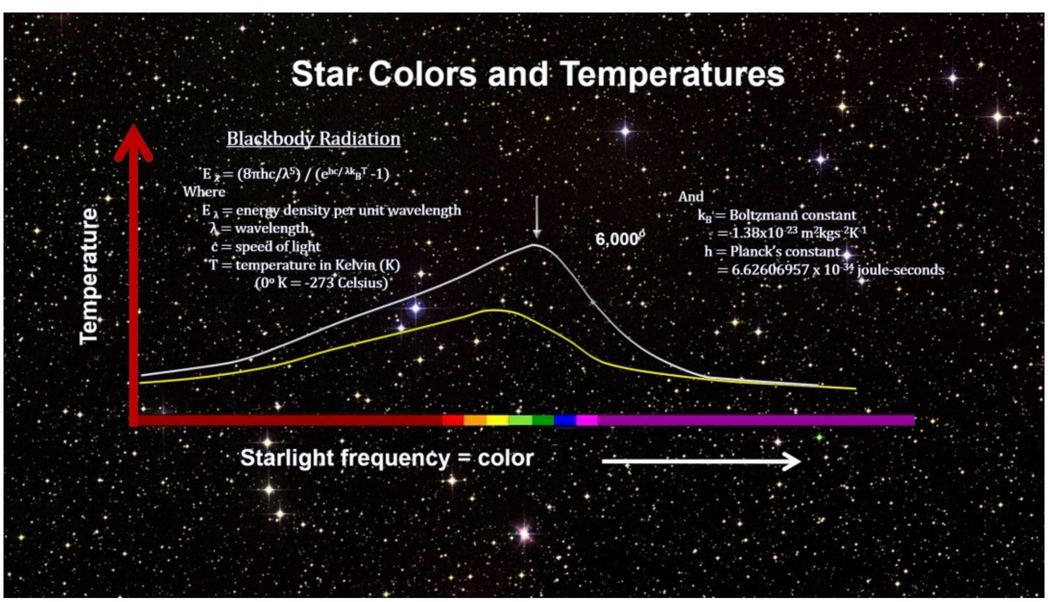
One of the very important relationships between light and matter is called **Blackbody Radiation**. It turns out that the color of most matter at high temperatures depends completely and totally on its temperature. Nothing else really matters.

Take a look at this iron rod as it heats up. See how it goes from red hot at the outer edges, through yellow to white hot at the center. If we could get it hot enough, you'd see it turning blue.

Here's why. As temperature increases and the electrons start moving more rapidly, two things happen:

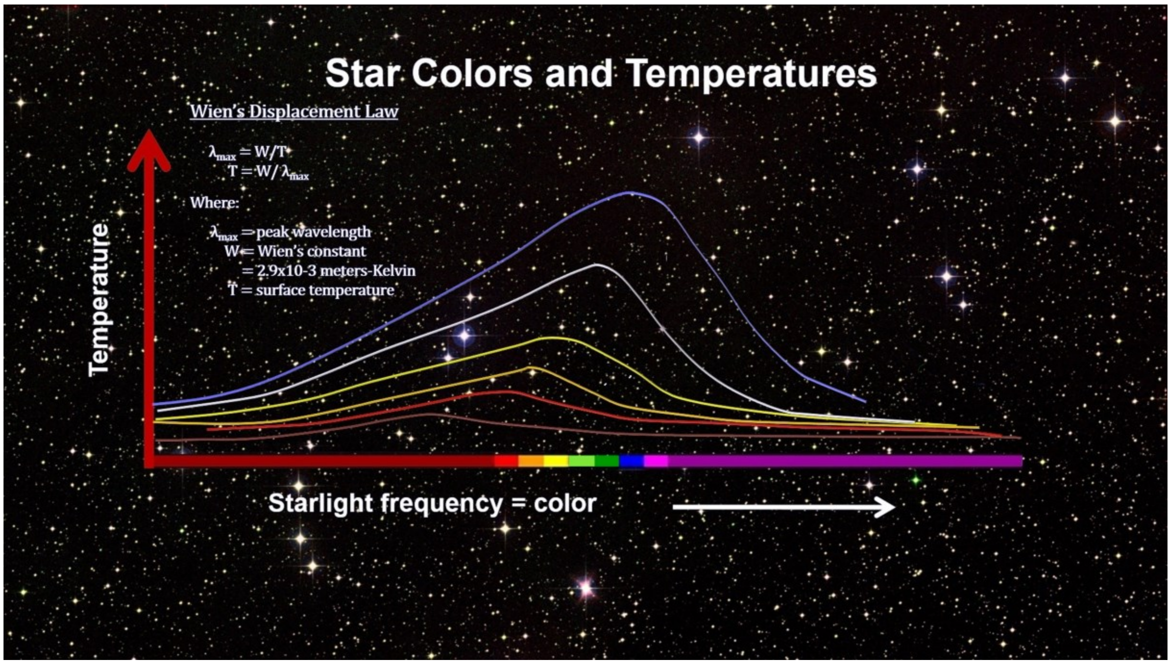
1. The object emits more radiation at all wavelengths.
2. And the peak emission frequency shifts toward shorter higher-energy (blue) wavelengths.

As the heating starts, the radiation is all in the infrared range – so we can't see it.
As the temperature approaches 2000 degrees Kelvin, we begin to see red. We've seen the red star Aldebaran. It's a good example of this. By 3000 degrees, the red has morphed to orange. Arcturus is an example of this. By 4000 degrees it is quite yellow. Capella and our own Sun are yellow. Around 6000 degrees it is turning white. The star Sirius A is an example of this. And by 10,000 degrees is has a distinct bluish color. Spica is a good example of a blue star.



Wien's Displacement Law

So, the bottom line is: Measure the color of a star via the frequency of the light it emits, and you've determined its temperature. It's that simple.



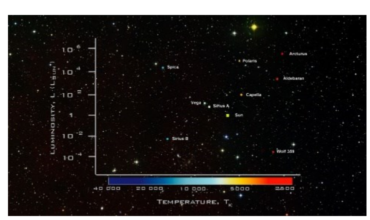
[Music @06:27 Mozart, Wolfgang Amadeus: Sinfonia concertante for violin, viola & orchestra in E flat major; Academy of St. Martin in the Fields – Sir Neville Marriner, Levon Chilingirian (violin), Csaba Erdelya (viola) from the CD 'Amadeus', 1988.]

The Hertzsprung - Russell diagram

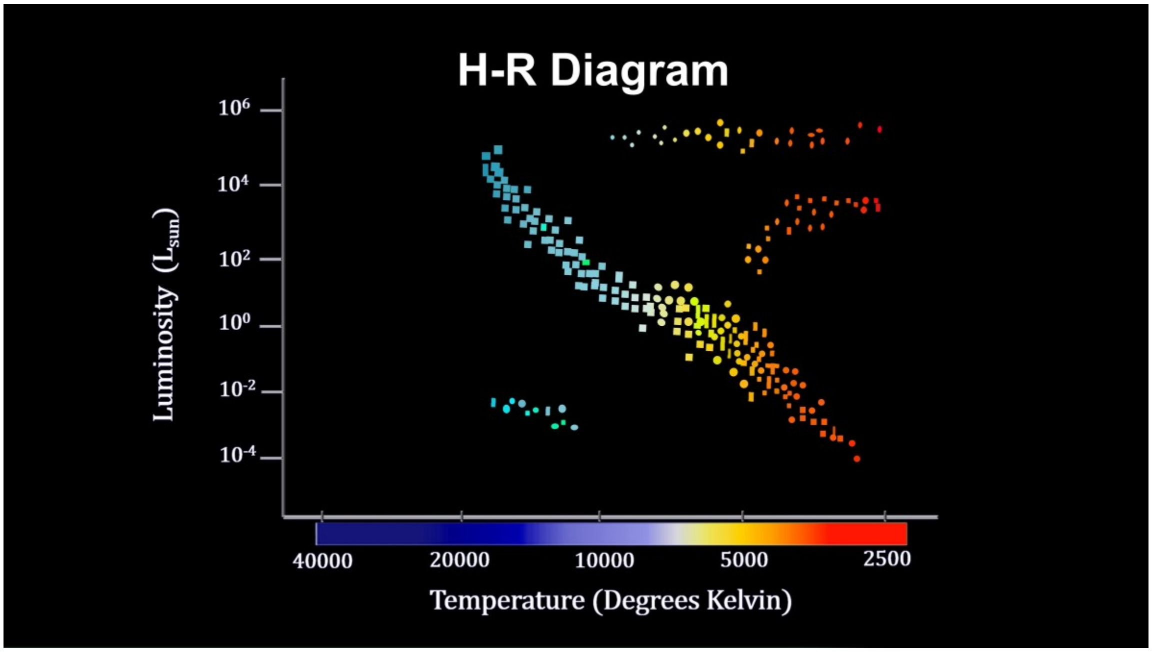
Now that we know star temperatures via their color, and luminosity via their parallax distance, we can build the diagram I mentioned in the introduction.

In 1913, Ejnar Hertzsprung and Henry Russell began mapping these star temperatures against their luminosity. (Note that the horizontal-axis is mapping temperatures in the **decreasing** direction.)

If we begin with the stars we used to illustrate blackbody radiation (Aldebaran, Arcturus, Capella, our Sun, Sirius A, and Spica) and throw in a few others like Sirius B, Wolf 359, Polaris, and Vega, we get a graph that looks like this.



With this small sample, it looks like any combination of temperature and luminosity is possible. But Hertzsprung and Russell meticulously plotted all the stars with known distances and luminosities. And they got this!



Here we see that most stars fall on the diagonal line from the upper-left (hot blue luminous stars) down to the lower right (cooler dimmer red stars). But there is also a grouping of stars well below the main line [that are hot but dim indicating that must be small], and two groupings of stars well above the main line [that are cold but bright indicating that they must be very large].

This is the Hertzsprung – Russell Diagram or H-R Diagram for short. It is one of the most important tools in understanding stars ever devised. It tells us a great deal about the life, death and age of stars. And, more importantly, for our purposes, it can tell us how far away stars are.

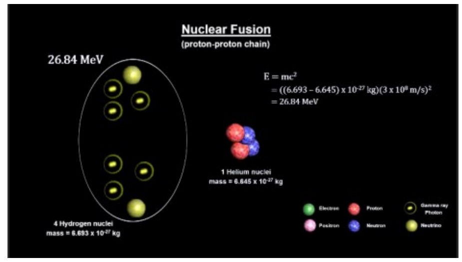
But in order for the H-R Diagram to do this:

- We need to know more about what makes stars shine, and
- We need to know more about the full spectrum of light we receive from stars.

__Main Sequence Star Lifecycle__

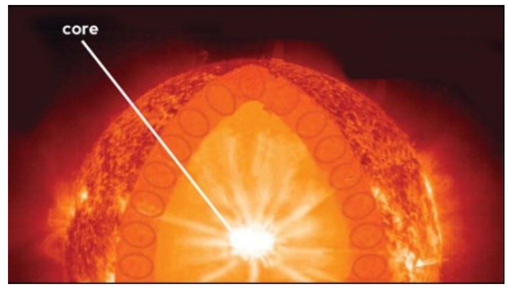
In our segment on star birth nebula, we'll cover how stars form from giant hydrogen clouds collapsing under the force of gravity. They start "shining" once the pressure and temperatures at their core reaches the levels needed to support hydrogen fusion.

The fusion of hydrogen into helium converts some of the mass into energy. And, because $E = mc^2$, and c is a very big number, the process generates a great deal of energy.



The simplest way to think of a star is to view it as a huge furnace where its mass is a measure of the amount of fuel it has, and its luminosity is a measure of how fast it is consuming this fuel.

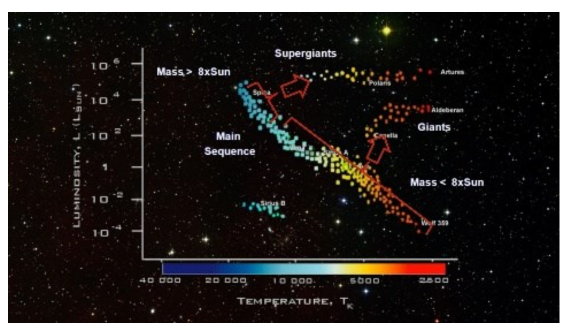
The more hydrogen there is in the collapsing cloud, the more massive the star. The more massive the star, the more intense the pressure in its core. The more intense the pressure, the higher the temperature. The higher the pressure and temperature, the faster the Hydrogen fuses into Helium. The faster the hydrogen burns, the greater the energy released and the greater the star's luminosity.



Thus, the diagonal line on the H-R Diagram represents the main sequence for stars burning hydrogen.

- The upper left blue and white-hot stars are high mass stars, many times more massive than the Sun.
- The middle region yellow and orange stars are closer to the mass of the Sun.
- The lower right red stars are cool low mass stars that are a fraction of the mass of the Sun.

When a star runs out of hydrogen fuel, the core contracts and gets hotter. This heat expands the outer layers reducing their density, and turning the star red. The star moves off the main sequence and enters the realm of giants or supergiants depending on their original mass.

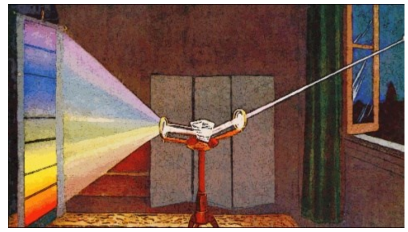


When a Red Giant, with a mass less than 5 times the mass of the Sun, runs out of fuel, it explodes and leaves behind a dim hot tiny star called a White Dwarf. We'll discuss this process more in our next segment on Planetary Nebula. We'll cover the end-game for more massive stars in our segment on Supernova.

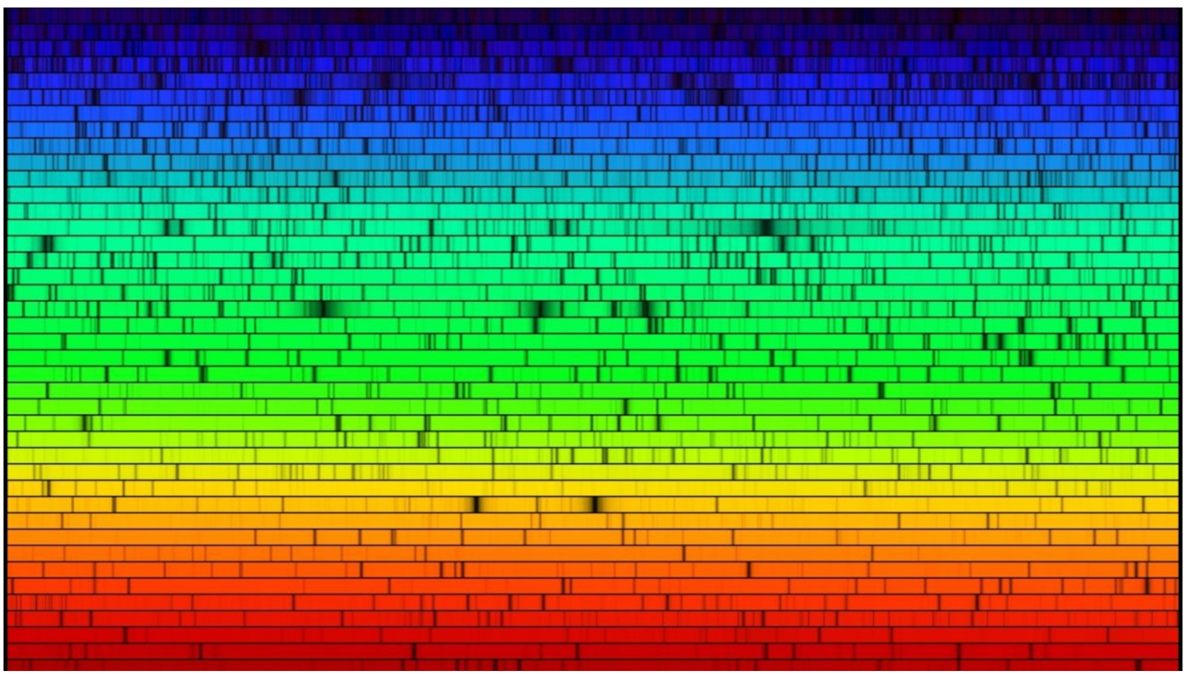
Spectral Analysis

Now we understand the meaning of the H-R diagram, let's see how we can use it to find out how far away a star is. For that, we need to view light as a particle and examine its spectrum.

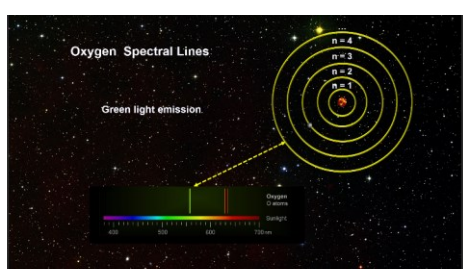
Early in the 19th century, the German chemist, Joseph Fraunhofer, invented the spectrascope - an instrument to automatically separate light and mark the wavelengths.



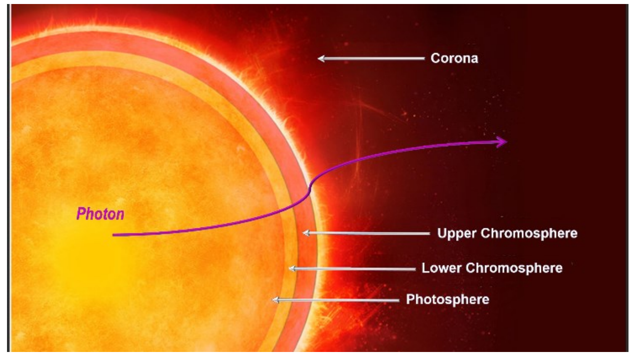
In so doing, he discovered that when he spread sunlight into a spectrum, the spectrum was crossed by great numbers of fine dark lines. He had no idea what these dark lines where, but today we know that they were the key to learning what stars are made of.



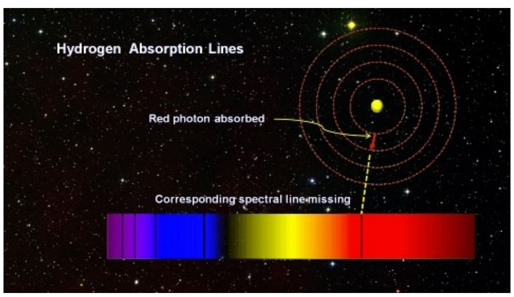
Remember the red and green light of the aurora borealis and the structure of molecules we discussed in our segment on the Heliosphere. The aurora is a good example of light being emitted as electrons change energy levels.



But for our purposes here, we want to examine what happens when light from the center of a star passes through the gasses in the outer layers on its way to us.

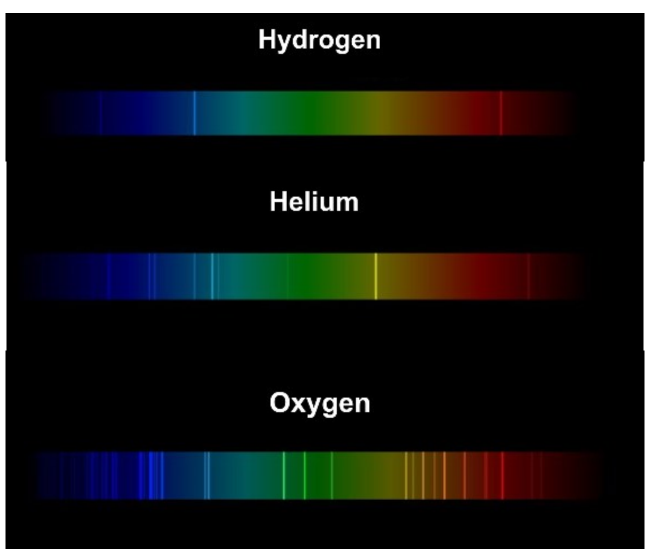


Here's how it works.

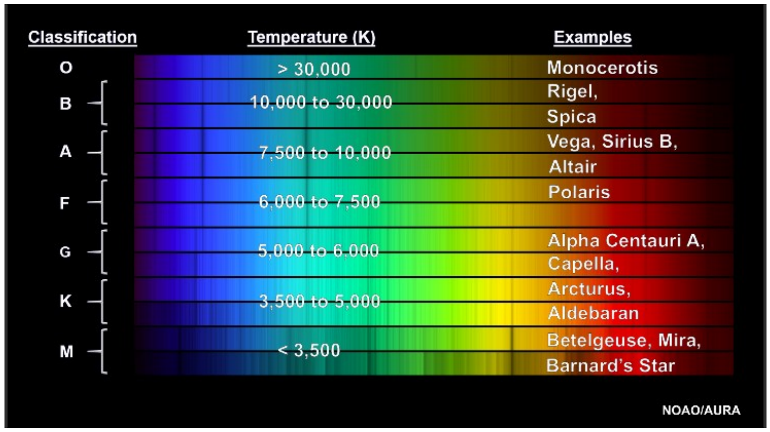


When a photon with exactly the right energy level hits an electron orbiting a nucleus, its entire energy is transferred to the electron which jumps to a higher energy level with a larger quantum number. The photon is eliminated. This creates 'absorption lines' in a star's spectrum as light from the star travels through the star's atmosphere.

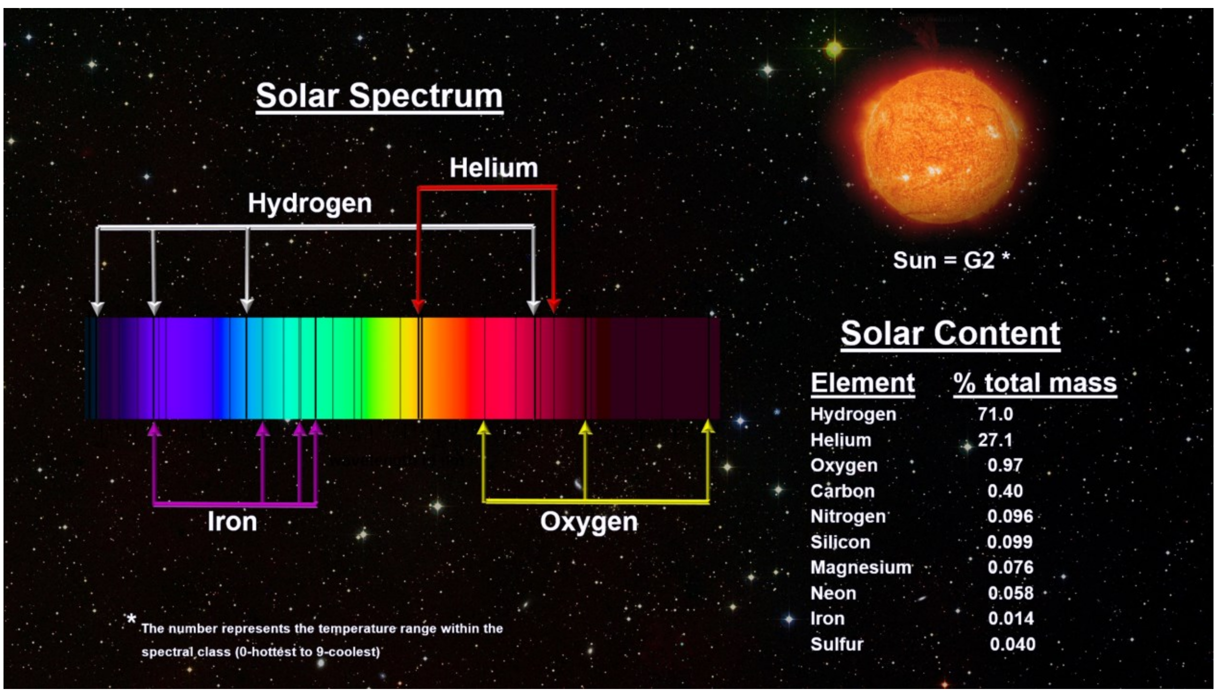
Every atom and molecule has its own spectral line signature. So, by observing the absorption lines in a star's spectrum, we can tell what elements are present. **[**Imagine that. Light from stars hundreds of trillions of miles away carries with its information on every element the star is made of!**]**



When scientists discovered connections between groups of spectral lines and star temperatures, they developed a set of spectral classifications to highlight this connection. Every star we have seen so far fits into one of these classifications.



Our Sun is spectral class G and has around 67 elements in its photosphere. [The number following the letter represents the temperature of the star within the classification from 0 (the hottest) to 9 (the coolest).] Here are a few identified by their spectral signature. It turns out that Hydrogen is 50 to 80 percent of most stars, and combined with Helium makes up 96 to 99 percent of all stars. [Other elements include magnesium, oxygen, nitrogen, carbon, silicon, sulfur, iron and chlorine.]

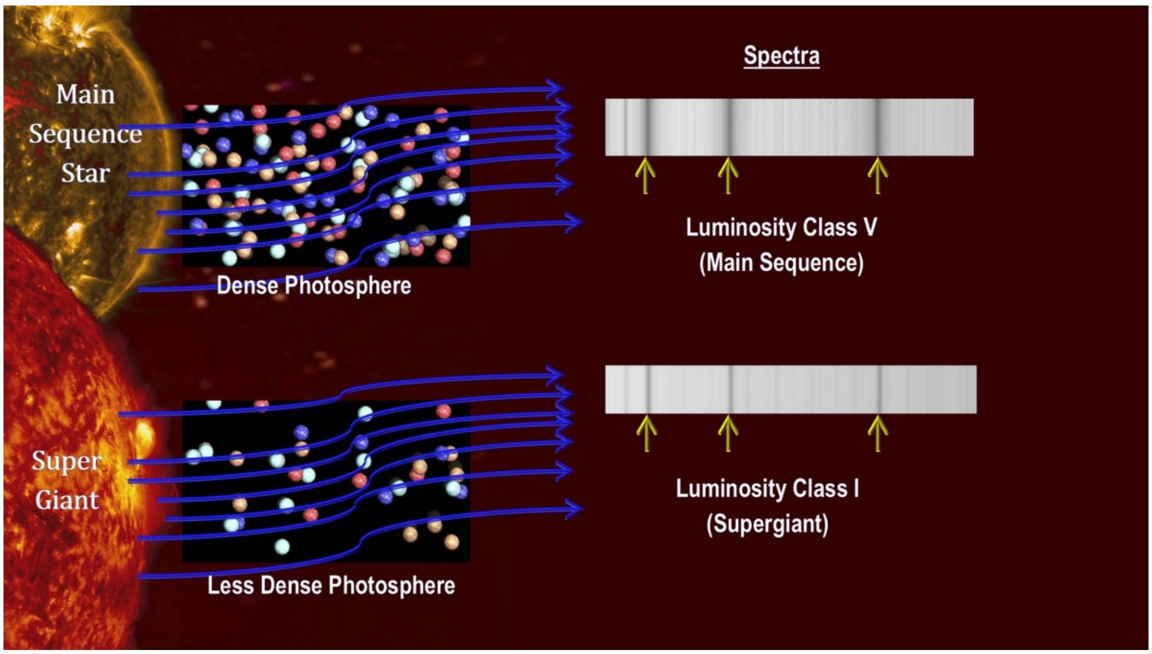


[Music @13:48** Puccini, Giacomo: Crisantemi; Radio Symphonie Orchester Berlin and Riccardo Chailly; from the album "Puccini without Words", 2006**]

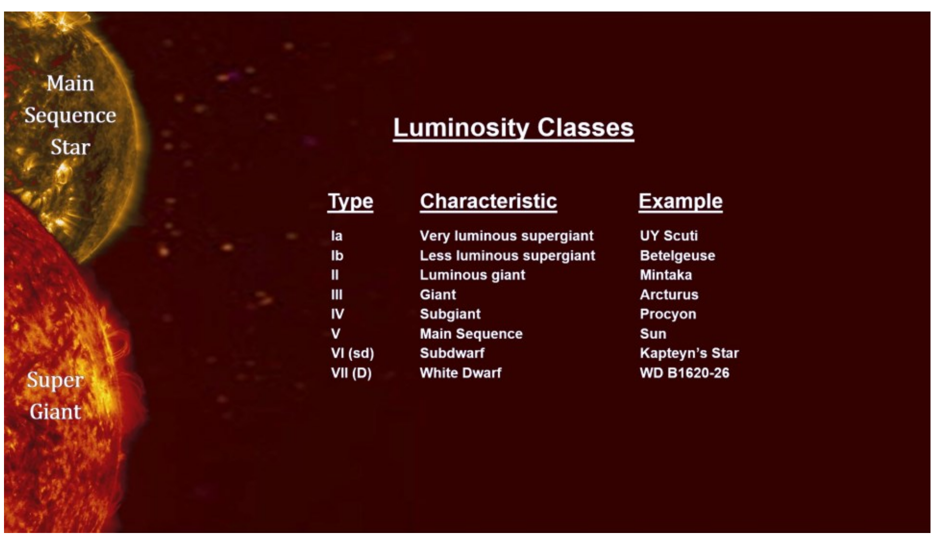
Luminosity Classes

Star spectra has one more characteristic called Luminosity Class that enable us to determine whether a star is on the Main Sequence or not. This is the key to using the H-R diagram to determine a star's distance.

If you recall, the evolution of a star off the Main Sequence involves the expansion of the outer layer to gargantuan proportions. This makes the density of the gas in the outer layer of a Giant much less than the density in the outer layer of a star on the Main Sequence. It turns out that the photon absorption characteristics of closely packed atoms, makes the spectral lines fuzzier. So, for a given spectral classification, the fuzzier the spectral line, the smaller the star.

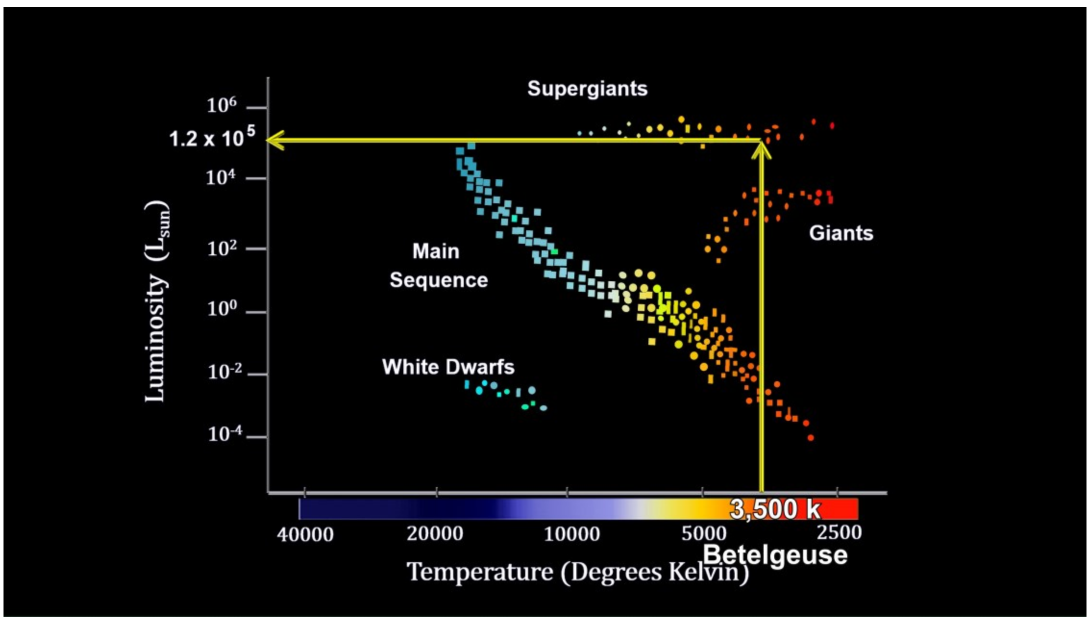


Roman numerals are used to identify luminosity classes. Our Sun is class V – a main sequence star.

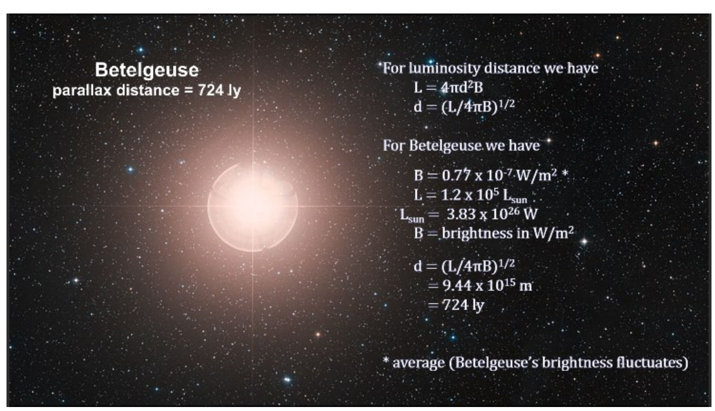


We'll use Betelgeuse to illustrate how star spectra works with the H-R Diagram to determine a star's distance.

1. First, we use the star's color, temperature and spectra to find its point on the horizontal axis.
2. Looking up the vertical luminosity axis, we see Betelgeuse could either be a main sequence start or a super giant.
3. Examining the luminosity class, we see that it is very sharp, implying that Betelgeuse is a Supergiant.
4. Now drawing the line to the vertical axis, we see that the star's intrinsic luminosity is 120,000 times greater than our sun's luminosity.
5. Measuring the apparent luminosity, and using the inverse square law, we get the distance: [Betelgeuse is 724 light years away].



If stars everywhere behave like the stars in our neighborhood, then the H-R Diagram can show us how far away they are. Astronomers call this technique spectroscopic parallax, but we'll just stick with "H-R Diagram".



Now let's take a look at some distant stars.

<u>V1331 Cyg - A8 to G5 1,800 ly</u>

This star, known as V1331 Cyg, is a young star that is starting to contract to become a main sequence star similar to the Sun. It lies inside a dust cloud. We looking down on one of its poles which allows us to see the dust cloud envelope around it. Usually, for young stars like this, all we get to see is the dust cloud.

<u>UY Scuti - M4Ia (9,500 light years)</u>

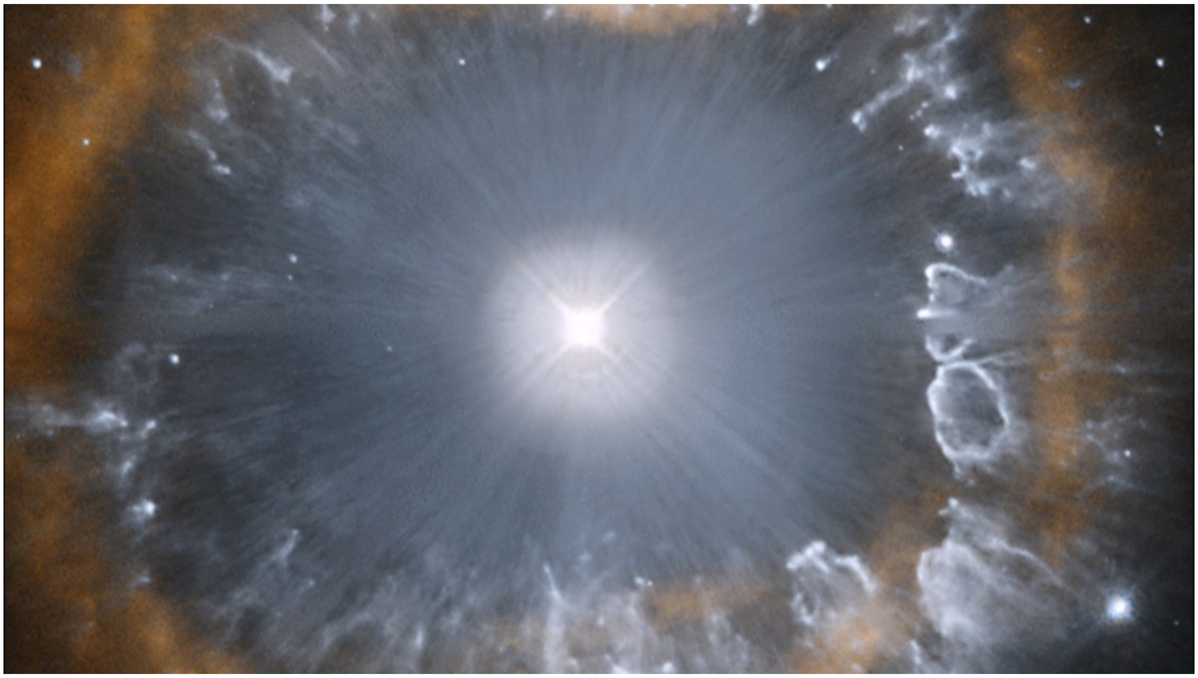
The star at the center of the picture is a red supergiant called UY Scuti. It is very dim. But appearances can be deceptive in astronomy. This star is actually about 340,000 times more luminous than the Sun. In fact, it's a candidate for being the largest star in the entire Milky Way Galaxy. Astronomers believe the actual size of UY Scuti is big enough to hold 5 billion Suns!

WR 124 – Wolf-Rayet (10,900 light years)

Here we see the super-hot star WR 124 — and the hot clumps of gas it is ejecting into the space around it. Ejection gasses are traveling at over 150,000 km per hour (that's 93 thousand miles per hour). The cloud, known as nebula M1-67, is estimated to be no more than 10,000 years old. It's just a baby in astronomical terms.

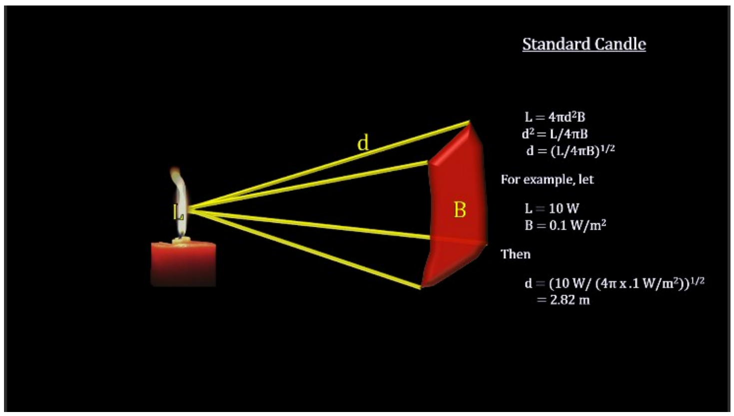
AG Carinae - LBV (20,000 light years)

Here's a Hubble image of the luminous blue variable star AG Carinae. It has evolved from the main sequence with twenty times the mass of the Sun. AG Carinae is losing its mass at a phenomenal rate. It's mass to energy conversion is creating powerful stellar winds with speeds of up to 7 million km/hour (4.3 million miles per hour). These powerful winds are responsible for the shroud of material visible in this image. [The winds exert enormous pressure on the clouds of interstellar material expelled by the star and force them into this shape. Despite its intense luminosity, it is not visible with the naked eye as much of its output is in the ultraviolet.]



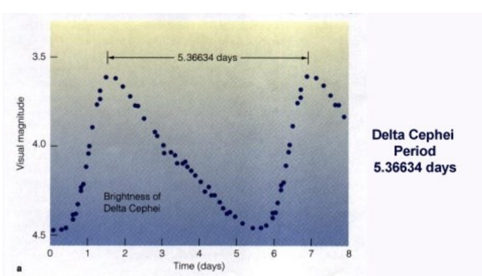
Standard Candles

You'll recall how we used the inverse square law when we covered star luminosity in the "Nearby Stars" segment. We measured the brightness and calculated the distance from parallax measurements to get the Luminosity. But if we had a way to know what the intrinsic luminosity of a star was, we could that along with the apparent brightness to get the distance. For example, if we measured the brightness of a 10-Watt candle to be 0.01 Watts per square meter, we can calculate that the candle is 1 meter away. A celestial object with a known luminosity is called a 'Standard Candle'. But until 1912, there were no known standard candle stars. That changed when Henrietta Leavitt published her findings on Cepheid variable stars.



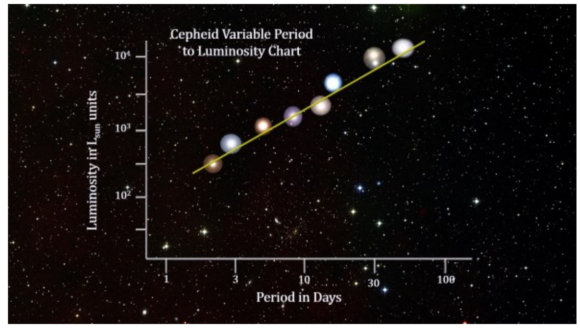
Delta Cephei – F5Ib to G1Ib (887 light years)

Like Polaris, Delta Cephei is a binary star system and a Cepheid variable star. Cepheid stars undergo periodic changes in luminosity. Delta Cephei is among the closest stars of this type of variable, with only Polaris being closer. Most stars have some variability in their luminosity. Even our sun varies on an 11-year cycle of sun spots. But, Delta Cephei's variability is caused by regular pulsation in the outer layers of the star.



Here's its light curve showing luminosity changes over time. The pattern is quite regular.

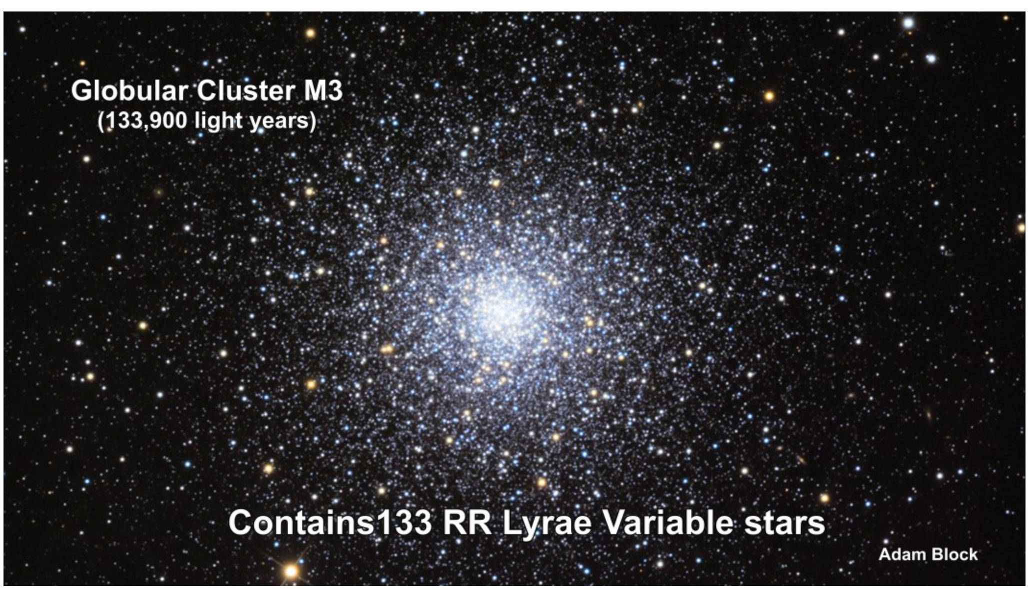
Early in the 1900s, Henrietta Leavitt thought to plot Cepheid luminosity cycle periods against luminosity. She found that the period of these stars varied in proportion to their absolute brightness. This was very interesting, because, as we have discussed, once we know the intrinsic luminosity of a star, we can easily calculate its distance. Leavitt's discovery made Cepheid stars true standard candles and changed the world of astronomy.



[Additional info: By 1918 work using Cepheid variables came up with the first decent estimations of the size of the Milky Way Galaxy and the sun's position within it. Delta Cephei is of particular importance as a calibrator for the H-R Diagram's ability to estimate distance since its distance is now among the most precisely established for a Cepheid. This accuracy is thanks in part to its membership in a star cluster and the availability of precise Hubble and Hipparcos parallaxes. In 2002, the Hubble Space Telescope determined the distance to Delta Cephei within a 4% margin of error. We'll see, in future sections of our video book, just how Cepheid variables have played an important role is measuring the size of the entire Universe.**]**

RR Lyrae - A7III to F8III (854 light years)

RR Lyrae is a variable star like Delta Cephei. As the brightest star in its class, it became the namesake for the RR Lyrae variable class of stars. The relationship between pulsation period and absolute magnitude of RR Lyraes makes them good standard candles. They are not as bright as Cepheid variables. But there are a lot more of them. They are extensively used in globular cluster studies, including the studies that helped us understand the form and size of our Milky Way galaxy.



[Music @20:40** Grieg, Edvard: Solveig's Song; from Peer Gynt; New Symphony Orchestra; from the album "60 Classical Tracks", 2011**]

Zeta Geminorum – F7Ib to G3Ib (1,183 light years)

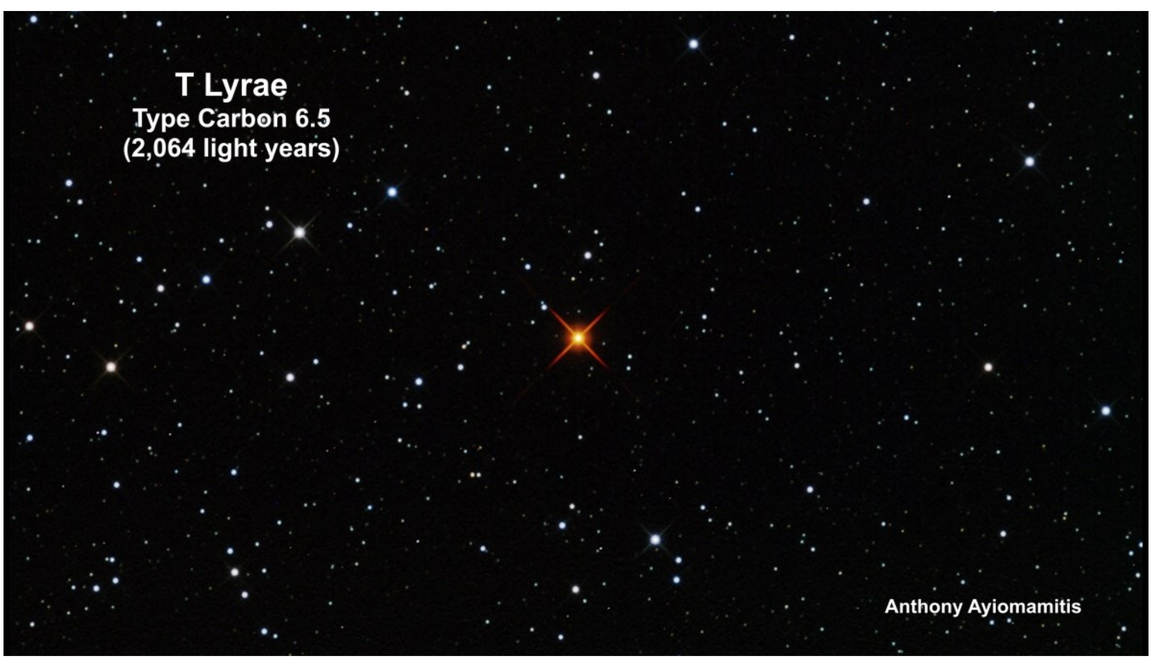
Zeta Geminorum is an intermediate luminous supergiant. It is also a Classical Cepheid variable. [Additional info: The star was recently discovered to belong to a star cluster. Just like with Delta Cephei, the Cepheid's cluster membership, along with recent Hubble and Hipparcos parallax measurements, makes Zeta Geminorum an important calibrator for establishing the Cepheid Standard Candle cosmic distance ladder rung.]

HIP 13044 – F2III (2,300 light years)

HIP 13044 came from outside our galaxy. It was part of a former dwarf galaxy that merged with the Milky Way between six and nine billion years ago. **[**One planet has been discovered in the orbit around the star.**]**

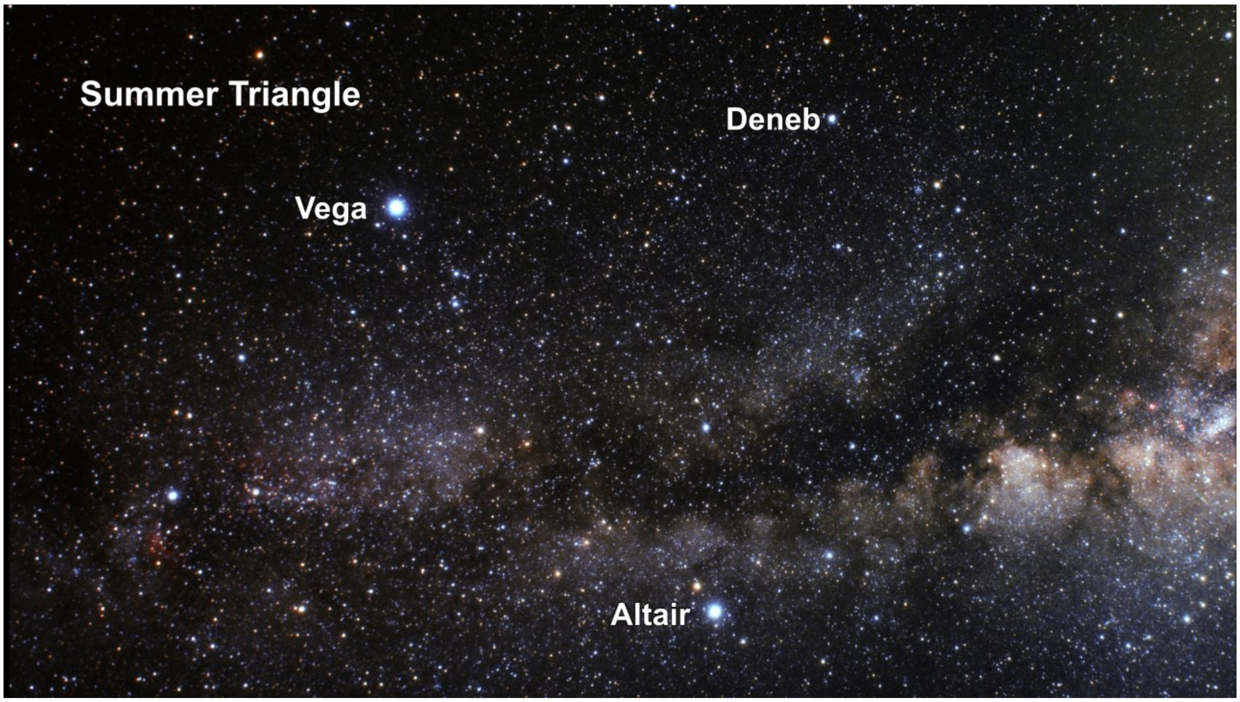
T Lyrae – C6.5 (2,064 light years)

T Lyrae is a Carbon Star. It has used up most of its Hydrogen fuel and is now fusing Helium into Carbon. **[**Currents in the star's structure bring some of the Carbon to the star's outer layers producing a "dust" in the star's atmosphere.**]**



Deneb – A2Ia (2,614 Light Years)

In this image we can see the "Summer Triangle" a giant triangle in the sky composed of the three bright stars Vega (top left), Altair (lower middle) and Deneb (far left).



Deneb is a blue-white supergiant. It's one of the biggest white stars known, at 203 times the size of the Sun, and around 19 times more massive. Deneb's solar wind is blowing away material at a phenomenal rate resulting in its losing mass at a rate 100,000 times greater than the Sun.

SDSS J102915+172927 – 4,140 light years

This star is very faint. It is made of almost purely hydrogen and helium, with only extremely small amounts of heavier elements. We estimate that the star is probably more than 13 billion years old. That would make it one of the oldest stars in the universe.

Mu Cephei – M2e Ia (6,000 light years)

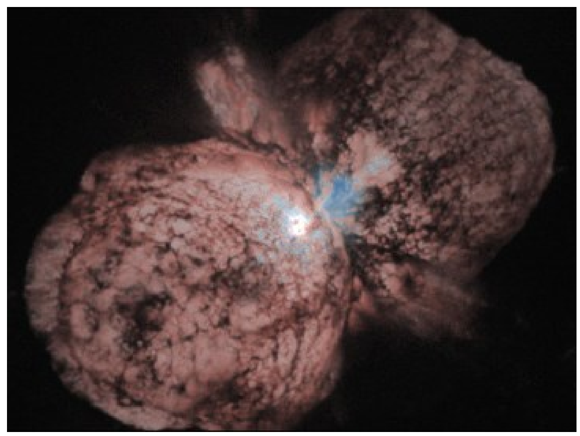
Mu Cephei is a red supergiant star. In fact, it is one of the largest and most luminous stars known in the Milky Way. This star could fit a billion Suns into its volume.

[Additional info: Mu Cephei is nearing death. It has begun to fuse helium into carbon. It is unstable and might explode soon. It is so big, that it might leave behind a black hole. We'll talk more about super nova and black holes in other sections of this video book.**]**

Eta Carinae – O (10,000 light years)

Eta Carinae, 10 thousand light years away is estimated to be 100 times more massive than our Sun. It is one of the most massive stars in our Galaxy. It radiates about five million times more power than our Sun. Its mass, as you can see, also makes it very unstable.

[Additional info: Eta Carinae was the site of a giant outburst about 150 years ago, when it became one of the brightest stars in the southern sky. Though the star released as much visible light as a supernova explosion, it survived the outburst. Somehow, the explosion produced two polar lobes and a large thin equatorial disk, all moving outward at about 1.5 million miles per hour. We know the speed because of a phenomenon called the Doppler Effect. We'll discuss this in our next section on Planetary Nebula.**]**



V838 Monocerotis - M6.3I 20,000 light-years

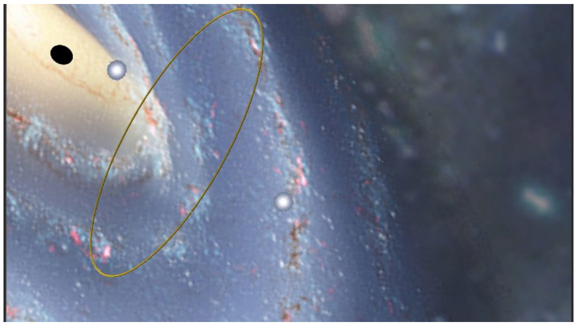
Hubble's latest image of the star V838 Monocerotis [Mon-**o**-ser-o-tis] reveals dramatic changes in the illumination of surrounding dusty cloud structures. The effect, called a light echo, has been unveiling never-before-seen dust patterns ever since the star suddenly brightened for several weeks in early 2002. During the outburst, the normally faint star suddenly brightened, becoming 600,000 times more luminous than our Sun. **[**We'll cover 'light echoes' in more depth in our segment on Supernova.**]**

HVS HE 0437-5439 – 267,320 light years

Hubble has captured this image of a hypervelocity star over a quarter of a million light years away. It is 200,000 light years above the galactic plane and traveling 722 km/s (that's 450 miles/s). That's fast enough to escape the galaxy's gravitational grip completely.

[Based on the speed and position of HE 0437-5439, the star would need 100 million years to have journeyed from the Milky Way's core. Yet its mass — nine times that of our Sun — and blue color mean that it should have burned out after only 20 million years — far shorter than the transit time it took to get to its current location. The most likely explanation for this paradox is that the star is a blue straggler, a pair of smaller and longer-lived stars that merged during flight.]

Astronomers think it was a member of a multiple-star system and was jettisoned by the black hole in the central galactic bulge. (We'll cover black holes when we get to the segment on the Milky Way.) The black hole's tremendous gravitational pull stripped one member while violently ejecting the other member into deep space at these very high-velocities (conserving the system's momentum).



US 708 – sdO (61,970 light years)

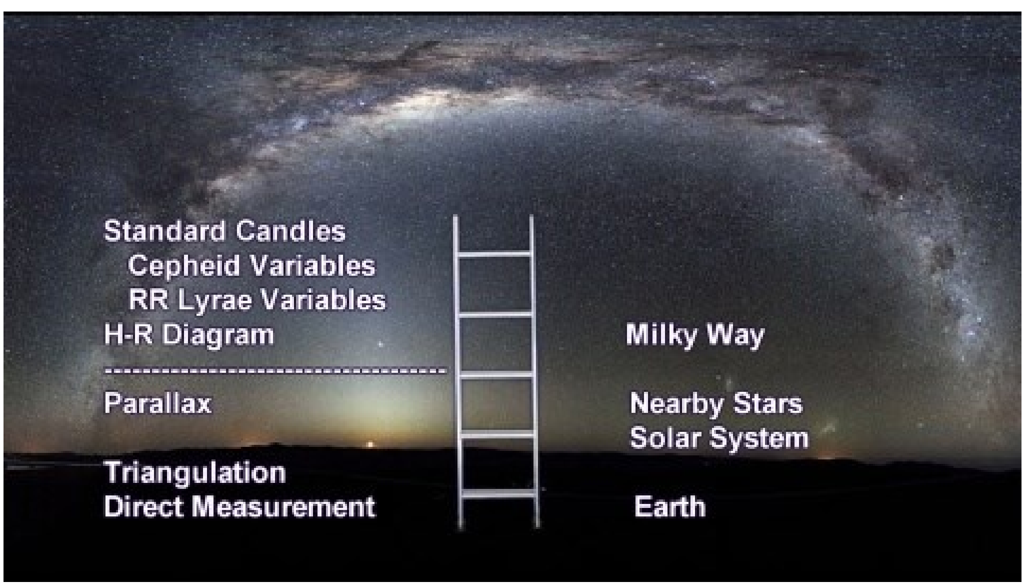
The first example of a hypervelocity star was discovered in 1995. This one, US 708, is the second such star to be discovered. It is an extremely rich Helium hot white dwarf moving at 1,200 km/s (that's 746 miles/s). That makes it the fastest star ever discovered.

Centre de Données astronomiques de Strasbour

It crossed the galactic plane around 14 million years ago, and is thought to be the companion of an exploding star that sent it out into intergalactic space. [Twenty-one hypervelocity stars have been discovered so far.]

Distance Ladder

In our segment on nearby stars, we reached as far as parallax can take us by using the space-based satellites Hipparcos and Gaia. If that's all we had, we'd know very little about our galaxy and almost nothing about the universe beyond. But in this segment on distant stars, we introduced two new rungs for our cosmic distance ladder. One is the Hertzsprung and Russell diagram for estimating a star's luminosity and therefore its distance. The other is variable stars that work as Standard Candles; stars that tell us their intrinsic luminosity by the period of their variable luminosity cycles. In particular, we covered Cepheid and RR Lyrae variables. These rungs in our distance ladder have taken us across the entire Milky Way. In subsequent sections, we'll use these distance ladder techniques on star clusters, star birth nebulae, star death nebulae (also known as planetary nebula – our next segment).



Planetary Nebula

***{Abstract** – In this segment of our "How far away is it" video book, we cover Planetary Nebula.*

We begin by introducing astrophotography and how it adds to what we can see through a telescope with our eyes. We use NGC 2818 to illustrate how this works. This continues into the modern use of Charge-Coupled Devices and how they work. We use the planetary nebula MyCn18 to illustrate the use of color filters to identify elements in the nebula.

We then show a clip illustrating the end-of-life explosion that creates objects like the Helix Planetary Nebula (NGC 7293), and show how it would fill the space between our Sun and our nearest star, Proxima Centauri.

Then, we use the Cat's Eye Nebula (NGC 6543) to illustrate expansion parallax. As a fundamental component for calculating expansion parallax, we also illustrate the Doppler Effect and how we measure it via spectral line red and blue shifts.

We continue with a tour of the most beautiful planetary nebula photographed by Hubble. These include: The Dumbbell Nebula, NGC 5189, Ring Nebula, Retina Nebula, Red Rectangle, Ant Nebula, Butterfly Nebula, , Kohoutek 4-55, Eskimo Nebula, NGC 6751, SuWt 2, Starfish, NGC 5315, NGC 5307, Little Ghost Nebula, NGC 2440, IC 4593, Red Spider, Boomerang, Twin Jet, Calabash, Gomez's Hamburger and others culminating with a dive into the Necklace Nebula.

*We conclude by noting that this will be the most likely end for our Sun, but not for billions of years to come, and we update the Cosmic Distance Ladder with the new 'Expansion Parallax' rung developed in this segment.***}**

Introduction

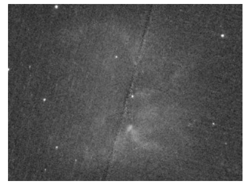
> ***[Music @00:00** Bizet, Georges: Entracte to Act III from "Carman"; Orchestre National de France / Seiji Ozawa, 1984; from the album "The most relaxing classical album in the world…ever!"***]**

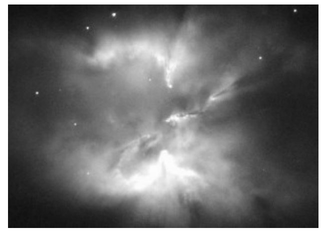
Planetary Nebulae represent some of the most beautiful objects in the Milky Way. In this segment, we'll talk about what they are and how far away they are. And I'll show you some of the spectacular pictures taken by the Hubble Space Telescope.

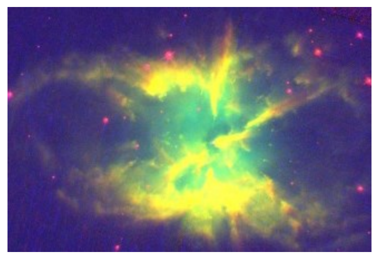
Astrophotography

But first, I'd like to take a minute to go over how we create these photographs. When someone looks through a telescope, the light from the object falls on a person's eye. To take a photograph, all you have to do is replace the eye with a photographic plate.

Here we see Planetary Nebula NGC 2818. It's what someone would see if they were looking through the telescope. It's just a wisp. It's very nebulous. That's how it gets its name Nebula by the way. To the untrained eye, it might look like nothing at all. But if we increase the time exposure, and let more and more light from the object fall on the photographic plate, we get dramatically better results. We get a much sharper image. It's no longer a wisp. We begin to see there's something serious there with structure. Then repeating the process with a filter using a small frequency band of light gives us the first pass on color.





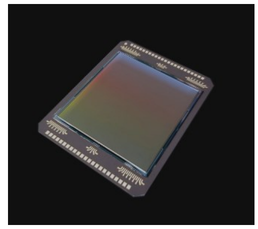


Repeating the process with different bands and combining the photo's produces the full astronomical photo effect. The frequencies bands chosen can represent different temperatures of gasses, or different colors might be used to represent different elements present in the nebula. In NGC 2818 we have: red represents nitrogen; green represents hydrogen; and blue represents oxygen.

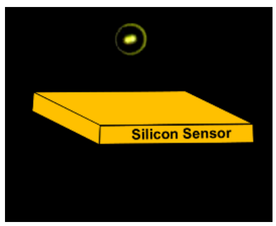
[Music @02:29** Puccini, Giacomo: La Boheme, Act I: Mimi's Aria - "Si, mi chiamano mimi" (Instrumental Version); Sofia Philharmonic Orchestra, 2015; from the album "100 Must-Have Opera Karaoke"**]

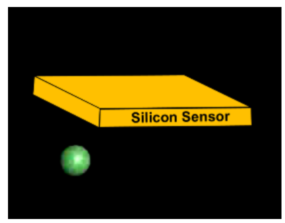
CCDs

Of course, today's telescopes no longer use photographic plates. Instead, a Charge Coupled Device (or CCD for short) is used. These enable direct connections between an object's incoming photons and its image on a computer. Here's how they work.



CCDs are based on a principle called the photo-electric effect. If a photon with sufficient energy hits an electron in the outer shell of an atom, the transfer of energy to the electron can be enough to free it from the atom altogether. [This is a foundational component of quantum mechanics first analyzed by Albert Einstein in 1905.]





CCDs use a thin wafer of silicon to produce electrons from photons because you can free a silicon electron with as little as 1.1 eV. That corresponds to a near infrared photon [λ = 1.13 μm]. And it doesn't start reflecting light instead of absorbing it until it reaches over 4.1 eV. That corresponds to blue-violet light [λ = 0.30 μm].

Photoelectric effect

$E = hc/\lambda$

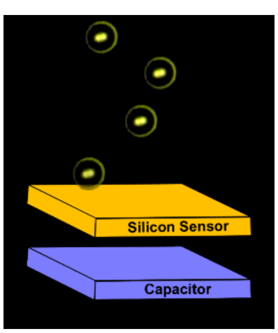
Where:

E = energy
λ = photon wavelength
c = speed of light
$= 2.998 \times 10^{8}$ m/s
h = Planck's constant
$= 4.136 \times 10^{-15}$ eV-sec

If $\lambda > 1.13$ μm
Then $E < 1.1$ eV
And no free electron is produced

If $\lambda < 0.30$ μm
Then $E > 4.1$ eV
And the photon is reflected,
and no free electron is produced

A tiny positively charged capacitor is attached to the silicon wafer in order to collect the freed electrons. If we get one electron for each photon in the range, we'd have 100% quantum efficiency. The highest quality CCDs can achieve up to 90% quantum efficiency. It's interesting to note that the quantum efficiency of the human eye's rods and cones is only 1%.

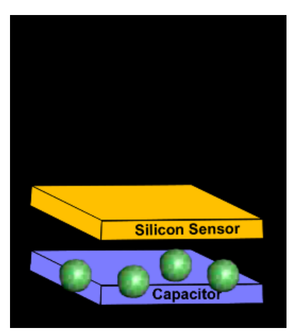


Quantum Efficiency

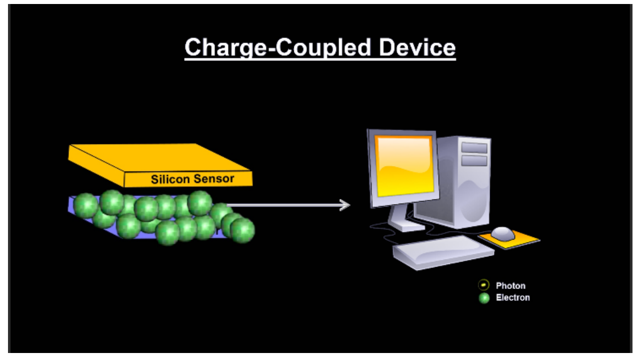
$(N_e/N_p) \times 100\%$

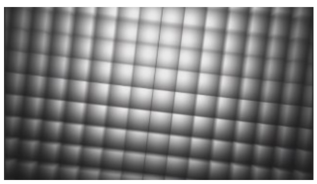
Where

N_e = number of electrons
N_p = number of photons



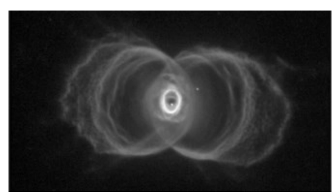
The phonons start producing electrons as soon as the shutter is opened. The capacitor collects the freed electrons until the shutter is closed. At that point, the voltage across the capacitor represents the number of electrons the capacitor collected. This information is sent to the computer.

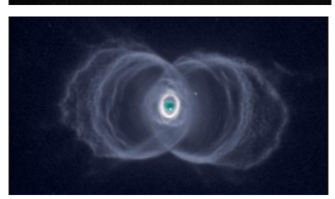


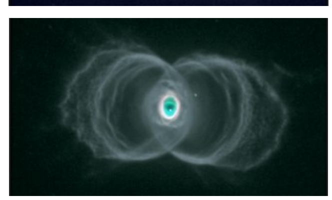


All of this is miniaturized into an integrated circuit and represents one pixel. CCDs are made of thousands or even millions of these, configured as an array. The CCD on Hubble's Wide Field Camera 2 has two 2k by 4k arrays for an 8-megapixel CCD.

And as before for color, we simply repeat observations with filters. For example, here's Hubble's photograph of the planetary nebula MyCn18, 8000 ly away. This picture has been composed from three separate images taken with a blue filter to identify light from oxygen, a greed filter to identify light from hydrogen, and a red filter to identify light from nitrogen. The element distribution is of great interest because it helps us understand the ejection of stellar matter which accompanies the slow death of Sun-like stars.







*[**Music @05:14** Bach, Johann Sebastian: Air 'on the G string'; Academy of St. Martin in the Fields – Sir Neville Marriner, 1974; from the album "The most relaxing classical album in the world…ever!"]*

Star End of Life Explosion

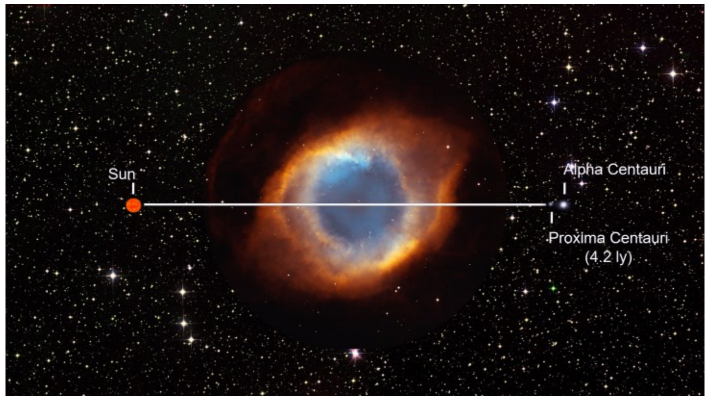
As you can see from these first two examples, Planetary Nebulae are not about planets. They're about stars. It got the name 'planetary' when early astronomers using small primitive telescopes first spotted these objects. They looked like disks similar to Jupiter and Neptune. Planetary Nebulae are actually stars like our Sun that are going through a typical end-of-life cycle.

They have ejected much of their mass into their surroundings and then collapsed in an explosion that ejects a massive amount of additional material at much higher velocities. The faster moving material crashes into the slower moving stuff to create spectacular formations.

Helix Nebula, NGC 7293 – 650 ly

This Helix Nebula is just one of them. Here we have the fluorescing tube or doughnut where we are looking right down the middle of it. A forest of thousands of comet-like filaments, embedded along the inner rim of the nebula, point back towards the central star, which is a small, super-hot white dwarf. That's what's left after the explosion. Each filament is around the size of our entire solar system!

Based on the nebula's distance of 650 light-years, triangulating its angular size corresponds to a huge ring with a diameter of nearly 3 light-years. It would fill most of the space between our Sun and our nearest star –Proxima Centauri.



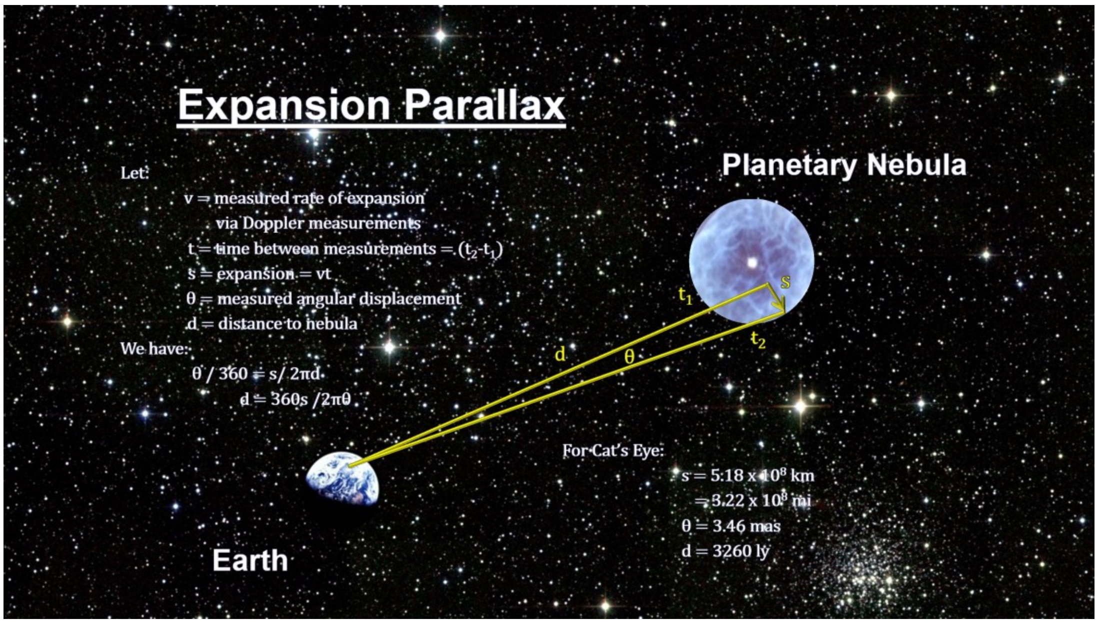
<u>Cat's Eye Nebula, NGC 6543 – 3,264 ly</u>

The Cat's Eye is one of the most complex planetary nebulae ever with surprisingly intricate structures including concentric gas shells, jets of high-speed gas and unusual shock-induced knots of gas. These features made the Cat's Eye Nebula perfect for developing a new way to figure out how far away Planetary Nebula are. The fact is we don't know a lot about the distance to most of these objects. There may be as many as 25,000 Planetary Nebula in the Milky Way, but only 300 have distances that have been measured with some reasonable accuracy. This is due primarily to the nature of the nebulae themselves.

You'll recall that two of our most useful tools for figuring out 'How far away is it?" are standard candles (like Cepheids) and parallax. But because Planetary Nebula stars are surrounded by the debris of their own ejection, it is hard to get a good luminosity reading for standard candles, and equally hard to locate a good star nearby to use for parallax calculations.

Expansion Parallax

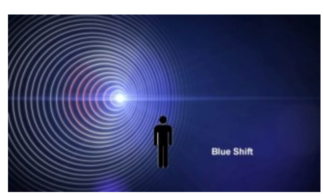
In recent years, however, observations made using the Hubble Space Telescope have allowed a new method of determining distances. All planetary nebulae are expanding, and observations several years apart and with high enough resolution can reveal the angular growth of the nebula in the plane of the sky. Using the Doppler Effect to approximate the velocity of the expanding material, we can calculate the distance the nebula expanded. With that, simple Trigonometry gives us the distance to the Cat's Eye – 3260 light years [plus or minus 877 light years].



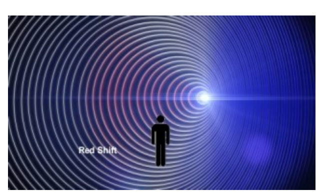
Doppler Effect

We mentioned the Doppler Effect as part of this expansion parallax derivation. We also mentioned the Doppler Effect in our section on stars. So, let me take a minute to go over how we measure and use this effect. Most people have had the experience of hearing the pitch of a car horn, train whistle or ambulance siren drop as the source moved past.

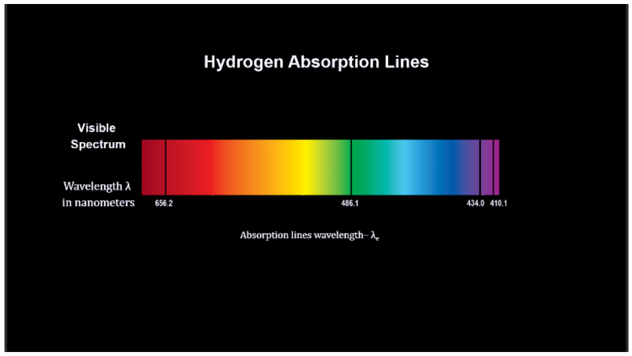
As the sound source moves toward the observer, the sound waves are compressed, making the pitch of the sound higher.



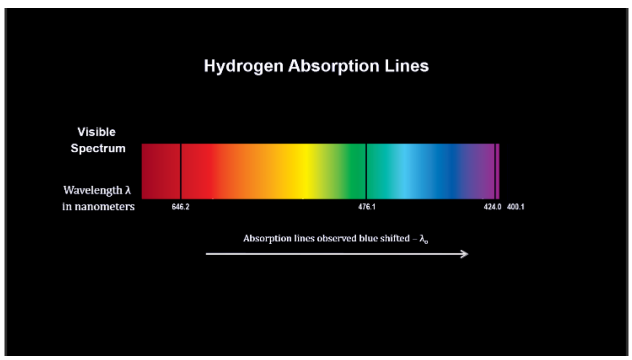
As the sound source moves away from the observer, the sound waves are stretched out, making the pitch of the sound lower.



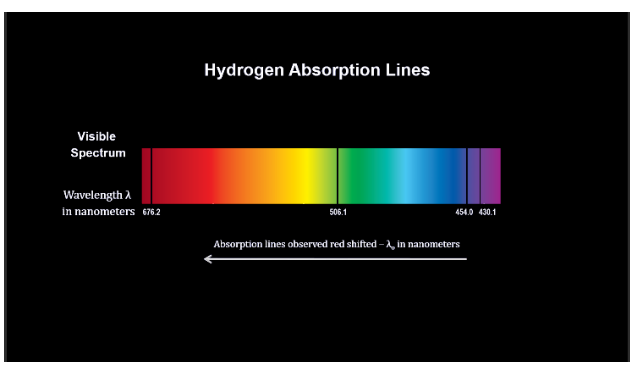
The same effect works for light. Here we have the visible spectrum from a star. Hydrogen in the star's atmosphere creates absorption lines with a unique pattern. Here's the pattern for a star at rest with respect to the observer.



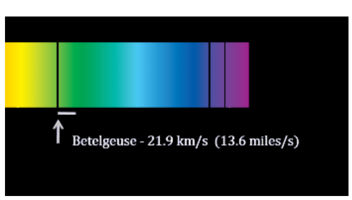
Light from an approaching star has its wavelengths shortened. We see that the lines shift to the blue. Their said to be 'blue shifted'.

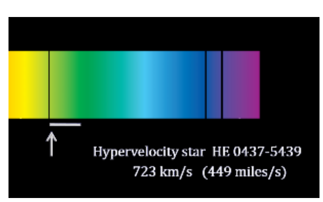


And light from a receding star has its wavelengths lengthened. We see that the lines shift to the red. Their said to be 'red shifted'.



The key to measuring the Doppler Effect is the measure the change in position of the spectral lines. The further the shift, the faster the radial velocity.





With this Doppler Effect, we can determine three important things about stars:

1. We can determine how fast stars and star materials are moving toward or away from us.
2. We can detect and measure the orbital motion of binary star systems.
3. We can even determine how fast a star is rotating.

Dumbbell Nebula, M27, NGC 6853 – 1,200 ly

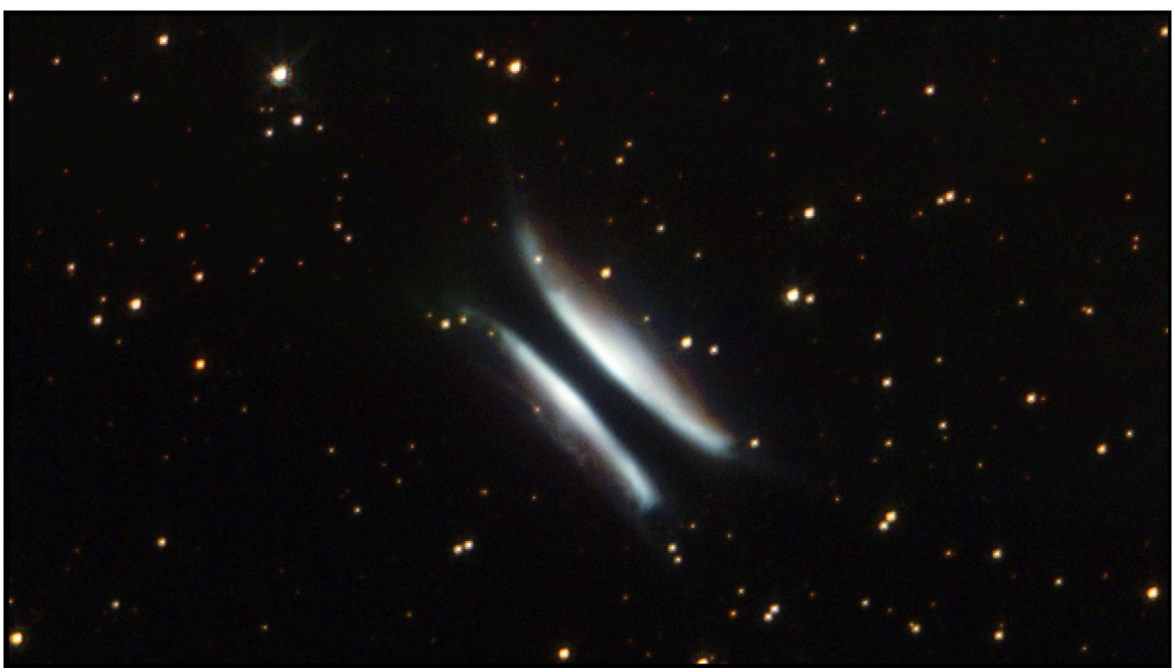
Let's take a look at just some of the most beautiful planetary nebula scattered across the galaxy. Here we have the Dumbbell nebula. It was the first planetary nebula ever discovered. Charles Messier found it back in 1764.

Here's a close-up taken by Hubble.

*[**Music: @11:47** Boccherini, Luigi: Minuet; from String Quintet in E Op. 13 No. 5 (arr Woohouse) Academy of St. Martin in the Fields – Sir Neville Marriner, 1980/1997; from the album "The most relaxing classical album in the world…ever!"]*

IRAS 18059-3211 – 1,600 ly

This object is nicknamed Gomez's Hamburger. The star has already expelled large amounts of gas and dust and is on its way to becoming a colorful, glowing planetary nebula. But at this point, it is simply reflecting its light off the dust.



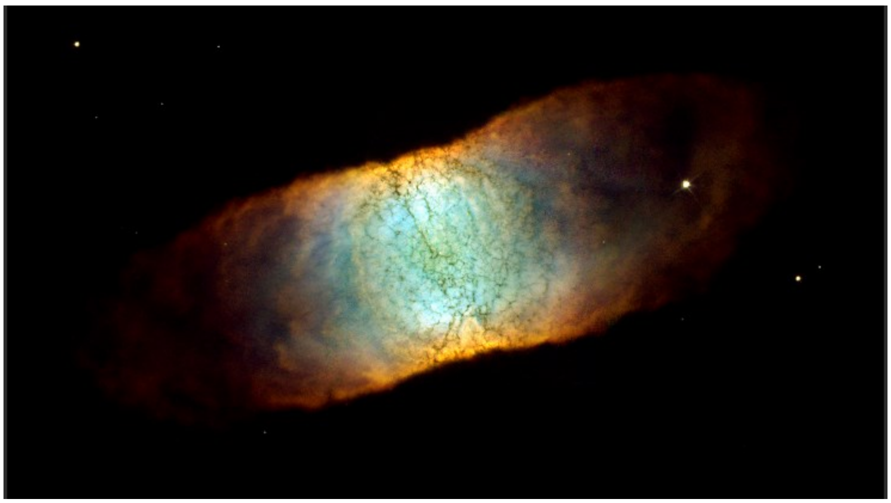
NGC 5189 – 1,780 ly

The intricate structure of the stellar debris forms a dramatic reverse S-shape. The structure visible within NGC 5189 is particularly dramatic. Looking at the detail, the nebula shows a series of dense knots in the clouds of gas. What's going on here is that the radiation from the dying star is carving the knots into shape, much like water flowing around a rock in a stream. And these are all pointing towards the center of the nebula. The knots are a reminder of just how vast the planetary nebula is. They might look like mere details in this image, but just like in the Helix Nebula, each and every one is the size of our entire Solar System. NGC 5189's shape is reminiscent of a lawn sprinkler, with matter being expelled from the star, which is wobbling as it rotates. Similar structures have been seen before, especially in planetary nebulae with binary stars at their centers. This is a likely explanation for 5189, but to date, only one star has been found at the nebula's center.

Ring Nebula, M57 – 2,300 ly

Here we are zooming into the Ring Nebula, one of the earliest and most famous of all planetary nebula. As you can see, it closely resembles the Helix Nebula we covered earlier.
We are looking almost directly down one the poles of the structure, with a brightly-colored barrel of material stretching away from us. From Earth's perspective, the Ring Nebula looks like a simple elliptical shape with a fuzzy boundary. But the new Hubble observations show clearly that the nebula is actually shaped more like a distorted doughnut. The main structure of the nebula is a broad ring of nitrogen. That's the red ring you see. The hotter gas is oxygen seen in green here and it fills the interior. What's even hotter still is helium seen here as blue oblong lobes stretching out perpendicular to the nebula's main structure and looking like a rugby ball.

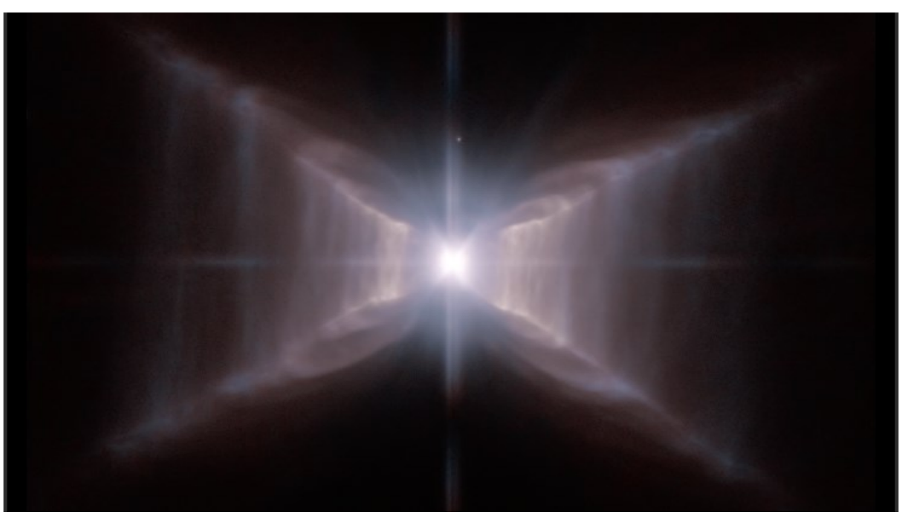
IC 4406, Retina Nebula 1,900 ly



Our first Planetary Nebulae were facing the Earth so that we could see down the tube. On this one, the Retina Nebula, we are viewing the donut from the side. **[Additional info:** This side view allows us to see the intricate tendrils of dust that have been compared to the eye's retina. In this one: Oxygen is rendered blue; Hydrogen is shown as green; and Nitrogen as red.

HD 44179, Red Rectangle – 2,300 ly

The red rectangle is one of the most unusual nebulae known in our Milky Way because of its unusual rectangular shape.



Ant Nebula, Mz 3 – 3,000 ly

This unique planetary nebula resembles the head and thorax of a garden-variety ant. It has intriguing symmetrical patterns. It could be that there is a binary star system at the heart of the nebula creating the symmetrical patterns.

[Music: @15:20** 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!"**]

Butterfly Nebula NGC 6302 – 3,800 ly

My favorite, and one of the most beautiful of all celestial objects, this planetary nebula looks like a delicate butterfly. But it is far from serene. What resemble dainty butterfly wings are actually roiling cauldrons of gas heated to more than 36,000 degrees Fahrenheit, tearing across space at more than 966,000 km/hr (that's 600,000 miles per hour).

NGC 6369 – 3,500

This object is known to amateur astronomers as the "Little Ghost Nebula," because it appears as a small, ghostly cloud surrounding the faint, dying central star.

NGC 2440 – 3,600 ly

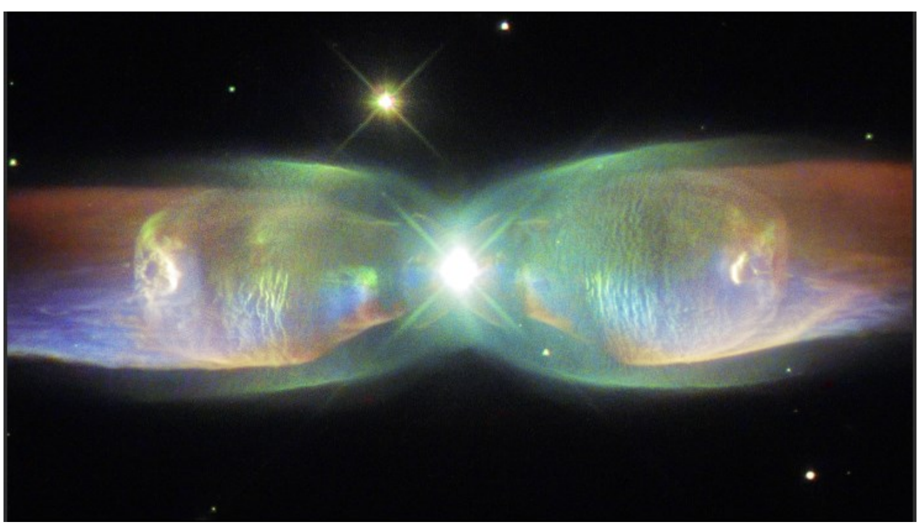
This nebula's chaotic structure suggests that the star shed its mass episodically. During each outburst, the star expelled material in a different direction. This can be seen in the two bow tie-shaped lobes.

NGC 6572 – 3,500 ly

This Hubble picture of NGC 6572 shows the intricate shapes that can develop as stars expel their atmosphere. You can see the central white dwarf star, the origin of the nebula - now a faint hot white dwarf. NGC 6572 only began to shed its gases a few thousand years ago, so it is a fairly young planetary nebula. As a result, the material is still quite concentrated, which explains why it is abnormally bright. [The envelope of gas is currently racing out into space at a speed of around 15 km/s (that's 9 mi/s).] As it becomes more diffuse, it will dim.

Twin Jet Nebula – 4,000 ly

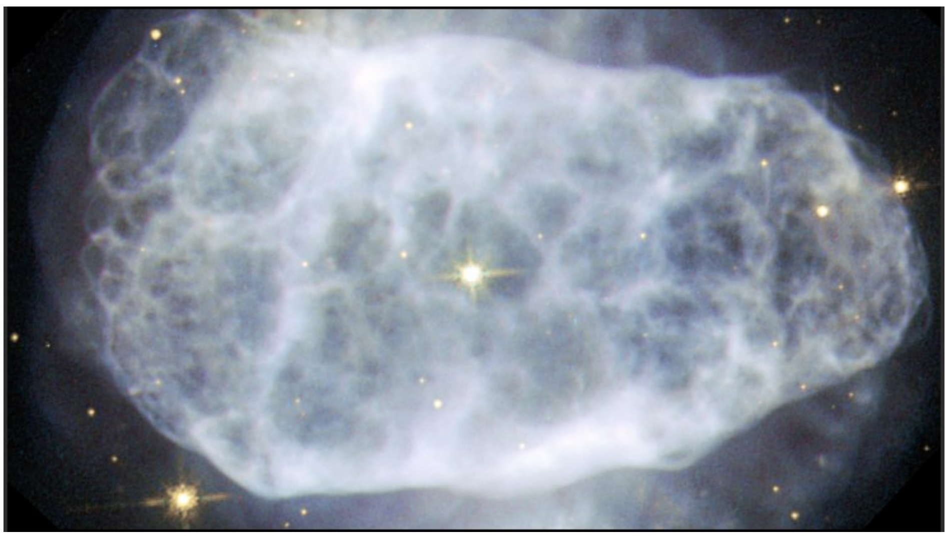
The Twin Jet Nebula, or PN M2-9, is a striking example of a bipolar planetary nebula. Bipolar planetary nebulae are formed when the central object is not a single star, but a binary system, Studies have shown that the nebula's size increases with time, and measurements of this rate of increase suggest that the stellar outburst that formed the lobes occurred just 1200 years ago.



[Music: @18:18** Mendelssohn, Felix: Violin Concerto in E minor; Yehudi Menuhin (violin), Philharmonia Orchestra – Efrem Kurtz 1959/1997; from the album "The most relaxing classical album in the world…ever!"**]

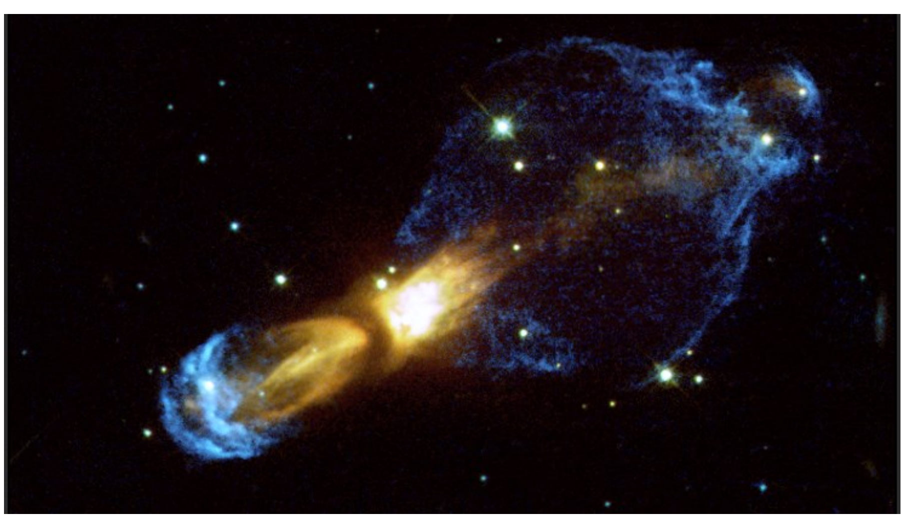
NGC 6153 – 4000 ly

NGC 6153 is a planetary nebula that is elliptical in shape, with an extremely rich network of loops and filaments, shown clearly in this Hubble image. However, this is not what makes this planetary nebula so interesting for astronomers. Measurements show that NGC 6153 contains large amounts of neon, argon, oxygen, carbon and chlorine — up to three times more than can be found in our Solar System. The nebula contains a whopping five times more nitrogen than the Sun! Although it may be that the star developed higher levels of these elements as it grew and evolved, but it seems more likely that the star originally formed from a cloud of material that already contained lots more of these elements.



Calabash Nebula, OH 231+4.2 – 4,500 ly

This new, detailed, Hubble image shows a planetary nebula in the making - a proto-planetary nebula. A dying star (hidden behind dust and gas in the center of the nebula) has ejected massive amounts of gas. Parts of the gas have reached tremendous velocities of up to one-and-a-half million kilometers per hour (that's 932,000 mi/hr). **[**This nebula is also known as the Rotten Egg nebula because it has a large amount of sulfur compounds.**]**

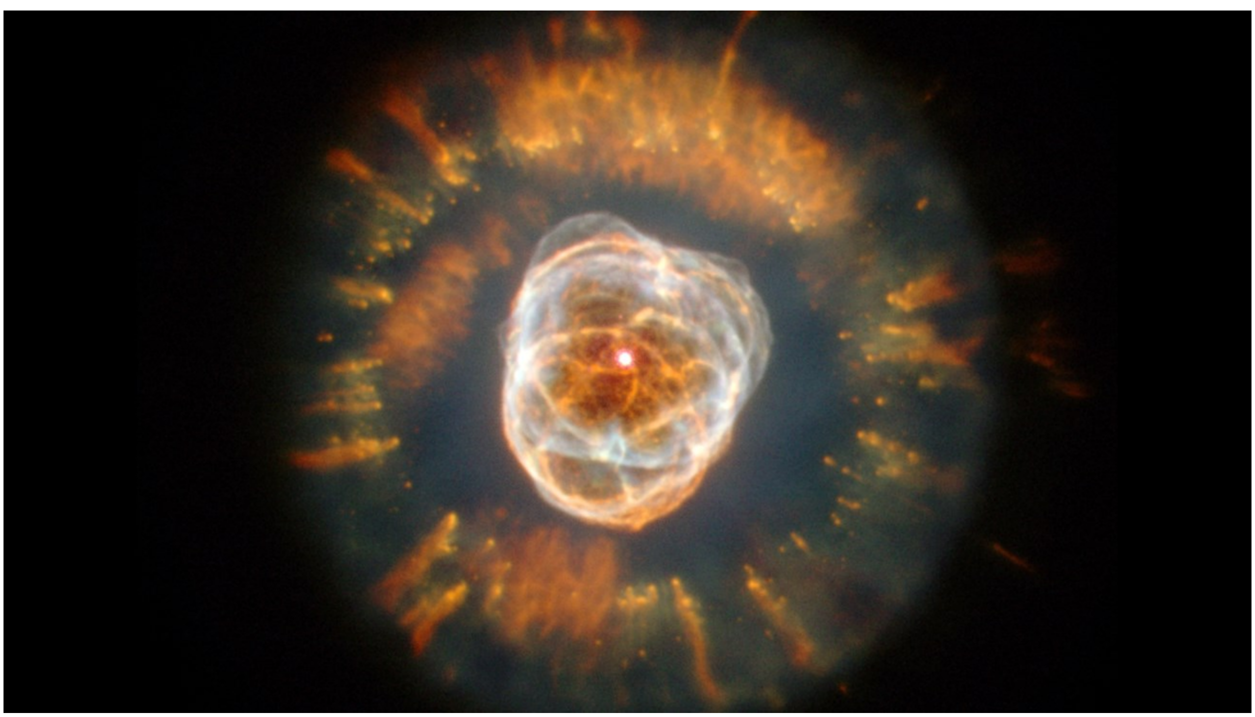


Kohoutek 4-55 – 4,600 ly

Kohoutek 4-55 is named after its discoverer, Czech astronomer Lubos Kohoutek. **[Additional info:** You may have heard about the comet he discovered that also bears his name.**]**

Eskimo Nebula, NGC 2392 – 5,000 ly

This is nicknamed the "Eskimo" Nebula because, when viewed through ground-based telescopes, it resembles a face surrounded by a fur parka. Although this bright central region resembles a ball of twine, it is, in reality, a bubble of material being blown into space by the central star's intense "wind" of high-speed material.



NGC 6751 – 6,500 ly

NGC 6751 is strikingly unusual for planetary nebula. It looks like a giant eye. The nebula is a cloud of gas ejected several thousand years ago from the hot star visible in its center.

Boomerang Nebula – 5000 ly

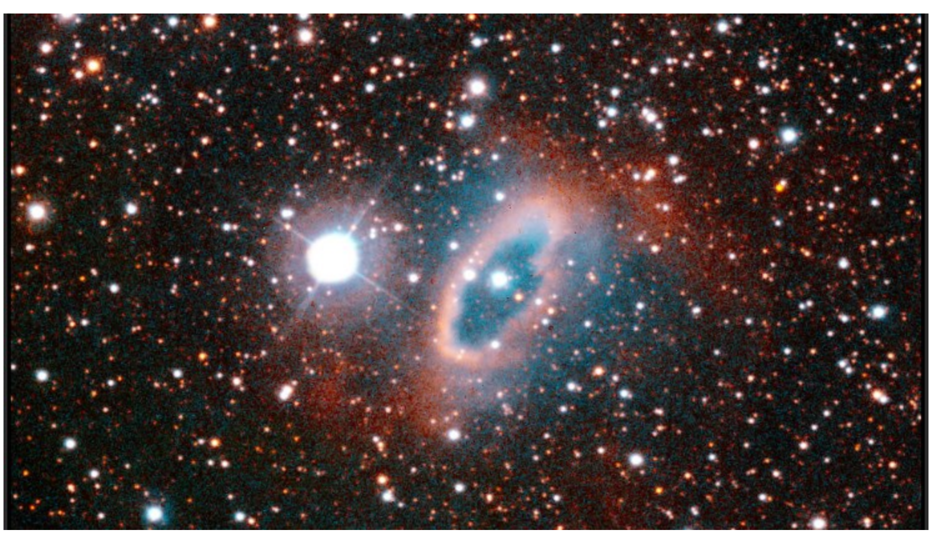
The Hubble telescope took this image in 1998. It shows faint arcs and filaments embedded within the diffuse gas of the nebula's smooth 'bow tie' lobes. The nebula's shape appears to have been created by a very fierce 500,000 kilometers-per-hour wind blowing gas away from the dying central star (that's 310,000 mi/hr). This rapid expansion of the nebula has made it one of the coldest known regions in the Universe.

Red Spider Nebula – 6,000 ly

Huge waves are sculpted in this two-lobed nebula. It harbors one of the hottest stars known and its powerful stellar winds generate waves 100 billion kilometers high. The waves are caused by supersonic shocks, formed when the local gas is compressed and heated in front of the rapidly expanding lobes. The atoms caught in the shock emit the spectacular radiation seen in this image.

SuWt 2 – 6,500 ly

SuWt2, the central star is actually a close binary system where two stars completely circle each other every five days. The interaction of these stars and the more massive star that sheds material to create the nebula formed the ring structure. The burned-out core of the massive companion has yet to be found inside the nebula.



[Music: @22:49** 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!"**]

Starfish Nebula, Hen 2-47 – 6,600 ly

This nebula is dubbed the "starfish" because of its shape. The six lobes of gas and dust, which resemble the legs of a starfish, suggest that Hen 2-47 puffed off material at least three times in three different directions.

NGC 5315 – 7,000 ly

NGC 5315 is a chaotic-looking nebula and reveals an x-shaped structure.

PK 329-02.2 – 7,000 ly

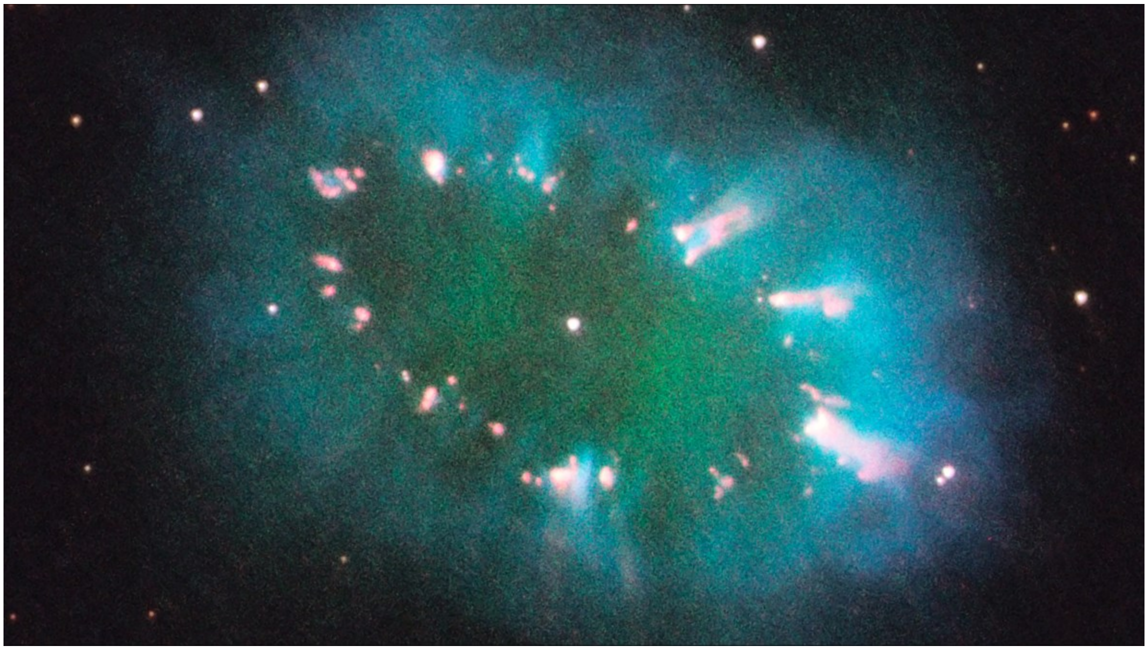
This nebula forms a winding blue cloud that perfectly aligns with two stars at its center. In 1999 astronomers discovered that the star at the upper right is in fact the central star of the nebula, and the star to the lower left is probably a true physical companion of the central star.

NGC 6326 – 11,000 ly

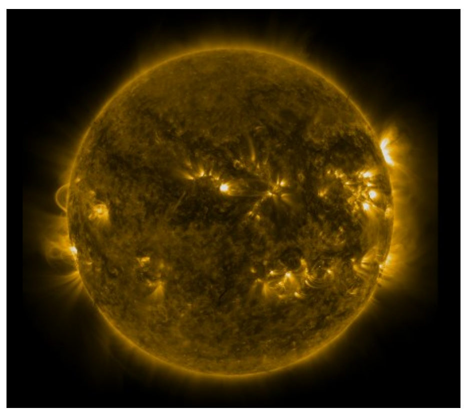
The Hubble Space Telescope captured this beautiful planetary nebula with glowing wisps of outpouring gas that are lit up by a central star nearing the end of its life. Planetary nebulae are one of the main ways in which elements heavier than hydrogen and helium are dispersed into space after their creation in the hearts of stars. Eventually some of this ejected material may form new stars and planets. The vivid red and blue hues in this image come from the material glowing under the action of the fierce ultraviolet radiation from the still hot central star.

Necklace Nebula, PN G054.2-03.4 – 15,000 ly

The Necklace Nebula consists of a bright ring, measuring 12 trillion miles across, dotted with dense, bright knots of gas that resemble diamonds in a necklace. The knots glow brightly due to absorption of ultraviolet light from the central stars. Although most stars go through this process, only a few can be seen in the Milky Way. This is because over a relatively short time (millions of years), the ejected gasses get so far away from the star, that they are no longer fluorescing or reflecting light from the central dying star. Then all we see are the White Dwarfs.



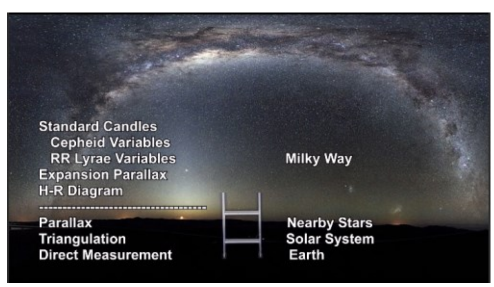
Conclusion



Our Sun will end its life as one of these Planetary Nebulas. The Hubble images like these show that our Sun's fate probably will be more interesting, complex, and striking than astronomers imagined just a few years ago, but not until several billions of years from now.

Distance Ladder

In our segments on stars, we introduced a number of rungs for our cosmic distance ladder – parallax, the H-R Diagram and two standard candles – Cepheids and RR Lyrae. In this segment, we added Expansion Parallax. In our next segment, we'll add star clusters and supernova.



Star Clusters and Supernova

{**_Abstract_** *– In this segment of our "How far away is it" video book, we cover Supernovae and star clusters.*

As we start Supernovae, we compare the magnitude of the exploding star that created the Helix Planetary Nebula with the explosion that created the Crab Nebula. We take the opportunity to describe the size and densities of White Dwarfs as compared to Neutron Stars. We also take a look at what the daytime sky might look like if Betelgeuse were to supernova.

We then cover the Neutron Star that that a star supernova leaves behind. We take a deep look at the Crab Nebula' Neutron star and cover the full spectrum view of the nebula from radio waves to x-rays. We then take a look at the beautiful Veil Nebula and the Cygnus Loop.

We then explain what a Type 1a Supernova is and how it works as a critically important standard candle. We show a binary star system with matter flowing through the L1 Lagrange point, and mention Subrahmanyan Chandrasekhar's solution to Einstein's equations. We then take a look at the amazing remnants of past supernova explosions scattered across our galaxy including: SN 1006, RCW 86, Tycho Supernova SN 1572, Cassiopeia A with its Light Echoes, RCW 103 with its Magnetar, Kepler's supernova SN 1604, N 63A, and Supernova 1987A. For RCW 103, we illustrate the impact on the Earth if it were Capella that went supernova. We conclude this section on SN with a look at how we find them with transient facilities like the Zwicky Transient Facility at the Palomar Observatory.

We continue on to Star Clusters by pointing out that there are two primary kinds of star clusters: open cluster and globular cluster. We visit some very beautiful open clusters including: the Pleiades, the Jewel Box (NGC 4755), Pismis 24 in NGC 6357, Terzan 5, NGC 6791, and the Quintuplet and Arches clusters. And then we visit some spectacular globular clusters including: 47 Tucanae, Omega Centauri, Terzan 5, M30 and M53.

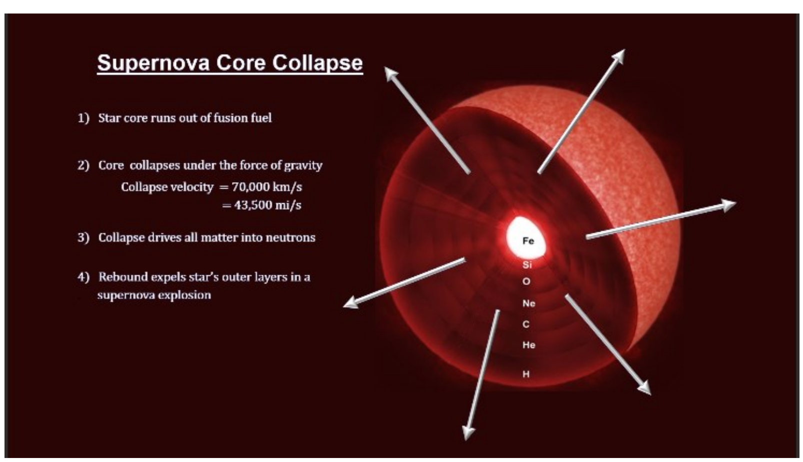
We conclude by adding brightest globular clusters and Type 1a Supernova as key standard candle rungs on our distance ladder.}

[Music:** Bach, Johann Sebastian: Air 'on the G string'; Academy of St. Martin in the Fields – Sir Neville Marriner, 1974; from the album "The most relaxing classical album in the world…ever!"**]

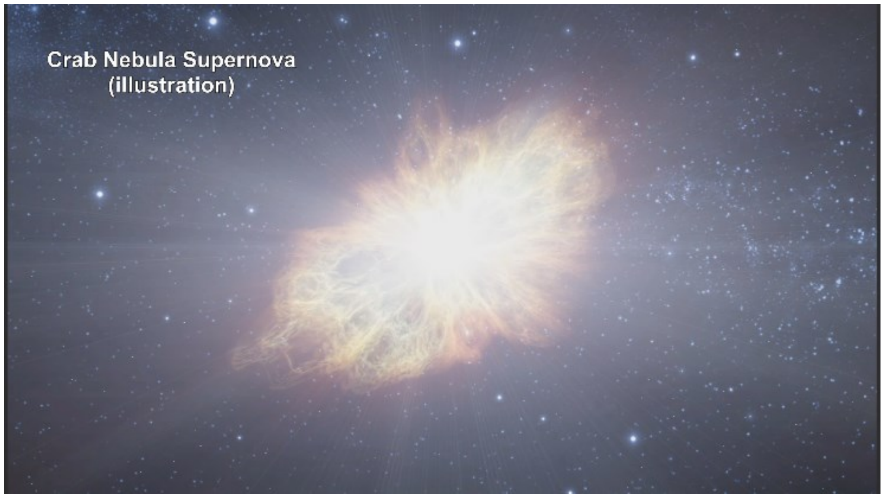
Supernovae

Welcome to our segment on supernovae and star clusters. These are two very important items for our distance ladder, and there're strikingly beautiful. We'll start with supernovae. You'll recall that Planetary Nebulae are the result of a star exploding at the end of its life. This is the expected end for the Sun and most stars less than 5 times the mass of the Sun. The star left behind at the end is called a white dwarf. The typical white dwarf is around the mass of the Sun but packed into a star about the size of the Earth. It's so dense that a spoonful of it would weigh several tons here on Earth.

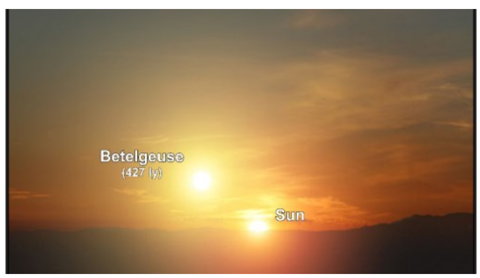
For massive red supergiant stars, a different end is in store. They undergo a core collapse when their nuclear fusion runs out of fuel. At that point, the star can no longer sustain the core's volume against its own gravity. The collapse happens in seconds reaching velocities of 70,000 km/s (that's over 43,000 mi/s). A rebound causes the violent expulsion of the outer layers of the star resulting in a supernova.



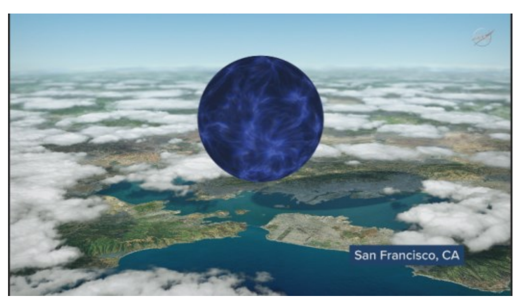
The supernova is billions of times larger than Planetary nebula explosions. A supernova may shine with the brightness of 11 billion suns! The total energy output can be as much as the total output of the sun during its entire 13 billion -ear lifetime!



Here's what the daytime sky might look like if and when Betelgeuse over 400 light years away supernovas.

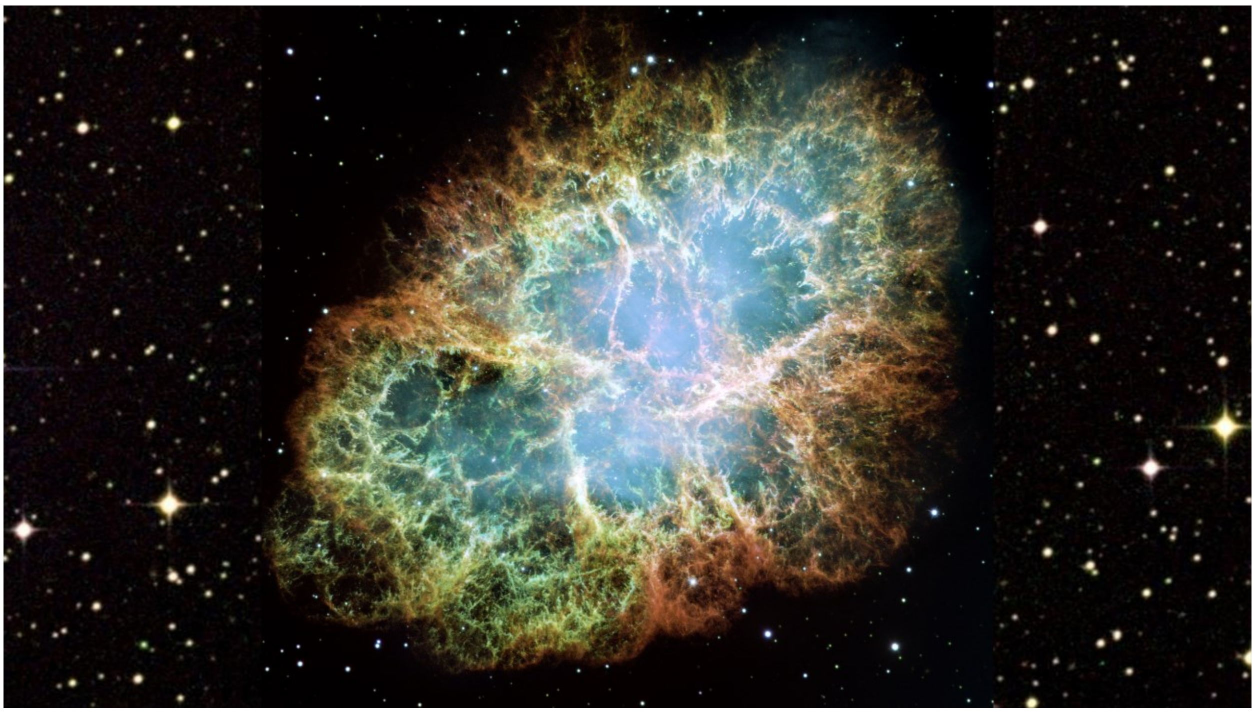


The star left behind at the end is called a neutron star because it is made entirely of neutrons. The typical neutron star is around one and a half times the mass of the Sun but packed into a star with a diameter of around 20 km (that's 12 and a half miles). It's so dense that a spoonful of it would weigh 10 million tons!

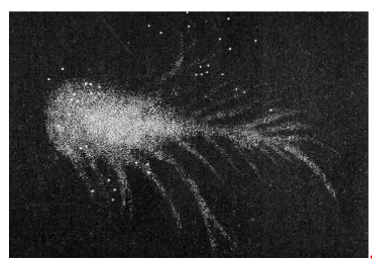


Crab Nebula - 6,500 light-years

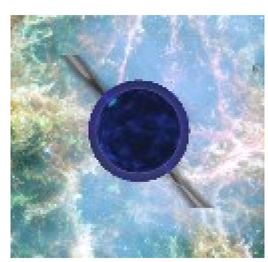
The debris left behind from a supernova is called the Supernova Remnant. These remnants can form spectacular nebulae, millions of times larger than Planetary Nebula. The Crab Nebula is a good example. The remnant is 6 light years wide and expanding at 1,500 km/s (that's 930 mi/s). The orange filaments are the tattered remains of the star and consist mostly of hydrogen.



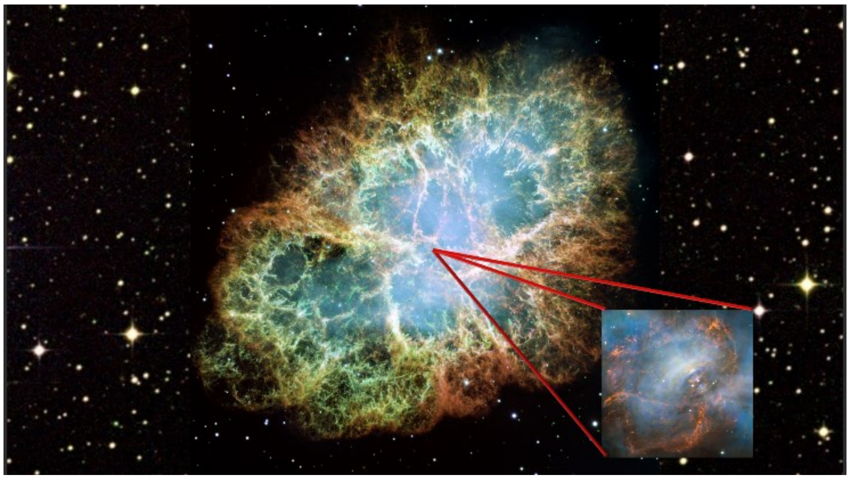
Japanese and Chinese astronomers recorded this event nearly 1,000 years ago in 1054. It got its name because of its appearance in a drawing made by Irish astronomer William Parsons in 1844.



The supernova's remnant neutron star is rotating like a lighthouse. It is ejecting twin beams of radiation that appear to pulse 30 times a second due to the star's extremely fast rotation rate. This kind of neutron star is called a Pulsar.



Pulsar PSR B0531+21

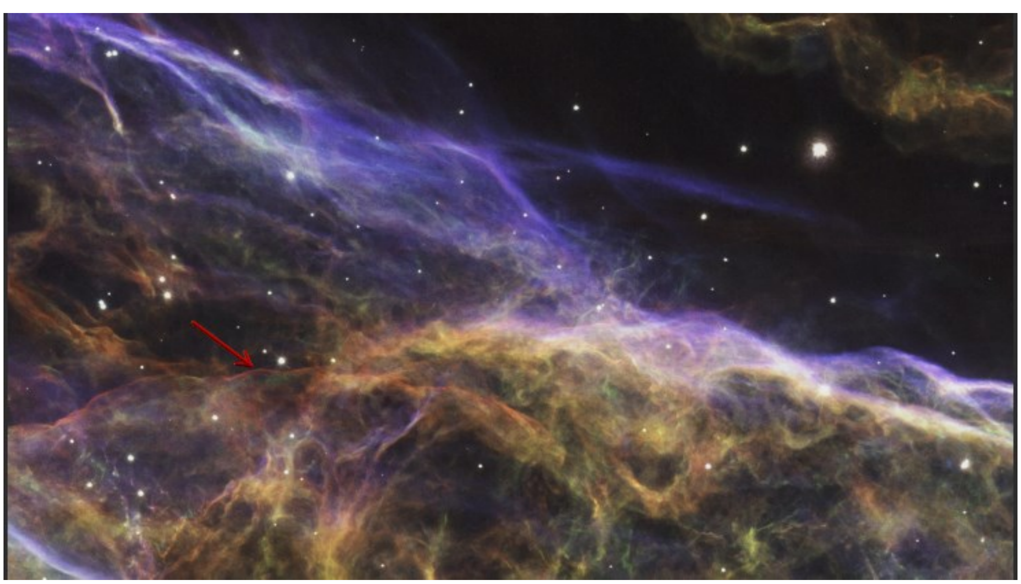


This Hubble image captures the region around the pulsar the rightmost of the two bright stars near the center of this image and the expanding filamentary debris surrounding it. Inside this shell is a blue glow that is radiation given off by electrons spiraling at nearly the speed of light in the powerful magnetic field around the pulsar. Bright wisps are moving outward from the star at half the speed of light to form an expanding ring. It is thought that these wisps originate from a shock wave that turns the high-speed wind from the pulsar into extremely energetic particles.

Veil Nebula – 1,500 light years

So, let's take a look at some of the fantastic celestial remnants of stars destroyed by supernovae explosions photographed by the Hubble Space Telescope. This Veil Nebula is the shattered remains of a supernova that exploded some 5-10,000 years ago. We are zooming into sections of the Veil Nebula photographed by Hubble in 1997. This series of images provides beautifully detailed views of the delicate, wispy structure resulting from this cosmic explosion.

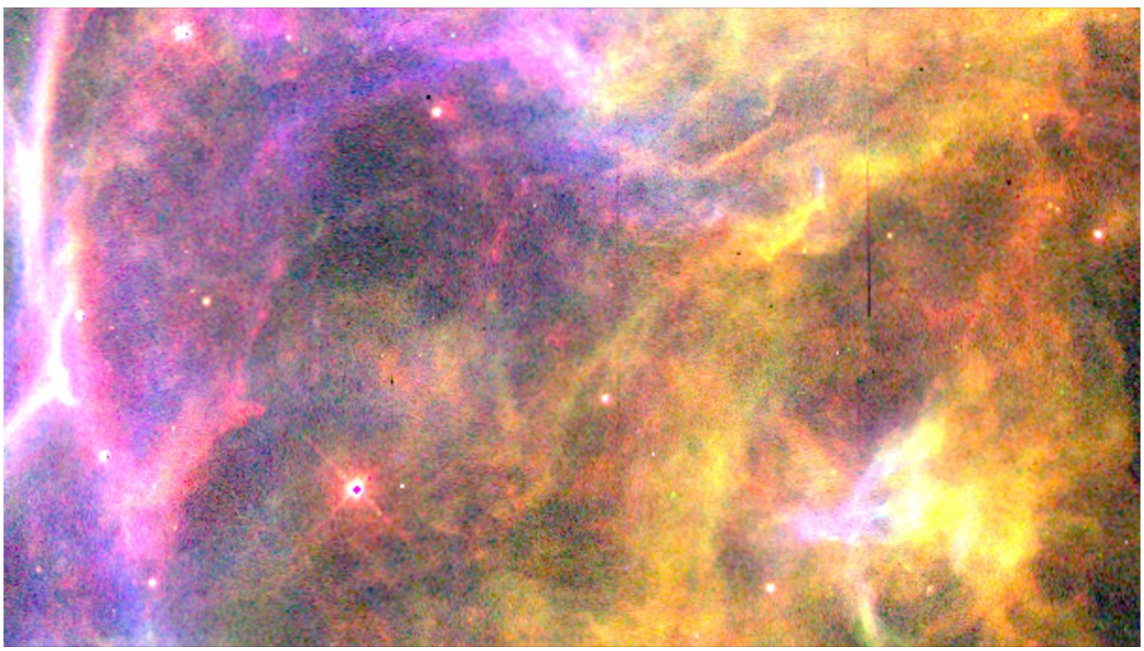
In 2015, Hubble took another look. Overlaying new images with the old, allows scientists to study how far the nebula has expanded since it was photographed over 18 years ago. Despite the nebula's complexity and distance from us, the movement of some of its delicate structures is clearly visible — particularly the faint red hydrogen filaments.



Cygnus Loop – 2,500 light years

The Veil Nebula is part of a larger nebula known as the Cygnus Loop. The Cygnus Loop marks the edge of a bubble-like, expanding blast wave from a colossal stellar explosion which occurred about 15,000 years ago. This image shows a small portion of this nebula.

[Additional info: In this image the supernova blast wave, which is moving from left to right across the field of view, has recently hit a cloud of denser than average interstellar gas. This collision drives shock waves into the cloud that heats interstellar gas, causing it to glow.**]**



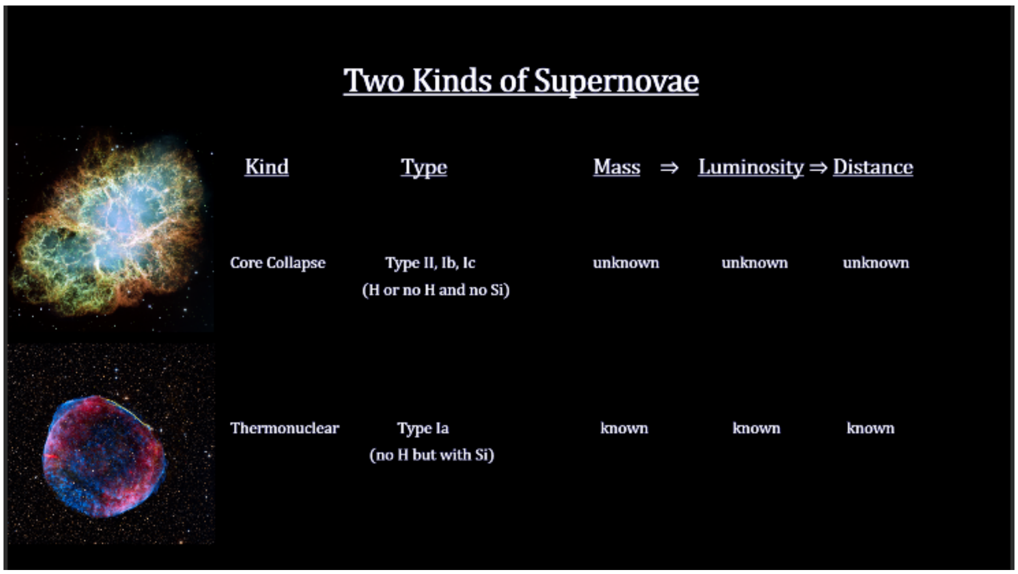
Although only a few stars per century in our Galaxy will end their lives in this spectacular way, these explosions are responsible for making some of the chemical elements heavier than iron in the Universe.

[Additional info: We'll cover other sources for the elements around us in subsequent chapters. Many elements, such as copper, mercury, gold, iodine and lead that we see around us here on Earth today were forged in these violent events billions of years ago: Supernovae, merging neutron stars, hypernovae, etc. The expanding shells of supernova remnants were mixed with other material in the Milky Way and became the raw material for new generations of stars and planets. That's why we are 'star dust', as Carl Sagan pointed out in his Cosmos series back in the 80s.**]**

[Music:** Puccini, Giacomo: Preludio Sinfonico; Radio-Symphonie-Orchester Berlin and Riccardo Chailly; from the album "Puccini Without Words", 2006**]

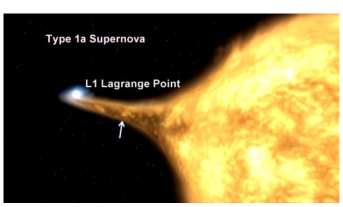
Type Ia Supernova

The luminosity of a supernova depends on the mass of the star. If we knew the mass, we'd have ourselves another standard candle, one that shines hundreds of thousands of times brighter than Cepheid Variables. But for most explosions across the cosmos, we don't have that information. But there is one scenario where we do. It is called a Type Ia Supernova. It is based on a particular binary star setup, and it is recognizable via light profiles and spectral analysis.



Here's how it works:

1) A massive red giant star has a small stellar companion.



2) Mass flows from the giant to the dwarf through the L1 Lagrange point. You'll remember Lagrange points from our discussion on Jupiter in the segment on our Solar System.

3) The mass of the dwarf star increases.

4) Once the mass of the smaller star reaches a critical level, its ability to hold off collapsing under the force of gravity ends. The result is a total collapse inside a few seconds. This creates the supernova explosion that rips the smaller star to pieces.

The critical mass needed for this explosion was calculated to be 1.44 solar masses by Subramanian Chandrasekhar in 1930 on a ship on the way from India to England to begin graduate study in physics at Cambridge University! The Chandra space telescope is named after this great physicist.

$$M_{Limit} = 2.13(hc/2\pi G)^{3/2} \times (\mu_e m_H)^{-2}$$
$$= 1.44\ M_{sun}$$

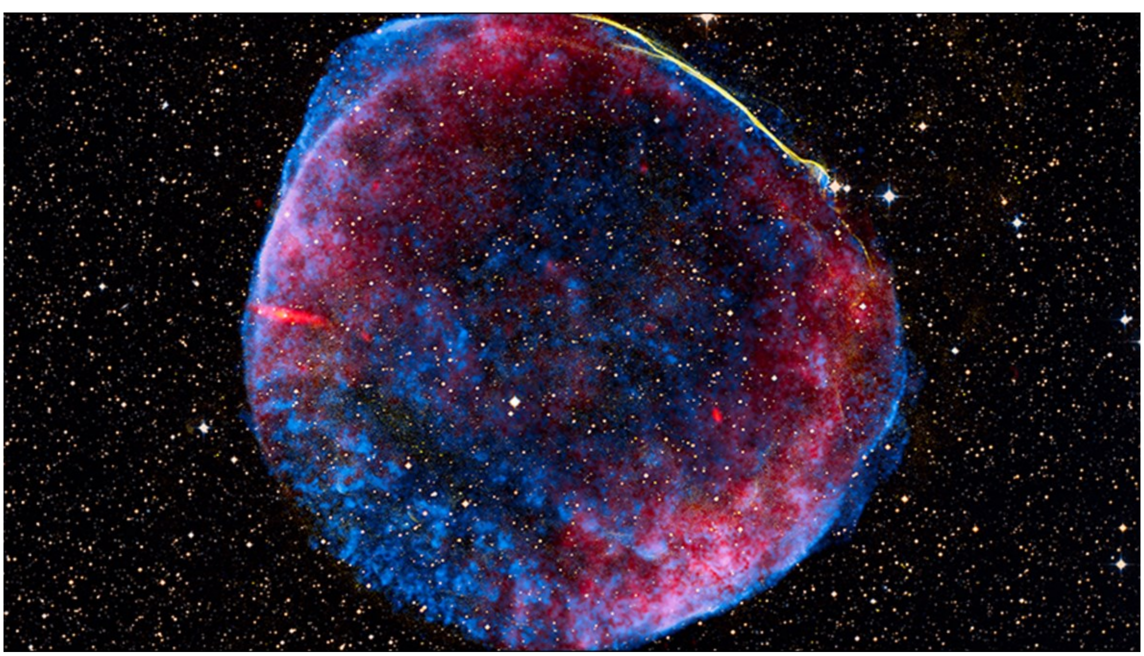
Where:

M_{Limit} = Chandrasekhar limit = maximum star mass that can be supported by electron degeneration pressure
h = Planck's constant
c = speed of light
G = Newton's gravitational constant
μ_e = average molecular weight per electron
m_H = mass of the hydrogen atom
M_{sun} = Mass of the sun

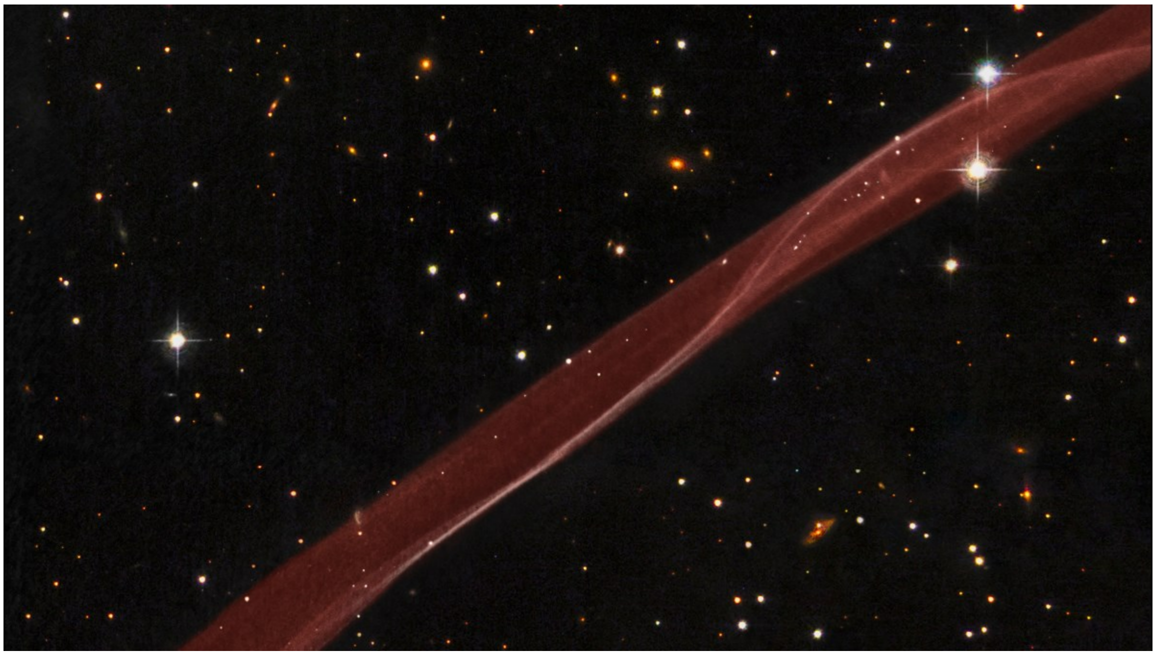
Type 1a supernovae provide a candle as accurate as Cepheid variables but with the advantage that they can be seen clearly at much larger distances. [Because we know the mass of a Type Ia supernova, we know the luminosity. This has made them very important standard candles and one of the most reliable distance measurements. They are thought to provide a distance measurement approaching 5% accuracy over vast distances. They are even used to help find out if the expansion of our Universe is accelerating or decelerating.]

SN 1006 – 7,000 light years

Just over a thousand years ago, the stellar explosion known as supernova SN 1006 was observed. It was brighter than Venus and visible during the day for weeks. The brightest supernova ever recorded on Earth, this spectacular light show was documented in China, Japan, Europe, and the Arab world. Ancient observers were treated to this celestial fireworks display without understanding its cause or implications. We now understand that SN 1006 was a Type 1a supernova.



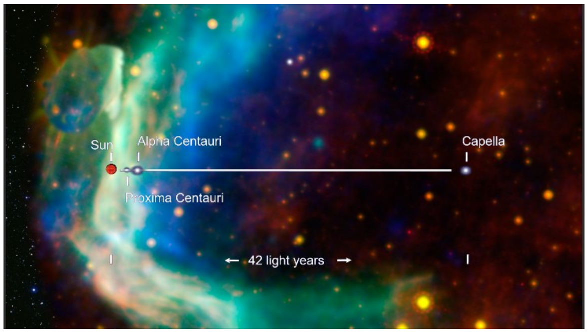
In 1976, the first detection of exceedingly faint optical emission of the supernova remnant was reported. A tiny portion of this filament is revealed in detail by this Hubble observation. The twisting ribbon of light corresponds to locations where the expanding blast wave from the supernova is now sweeping into very tenuous surrounding gas. The size of the remnant implied that the blast wave from the supernova had expanded at nearly 32 million km/hr (or 20 million miles per hour) every hour for over 1,000 years.



RCW 86 - 8,000 light-years

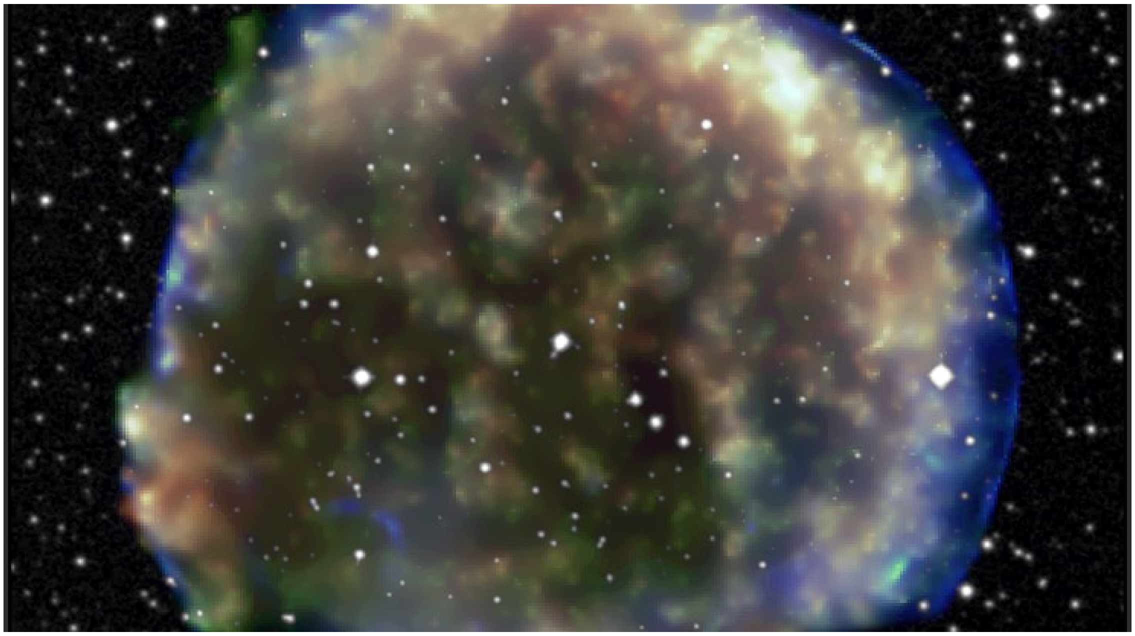
The Chinese witnessed this supernova event in 185 A.D., documenting a mysterious "guest star" that remained in the sky for eight months. This combined visible light and X-ray image shows the interstellar gas that has been heated to millions of degrees by the passage of the shock wave from the supernova.

RCW 86 is approximately 85 light-years in diameter. If it were the star Capella, the shock wave would be tearing us apart right now.



Tycho Supernova SN 1572 - 9,800 light-years

Here we are zooming into the surviving companion star to a titanic supernova explosion witnessed in the year 1572 by the great Danish astronomer Tycho Brahe. On November 11, 1572, Tycho Brahe noticed a star in the constellation Cassiopeia that was as bright as the planet Jupiter. No such star had ever been observed at this location before. It soon equaled Venus in brightness. For about two weeks the star could be seen in daylight. At the end of November, it began to fade and change color, from bright white to yellow and orange to faint reddish light, finally fading away from visibility in March 1574.



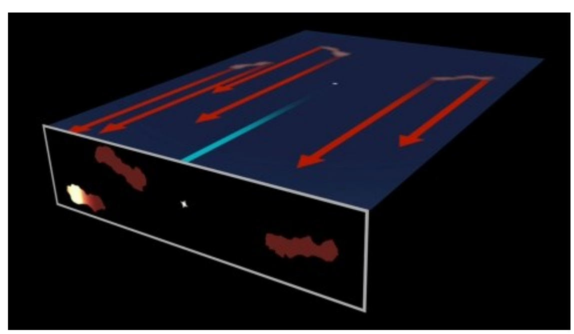
Tycho's meticulous record of the brightening and dimming of the supernova now allows us to identify its "light signature" as that of a Type 1a supernova. Tycho Brahe's supernova was very important in that it helped 16th-century astronomers abandon the idea of the immutability of the heavens.

Cassiopeia A - 10,000 light-years

These supernova star's shredded remains are called Cassiopeia A, or "Cas A" for short. Cas A is the youngest known supernova remnant in our Milky Way Galaxy. The light from this exploding star reached Earth in the late 1600s.

This photo shows the upper rim of the supernova remnant's expanding shell. The colors highlight parts of the debris where chemical elements are glowing. The dark blue fragments, for example, are richest in oxygen; the red material is rich in sulfur. **[**The star that created this colorful show was a big one, about 15 to 25 times more massive than our Sun.**]**

These Spitzer Infrared Space Telescope images show shifting patterns of glowing dust beyond the remnant itself. These changes are so fast that they indicate motion at the speed of light!

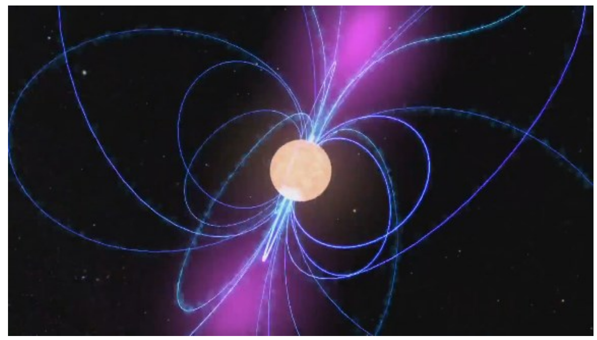


These are light echoes just like what we saw with the star Monocerotis. The light from a supernova can take hundreds of years to reach surrounding dust clouds. Following the arrows of light, it's clear we'll see the supernova flash first. The light echoing off of the dust clouds will arrive later - at various times, delayed by hundreds of years from the original flash.
So, we're not seeing the dust move, we're seeing the light from the supernova move through the dust. It's Spitzer that can detect this brief boost in the thermal infrared glow.

[Music: *Bach, Johann Sebastian: Herz und Mund und Tat und Leben, Cantata BWV 147 - Arr. Guillermo Figueroa - 10. Jesu, Joy of Man's Desiring, Orpheus Chamber Orchestra, from the album "Baroque – The Essentials, 2018*]

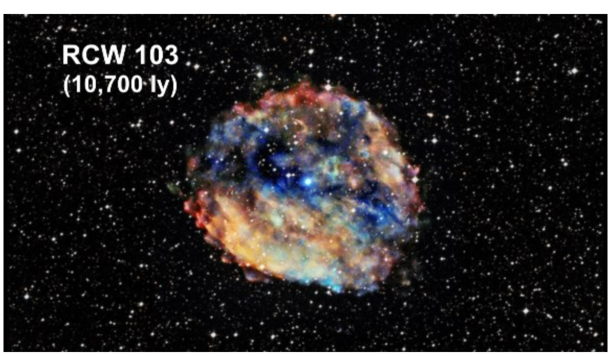
Magnetars

A magnetar is a spinning neutron star with an intense magnetic field. Magnetic field strength is measured in units called gauss. A refrigerator magnet is around 50 gauss. MRI's use up to 70,000 gauss. A magnetar's field strength is a thousand trillion gauss – enough to tear atoms apart a 1000 km away. Only around one in ten neutron stars start out as a magnetars. We do not yet know what makes their magnetic fields so strong. But it looks like they don't last long. They settle into normal neutron star status after around 10,000 years.



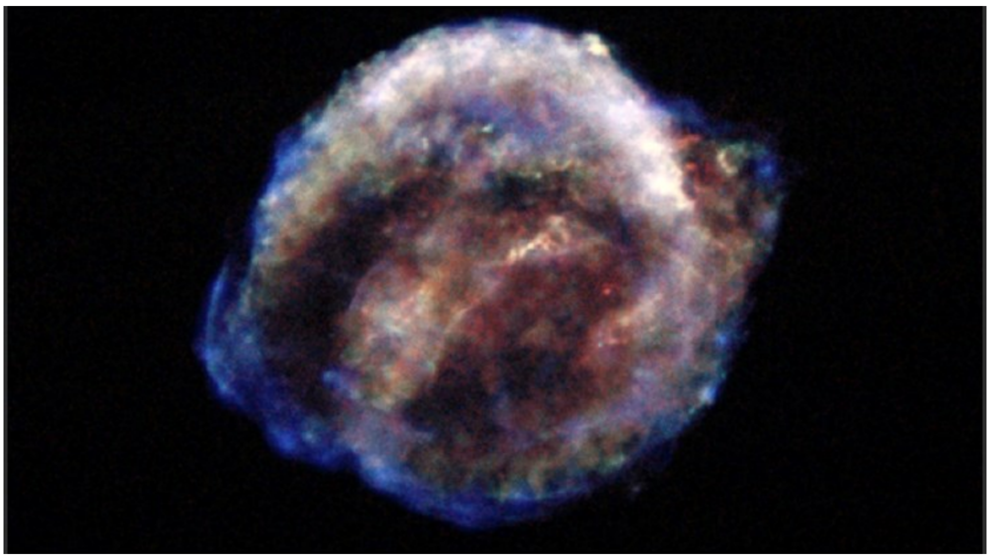
RCW 103 Magnetar – 10,700 ly

On June 22, 2016, an instrument aboard NASA's Swift telescope captured the release of a short burst of X-rays from 1E 1613, a star in the middle of the supernova remnant RCW 103, indicating that it may be a magnetar. Seeking to investigate further, astronomers had the Chandra X-ray Observatory and other telescopes follow up with observations of their own. They confirmed that 1E 1613 has the properties of a magnetar, making it the 30th magnetar ever discovered.



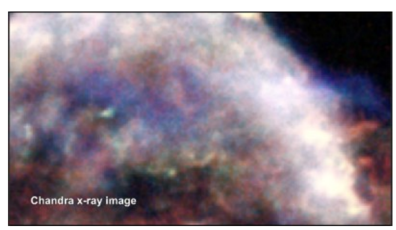
Kepler's supernova SN 1604 - 13,000 light-years

Four hundred years ago, sky watchers, including the famous astronomer Johannes Kepler, were startled by the sudden appearance of a "new star" in the western sky, rivaling the brilliance of the nearby planets. **[**When a new star appeared alongside Jupiter, Mars, and Saturn on Oct. 9, 1604, observers could only use their eyes to study it. The telescope would not be invented for another four years.**]**

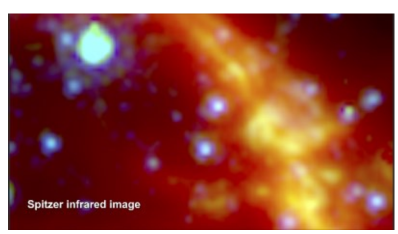


Modern-day astronomers examine the remnant:

In X-rays, that show regions of very hot gas.



In infrared radiation, that shows heated microscopic dust particles that have been swept up by the supernova shock wave.



And in visible light, that reveals where the supernova shock wave is slamming into the densest regions of surrounding gas.

You can see the value of going beyond visible light. Hubble's visible light image doesn't 'see' the full nature of the supernova remnant. The X-ray and infrared cameras do.

[Additional info: The combined image unveils a bubble-shaped shroud of gas and dust that is 14 light-years wide and is expanding at 4 million miles per hour. Observations from each telescope highlight distinct features of the supernova remnant, a fast-moving shell of iron-rich material from the exploded star, surrounded by an expanding shock wave that is sweeping up interstellar gas and dust at more than 22 million miles per hour, like an interstellar tsunami.**]**

N 63A – 160,000 light years

A violent and chaotic-looking mass of gas and dust is seen in this Hubble Space Telescope image of a nearby supernova remnant denoted N 63A.

Many of the stars in the immediate vicinity of N 63A are extremely massive. It is estimated that the progenitor of the supernova that produced the remnant seen here was about 50 times more massive than our own Sun.

[Additional info: Such a massive star has strong stellar winds that can clear away its ambient medium, forming a wind-blown bubble. The supernova that formed N 63A is thought to have exploded inside the central cavity of such a wind-blown bubble. Color filters were used to sample light emitted by sulfur (shown in red), oxygen (shown in blue), and hydrogen (shown in green).**]**

[Music: *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!"***]**

Supernova 1987A – 163,000 light years

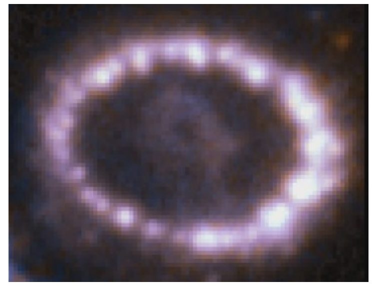
Three decades ago, astronomers spotted one of the brightest exploding stars in more than 400 years. The titanic supernova, called 1987A (SN 1987A) blazed with the power of 100 million Suns for several months following its discovery **[**on Feb. 23, 1987**]**.

Here we have an archival photographic plate of the star before it exploded next to one where it had.

A dense ring of gas around the supernova is glowing in optical light, and has a diameter of about one light-year. A flash of ultraviolet light from the explosion energized the gas in the ring, making it glow for decades. [The ring was created when the star was a red giant - around 20,000 years before the star exploded.]

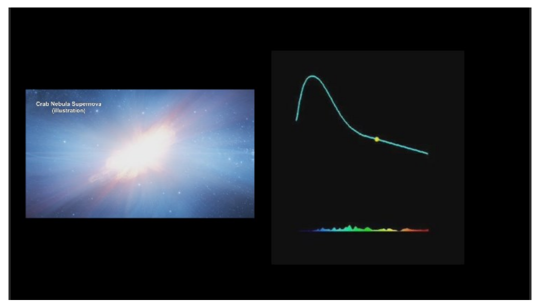
This time-lapse video sequence of Hubble images shows the effects of the shock wave from the supernova blast smashing into the ring. The ring begins to brighten as the shock wave hits it. [The ring is about one light-year across.]

In the past few years, the ring's X-ray light has stopped getting brighter. And, the bottom left part of the ring has started to fade. These changes provide evidence that the explosion's blast wave has moved into the region beyond the ring. This represents the end of an era for this supernova. We expect to learn more about this new region as the blast wave impacts its contents.

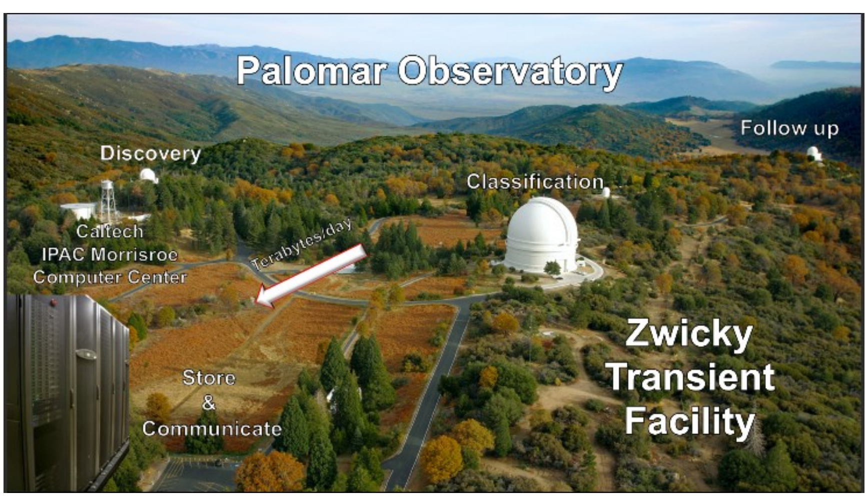


Finding Supernovae

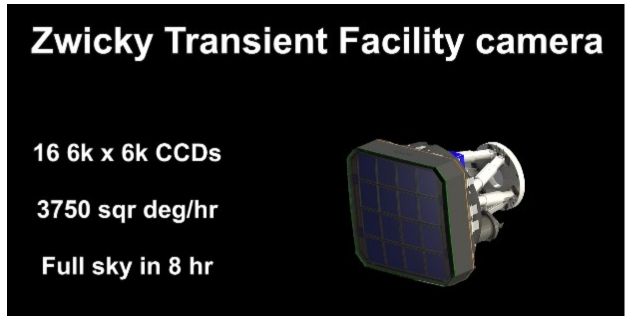
The key to understanding supernovae behavior is to examine its early light profile. But because these explosions are transient events without location foreknowledge. We haven't analyzed very many from their earliest minutes.



But modern astronomy has new facilities to rapidly identify transient events and communicate them around the globe in real time. One of these is the new Zwicky Transient Facility (ZTF for short) at the Palomar Observatory in Southern California, operated by Caltech.



Every night, ZTF will a large portion of the Northern sky, discovering objects that erupt, move or vary in brightness including asteroids, comets and supernovae. Each image is more than 24,000 by 24,000 pixels. 4 terabytes of data will be collected each night.



This new facilities and others like it will greatly improve our chances for finding Supernovae very early in their explosive stage.

Star Clusters

There are two kinds of clusters:

Open clusters: usually a few hundred young stars lightly bound by gravity.

And **Globular clusters**: like this one, hundreds, sometimes hundreds of thousands of older stars tightly bound by gravity.

[Additional info: A few of the nearest clusters such as Pleiades are close enough for their distances to be measured using parallax. A Hertzsprung–Russell Diagram can be plotted for these clusters which has absolute values known on the luminosity axis. Then, when a similar diagram is plotted for a cluster whose distance is not known, the position of the main sequence can be compared to that of the first cluster and the distance estimated. This can then be compared to Cepheid variables found in the cluster to improve the accuracy of the H-R diagram process itself.**]**

Open Clusters

Pleiades - 456 light years

The Pleiades or Seven Sisters is an open cluster of extremely luminous blue stars. And it is one of the nearest star clusters to Earth. It is one of only a few open clusters whose distance can be measured via parallax.

Jewel Box – 6,500 light years

This image is a "close-up' view of the Jewel Box cluster taken by Hubble.

Several very bright, pale blue supergiant stars, a solitary ruby-red supergiant and a variety of other brilliantly colored stars are visible in the image, as well as many much fainter ones, often with intriguing colors. The huge variety in brightness exists because the brighter stars are 15 to 20 times the mass of the Sun, while the dimmest stars are less than half the mass of the Sun.

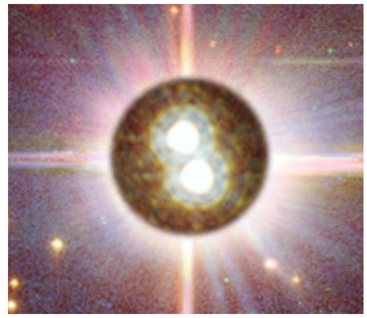
Trumpler 16 – 7,500 ly

The image shows a pair of colossal stars, WR 25 and Tr16-244, located within the open cluster Trumpler 16. This cluster is embedded within the Carina Nebula, an immense cauldron of gas and dust that lies approximately 7500 light-years from Earth. WR 25 is the brightest, situated near the center of the image. The neighboring Tr16-244 is the third brightest, just to the upper left of WR 25. The second brightest, to the left of WR 25, is not in the cluster. It's a low mass star located much closer to the Earth.

Pismis 24 - 8,000 light-years

The small open star cluster Pismis 24 lies in the core of the large emission nebula NGC 6357. We'll cover emission nebula in another segment on the Milky Way. The brightest object in the picture is designated Pismis 24-1. It was once thought to weigh as much as 200 times the mass of the sun.

However, the high-resolution Hubble Space Telescope images of the star show that it is really two stars orbiting one another.



[Music: *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!"***]**

Trumpler 14 – 8,000 ly

This image from Hubble shows a glittering open star cluster that contains a collection of some of the brightest stars seen in our Milky Way galaxy. Called Trumpler 14, it is located 8,000 light-years away in the Carina Nebula.

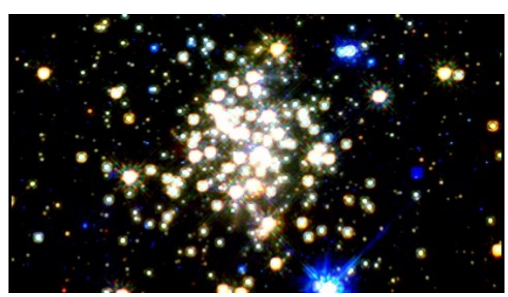
Because the cluster is only 500,000 years old, it has one of the highest concentrations of massive, luminous stars in the entire Milky Way. These blue-white stars are burning their hydrogen fuel so ferociously that they will explode as supernovae in just a few million years. The combination of outflowing stellar "winds" and, ultimately, supernova blast waves will carve out cavities in nearby clouds of gas and dust. These fireworks will kick-start the beginning of a new generation of stars in an ongoing cycle of star birth and death. **[**The small, dark knot left of center is a nodule of gas laced with dust, and seen in silhouette.**]**

NGC 6791 – 13,300 light years

NGC 6791 is one of the oldest and largest open clusters known. It is 10 times larger than most open clusters and contains roughly 10,000 stars. **[**It is unusual in that it contains a large number of White Dwarf binary star systems.**]**

Quintuplet Cluster & Arches Cluster - 25,000 light-years

Penetrating 25,000 light-years of obscuring dust and stars, Hubble uses infrared to provide the clearest view yet of a pair of the largest young clusters of stars in our Milky Way galaxy. They are located less than 100 light-years from the very center of the Galaxy. Having the equivalent mass greater than 10,000 stars like our sun, the monster clusters are ten times larger than typical young star clusters scattered throughout the galaxy. Arches cluster is so dense, over 100,000 of its stars would fill a spherical region that only contains 5 stars in our local neighborhood.



Globular Clusters

47 Tucanae – 15,000 light years

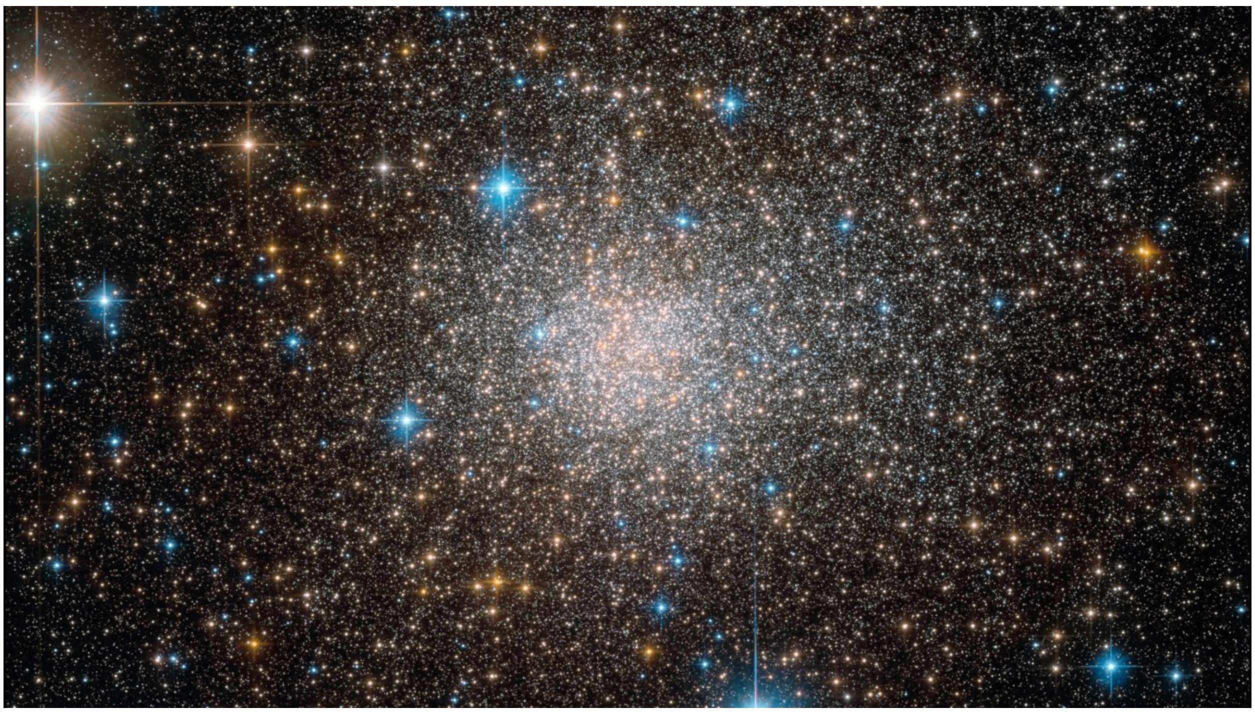
47 Tucanae is one of the densest globular clusters in the Southern Hemisphere containing around a million stars. Multiple Hubble photos of this region allowed astronomers to track the "beehive swarm" motion of stars. Using Doppler shifts and proper motion measurements, precise velocities were obtained for nearly 15,000 stars in this cluster.

This has provided astronomers with the best observational evidence to date that globular clusters sort out stars according to their mass, governed by a gravitational billiard ball game between stars. Heavier stars slow down and sink to the cluster's core, while lighter stars pick up speed and move across the cluster to its periphery.

Omega Centauri - 16,000 light-years

Omega Centauri is among the biggest and most massive of some 200 globular clusters in the Milky Way. Hubble snapped this panoramic view of a colorful assortment of 100,000 stars residing in the crowded core of a giant star cluster that contains nearly 10 million stars. All of the stars in the image are cozy neighbors. The average distance between any two stars in the cluster's crowded core is only about a third of a light-year, roughly 13 times closer than our Sun's nearest stellar neighbor, Alpha Centauri.

Terzan 5 – 19,000 ly



This stellar system resembles a globular cluster, but it's like no other cluster known. A team of astronomers found that there are two distinct kinds of stars in Terzan 5 which not only differ in the elements they contain, but also have an age-gap of roughly 7 billion years. The ages of the two populations indicate that the star formation process in Terzan 5 was not continuous, but was dominated by two distinct bursts of star formation. While the properties of Terzan 5 are uncommon for a globular cluster, they are very similar to the stellar populations which can be found in the galactic bulge. These similarities lead us to believe that Terzan 5 is relic of galaxy formation, representing one of the earliest building blocks of the Milky Way.

Globular Cluster M30 - 28,000 light-years

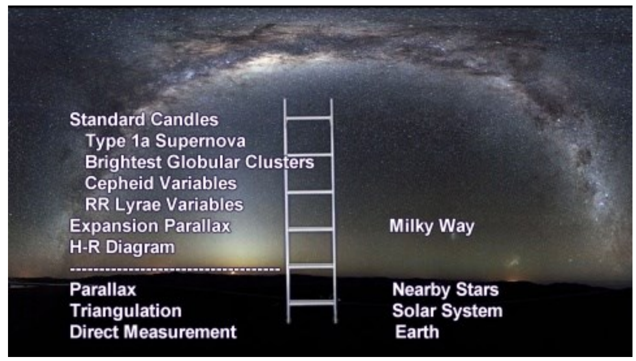
Globular cluster M 30 is a dense swarm of several hundred thousand stars. It's about 90 light-years across.

M53, NGC 5024 – 60,000 ly

Thousands and thousands of brilliant stars make up this globular cluster. Bound tightly by gravity, the cluster is roughly spherical and becomes denser towards its center. [There are over 150 of these enormous spherical clusters in the Milky Way. Because globular clusters are much older than open clusters, they are generally expected to contain more old red stars and fewer massive blue stars. But Messier 53 has an unusually large number of a type of star called blue stragglers. Stars in a globular cluster are expected to form around the same time, but blue stragglers appear to be brighter and younger than the rest. Although their precise nature remains unknown these unusual objects are probably formed by collisions between stars in the crowded centers of globular cluster.]

Distance Ladder

In previous segments, we have used parallax to verify and calibrate the H-R Diagram (aka Spectroscopic Parallax) and standard candles like Cepheid and RR Lyrae Variables. These standard candles then enabled distance measurements far beyond what can be done with parallax. In this segment, we saw how to calculate the luminosity of Type 1A Supernovae. And, although globular star clusters come in a variety of sizes and magnitudes, it appears that the brightest clusters have a similar luminosity. Astronomers used the Cepheids and other known standard candles to verify and calibrate these two new standard candle rungs on our cosmic distance ladder – Type 1a Supernovae and the brightest globular clusters.



Supernovae and Planetary Nebula are about star death. In our next segment, we'll be covering star birth nebula like this one – the Orion Nebula as seen by the Zwicky Transient Facility.

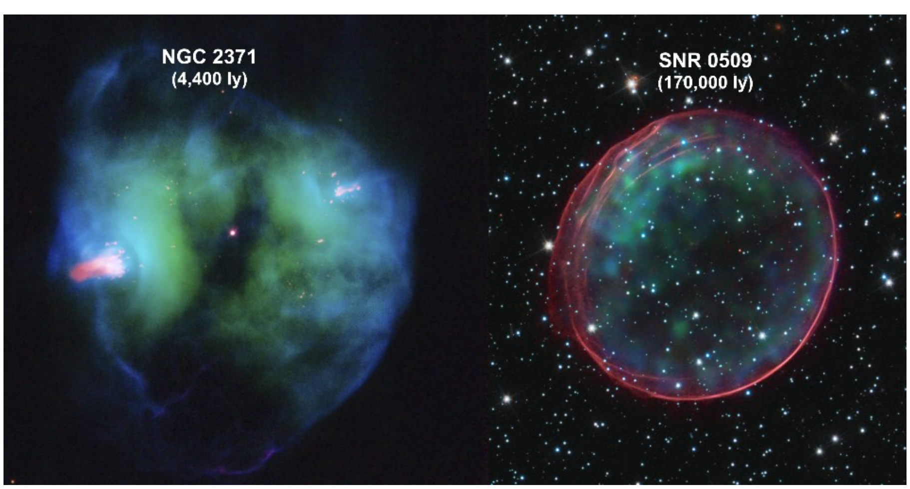
Star Birth Nebula

*{***Abstract** *– Planetary nebula, such as NGC 2371, and supernova remnants, such as SN 0509, form when stars die. In this segment of our "How far away is it" video book, we'll cover the nebula associated with stars being born. We begin by showing the three kinds of nebula: Reflective like the Witch Head Nebula, emission like the Rosette Nebula NGC 2237 along with a description of H II Regions, and dark nebula like the Horsehead Nebula shown in visible and infrared light.*
We then begin a tour of some of the most spectacular star birth nebula across the Milky Way including: Rho Ophiuchi; the Blue Horsehead Nebula; R Coronae Australis, with its Herbig–Haro objects; T Tauri stars XZ and HL Tauri; the Iris Nebula, NGC 7023; the Great Orinon Molecular Cloud behind Minitaka, Alnilam, and Alnitak, with the Flame Nebula, the Horsehead Nebula, the Runing Man Nebula, and a deep look at the Orion Nebula with its Trapezian open star cluster; Young stellar objects V 633 & V376; S2-106; the Cone Nebula, NGC 2264 along with the Christmas Tree star cluster; the Lagoon Nebula, M8; the Trifid Nebula; the Cat's Paw Nebula, NGC 2237; the Omega Nebula; the Eagle Nebula, with its EGGs; a deep look at the Carina Nebula, NGC 3324, with its jets, walls, dust clouds and pillars; the Heart and Soul Nebulae; Statue of Liberty Nebula; RCW 34; NGC 2467; and NGC 3603.
We conclude by adding brightest H II Regions as a key standard candle rung on our distance ladder.}

Introduction

[Music: *Franz Liszt - Hungarian Rhapsody No. 2; Israel Philharmonic Orchestra - Zubin Mehta; from the album "Liszt: Hungarian Rhapsodies", 1989***]**

Welcome to our segment on Nebulae. We'll be seeing some amazing scenes from across our galaxy. In recent segments, we've seen two types of nebula. Both have been connected with stars dying. Planetary Nebula, such as NGC 2371, are all about normal stars at the end of their hydrogen burning life. And Supernova remnants, such as SNR 0509-67.5, are the remains of giant star explosions at the end of their fusion factory life. But the most beautiful nebulae come from vast molecular hydrogen clouds were new stars are being born.



H II Regions

To understand these areas a bit better, we need to know a little more about nebulae. There are three kinds of nebulae: Reflection Nebula, Emission Nebula, and Dark Nebula.

Reflection Nebulae are clouds of interstellar dust grains that are reflecting light from a nearby bright star.

Witch Head Nebula, IC 2118 – 800 light years

This Witch Head nebula is an example. It is reflecting light from the nearby star Rigel. In this photograph, the blue color of the Witch Head Nebula is caused by the dust grains scattering blue light. The same physical process causes Earth's daytime sky to appear blue.

Emission nebulae are shining their own light. In order to do that, the gas and dust needs to be excited to the point of luminesing.

This is accomplished in two primary ways:

1. By exploding stars at the end of their lives like the two we just saw

2. By new stars exciting the clouds they are born in.

Rosette Nebula – 5,500 light years

The Rosette nebula is a good example of this.This nebula is a vast cloud of dust and gas, extending over an area of almost 100 light years wide. It would cover our entire solar neighborhood. As parts of a Great Molecular Cloud condense, new stars are created. These hot new stars shine brightly in the ultraviolet. This is exactly the right wavelength for radiation to ionize hydrogen molecules and atoms by stripping away their elections. This sets off a series of quantum effects that create photons in very large numbers –

creating the light we see with our telescopes. You can see the young recently formed stars situated within this nebula. They formed from the nebula's material. These are the stars that make the nebula shine. Star formation is still in progress in this vast cloud of interstellar matter.

Areas like the one creating the Rosette stars are called **HII Regions**. There are only a few thousand of these in the Milky Way because they only last a few million years. Radiation pressure from the hot young stars drives most of the gas away.

The Pleiades are an example of a cluster which has 'boiled away' most the HII region from which it formed. Only a trace of blue reflection nebulosity remains.

Our third kind of nebulae, **Dark nebulae**, are not shining at all. They are clouds of dust and gas that are positioned in front of a bright nebula obstructing its view.

<u>Horsehead nebula – 1,600 light years</u>

The Horsehead Nebula is an excellent example of this. Rising from a sea of dust and gas like a giant seahorse, the nebula is one of the most photographed objects in the sky. It is a cold, dark cloud of gas and dust, silhouetted against a bright emission nebula.

Here's what it looks like in infrared where we can see lower wavelength light – the kind of light that can pass through the nebula's dust.

<u>Rho Ophiuchi – 400 light years</u>

The most interesting nebulae in the Milky Way are made up of all three types: emission, reflection, and dark. So let's take a look at some of these scattered across our galaxy.

The clouds surrounding the star system Rho Ophiuchi (oh'-fee-yu-kee) or Rho Oph for short is one of our closest star forming regions. Rho Oph itself is a binary star system visible in the light-colored region on the right side of this image. The star system is distinguished by its colorful surroundings, which include a red emission nebula and numerous light and dark brown dust lanes around 5 light years wide.

Near the image bottom lies IC 4592, the Blue Horsehead nebula. The blue glow that surrounds the Blue Horsehead's eye is a reflection nebula.

You can’t see the stars behind the clouds in visible light, but x-ray and infrared brings them into view. The bright pink objects just left of center are young stellar objects. These baby stars are just now forming; many of them are still enveloped in their own tiny compact cloud called their baby blanket. There are more than 300 young stellar objects within the large central cloud. Their median age is only 300,000 years. This is very young compared to some of the universe's oldest stars, which are 12 to 13 billion years old.

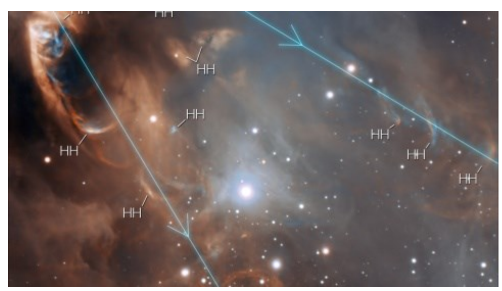
R Coronae Australis – 420 light years

This spectacular wide field image shows the area around the star R Coronae Australis. A huge dust cloud, about eight light-years long, dominates the centre of the image. At its tip (upper right) is a group of lovely reflection nebulae. It is the smaller yellowish nebula (NGC 6729) that surrounds the young variable star R Coronae Australis.

[Additional info: Note the globular star cluster NGC 6723 toward the upper right corner of the view. While the foreground clouds and stars are only 420 light years away, NGC 6723 lies nearly 30,000 light-years away, far beyond the Corona Australis dust clouds.**]**

NGC 6729

Here's a close-up image that shows the dramatic effects of very young stars on the dust and gas from which they were born. The baby stars are invisible in this picture, being hidden behind the dust clouds at the upper left. But the material they are ejecting is crashing into the surroundings at speeds that can reach eight hundred thousand km/hr (that's a half a million miles per hour).



These shocks cause the gas to shine and create the strangely coloured glowing arcs and blobs known as Herbig–Haro or HH objects.

XZ and HL Tauri - 450 light-years

Here's a striking view of two stars called XZ Tauri and HL Tauri, and several nearby young stellar objects. XZ Tauri is blowing a hot bubble of gas into the surrounding space, which is filled with bright proto-stars that are emitting strong winds and jets, illuminating the region, and creating a number of HH objects.

Around HL Tauri, wisps of deep red seem to be streaking away from the blue-tinged clumps on the right. This star is associated with Herbig-Haro object HH 150.

These two stars are textbook examples of a class of stars known as T Tauris — young and rapidly rotating, with strong magnetic fields and powerful winds. They have yet to reach the temperatures necessary for hydrogen fusion deep in their cores. It will take around 100 million years for these stars to trigger these reactions and evolve into fully-fledged stars like the Sun.

<u>Iris Nebula – 1,400 light years</u>

Four light years across, this close-up of an area in the northwest region of the large Iris Nebula seems to be clogged with cosmic dust. With bright light from the nearby star HD 200775 illuminating it from above, the dust resembles thick mounds of billowing cotton. It's actually made up of tiny particles of solid matter, with sizes from ten to a hundred times smaller than a grain of dust we'd find here in our homes.

The Orion Molecular Cloud – 1,500 light years

> ***[Music:** Eric Leslie Satie - Gymnopédie No.1 City of Birmingham Symphony Orchestra – Louis Fremaux, 1974; from the album "The most relaxing classical album in the world…ever!".**]***

This is the Giant Orion Molecular Cloud Complex. The image covers an area with objects that span about 75 light years. It holds a number of beautiful and well know nebula, including of course, the Orion Nebula itself in the upper right of this deep exposure.

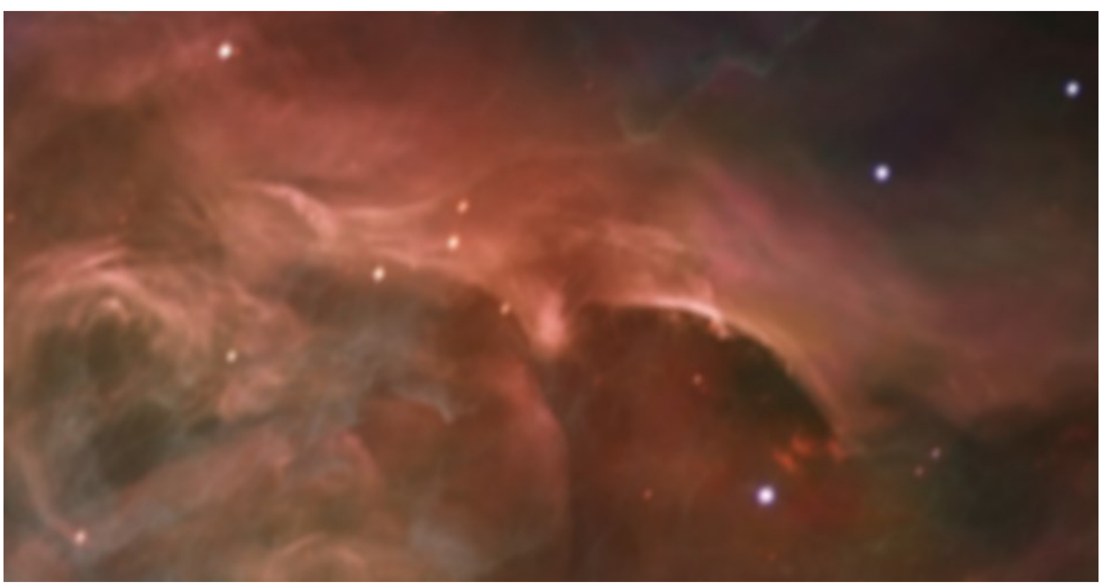
The brightest three stars on the left are the three stars that make up Orion's belt. The top star is Mintaka around 900 light years way. The middle star is Alnilam. It is a blue-white supergiant around 1,300 light years way. The lowest is the star Alnitak. It is only 700 light years away. So you can see that these 3 stars are in line with the Orion cloud, but not a part of it.

Below Alnitak is the Flame Nebula, an emission nebula in filaments of dark brown dust. Just to the right of Alnitak is the famous Horsehead Nebula. Moving over and up to the Orion nebula, we also see the Running Man nebula just to the left of Orion.

Orion Nebula, M42 – 1,500 light years

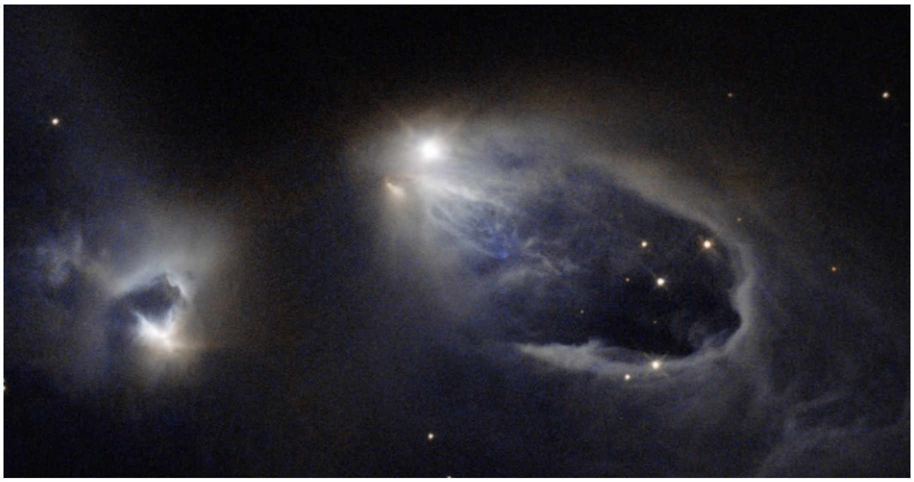
This Hubble mosaic of the Orion Nebula covers 24 light years across and reveals numerous features that reside within this nearby, intense star- forming region. More than 3,000 stars of various sizes appear in the image. The Trapezium open star cluster contains hundreds of brand-new stars. These new stars have cut out a cavern in the dust cloud and illuminate the nebula they were born in. The first of these were discovered by Galileo. They got their name because these first stars looked like a trapezoid.

As we scan to the outer edges of the nebula, you can see the illuminated walls of the Orion cavern along with beautiful elongated jets created by nearby stars being born.



V 633 & V376 – 1,956 ly

Here are two interesting extremely young stellar objects surrounded by the dusty material left over from their formation. These stars are firing off salvos of super-hot, super-fast gas. These expulsions can contain as much mass the entire planet Earth, and this mass is traveling at hundreds of kilometers per second. As it crashes into the interstellar material around them, they have created a number of HH Objects. (HH 161, HH 162 and HH 164).



[Music:** Jules Émile Frédéric Massenet – 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!"**]

Sharpless 2-106 – 2,000 light years

This is one of my personal favorites. It's the bipolar star-forming region, called Sharpless 2-106. It appears in a relatively isolated region of the Milky Way galaxy and measures several light-years in length. A massive, young star, IRS 4 (Infrared Source 4), is responsible for the furious activity we see in the nebula. Twin lobes of super-hot gas, glowing blue in this image, stretch outward from the central star. A ring of dust and gas orbiting the star acts like a belt, cinching the expanding nebula into an "hourglass" shape. Hubble's sharp resolution reveals ripples and ridges in the gas as it interacts with the cooler interstellar medium. The dusky red veins that surround the blue emission area are illuminated by the central star.

<u>Cone Nebula – 2,500 light years</u>

This pillar of gas and dust is called the Cone Nebula. We're looking at the upper 2.5 light-years of the pillar. The entire nebula is 7 light-years long. Radiation from hot young stars, located beyond the top of the image, have slowly eroded the nebula over millions of years.

But the Cone Nebula is just a small part of an even larger nebula covering about 30 light-years. It includes the Fox Fur Nebula, whose convoluted pelt lies on the lower right and the bright variable star S Mon visible just above the Fox Fur. Given their distribution, the stars of NGC 2264 are also known as the Christmas Tree star cluster.

<u>Lagoon Nebula, M8 – 5,000 light years</u>

Swirling dust clouds and bright newborn stars dominate the view in this image of the Lagoon nebula. Within these clouds of dust and gas, a new generation of stars is forming. This Hubble image reveals a pair of one-half light-year long interstellar "twisters" — eerie funnels and twisted-rope structures — in the heart of the Lagoon Nebula. Analogous to Earth tornadoes, the large difference in temperature between the hot surface and cold interior of the clouds, combined with the pressure of starlight, produce strong horizontal shear to twist the clouds into their tornado-like appearance.

This Hubble image shows only a small part of this turbulent star-formation region, about four light-years across. The whole nebula is an incredible 55 light-years wide and 20 light-years tall.

<u>Trifid Nebula, M20 – 5,200 light years</u>

Three huge intersecting dark lanes of interstellar dust make the Trifid Nebula one of the most recognizable and striking star birth regions in the night sky.

The dust, silhouetted against glowing gas and illuminated by starlight, cradles the bright stars at the heart of the nebula. This image from Hubble offers a close-up view of the center of the Trifid Nebula, near the intersection of the dust bands, where a group of recently formed, massive, bright stars is easily visible.

__Cat's Paw Nebula NGC 6334 – 5,500 light years__

The Cat's Paw Nebula is a vast 50 light-years across region of star formation. It is one of the most active nurseries of massive stars in our galaxy and has been extensively studied by astronomers. The nebula conceals freshly minted brilliant blue stars — each nearly ten times the mass of our Sun and born in the last few million years. The region is also home to many baby stars that are buried deep in the dust, making them difficult to study. In total, the Cat's Paw Nebula could contain several tens of thousands of stars.

GGD 27 – 5,500 ly

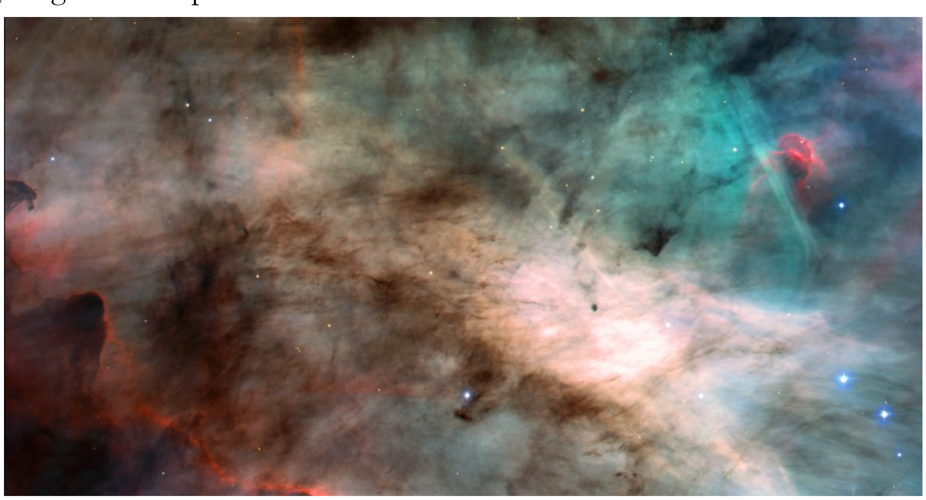
Here's a region of stellar birth known as GGD 27. At first glance it looks chaotic. However, this seemingly random cloud of gas and dust is home to several nascent stars interacting in complex, but predictable ways. Millions of years from now the prenatal cloud of gas and dust will disperse and a cluster of stars will emerge.

Monkey Head Nebula NGC 2174 – 6,400 light-years

Here's a beautiful image of the Monkey Head Nebula from the Hubble Space Telescope. This colorful H II region is filled with young stars embedded within bright wisps of cosmic gas and dust. It is the young white and pink stars sprinkled amongst the glowing clouds that are pushing away the dark stellar nurseries in which they formed.

<u>Omega or Swan Nebula M17 – 5,500 light years</u>

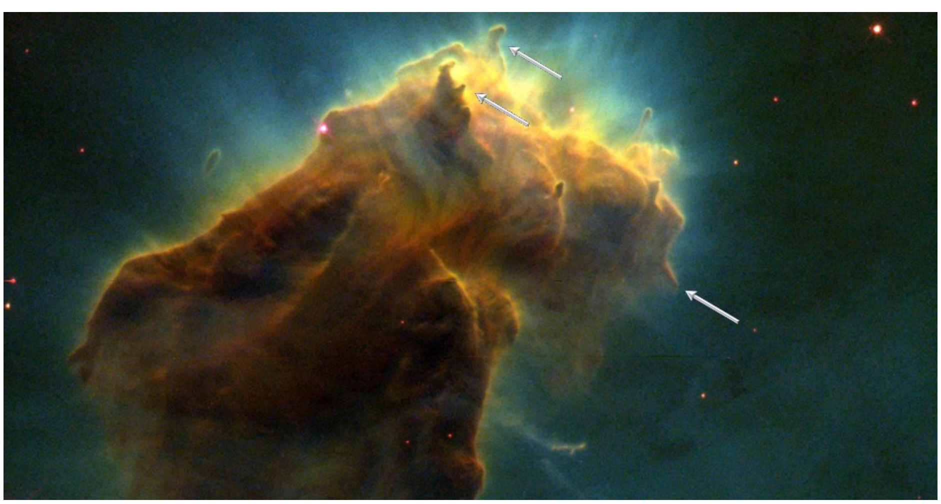
This is an image of the center of the Omega Nebula, a hotbed of newly born stars wrapped in colorful blankets of glowing gas and cradled in an enormous cold, dark hydrogen cloud 15 light years in diameter. The region of the nebula shown in this photograph is about 3,500 times wider than our solar system. The powerful radiation from its stars evaporate and erode the dense cloud of cold gas within which the stars formed. The blistered walls of the hollow cloud shine primarily in the blue, green, and red light emitted by excited atoms of hydrogen, nitrogen, oxygen, and sulphur. Particularly striking is the rose-like feature, seen to the right of center, which glows in the red light emitted by hydrogen and sulphur.



<u>Eagle Nebula – 6,500 light years</u>

The Eagle Nebula is 20 light years wide. Inside the Eagle, there are a number of spectacular formations. These eerie, dark pillar-like structures are columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. The tallest pillar is about 4 light-years long from base to tip. In some ways, these pillars are akin to buttes in the desert, where dense rock has protected a region from erosion, while the surrounding landscape has been worn away over millennia. In this celestial case, it is especially dense clouds of molecular hydrogen gas and dust that have survived longer than their surroundings in the face of a flood of ultraviolet light from hot, massive newborn stars (located just off the top edge of the picture).

As the pillars themselves are slowly eroded away by the ultraviolet light, small globules of even denser gas buried within the pillars are uncovered. These globules have been dubbed "EGGs." EGGs is an acronym for "Evaporating Gaseous Globules," but it is also a word that describes what these objects are. Because forming inside at least some of the EGGs are embryonic stars. Eventually, the stars themselves emerge from the EGGs as the EGGs themselves evaporate.



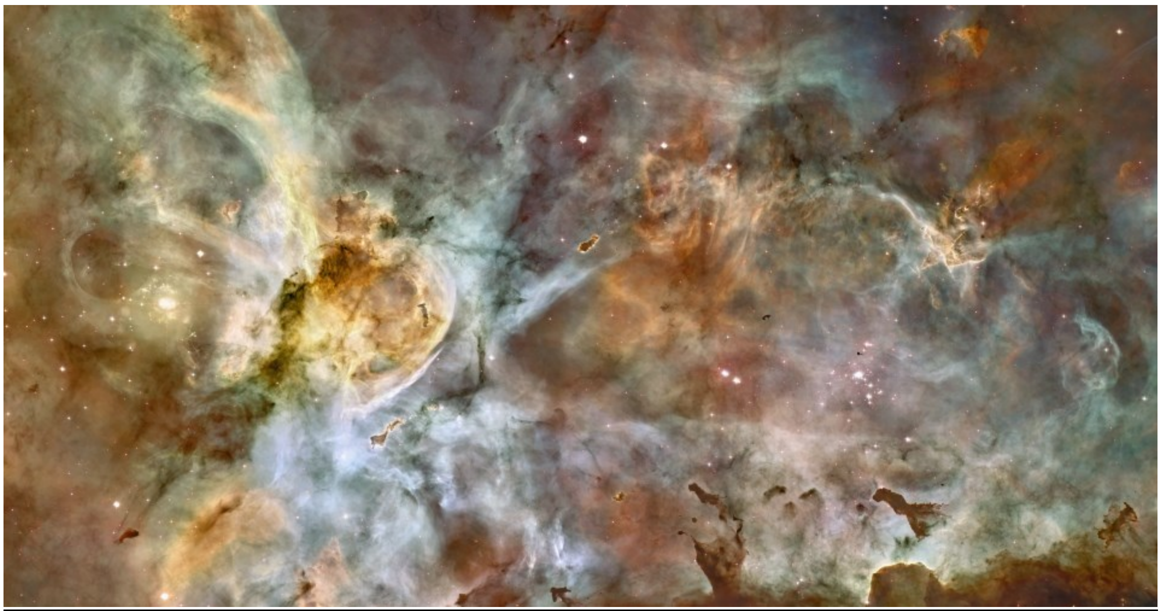
Hubble has also produced an infrared image. Infrared penetrates much of the obscuring dust and gas and unveils newborn stars, hidden in the visible-light view.

This soaring tower is 9.5 light-years high or about 90 trillion km. (That's 57 trillion miles.) The bumps and fingers of material in the center of the tower are examples of EGGs. These regions may look small but each one is roughly the size of our solar system.

The Carina Nebula – 7,500 light years

[Music:** Puccini - Manon Lescaut, Act II Intermezzo; Belgian Radio and Television Philharmonic Orchestra; Miriam Gauci; from the album "Puccini: The Best of Puccini", 1993**]

Here we are zooming into the giant Carina Nebula. It is a very large bright nebula that surrounds several clusters of stars. The nebula itself measures some 260 light years across, - that's about 7 times the size of the Orion Nebula! Let's take a look at some of the amazing structures contained in Carina.



NGC 3324 – 7,200 light years

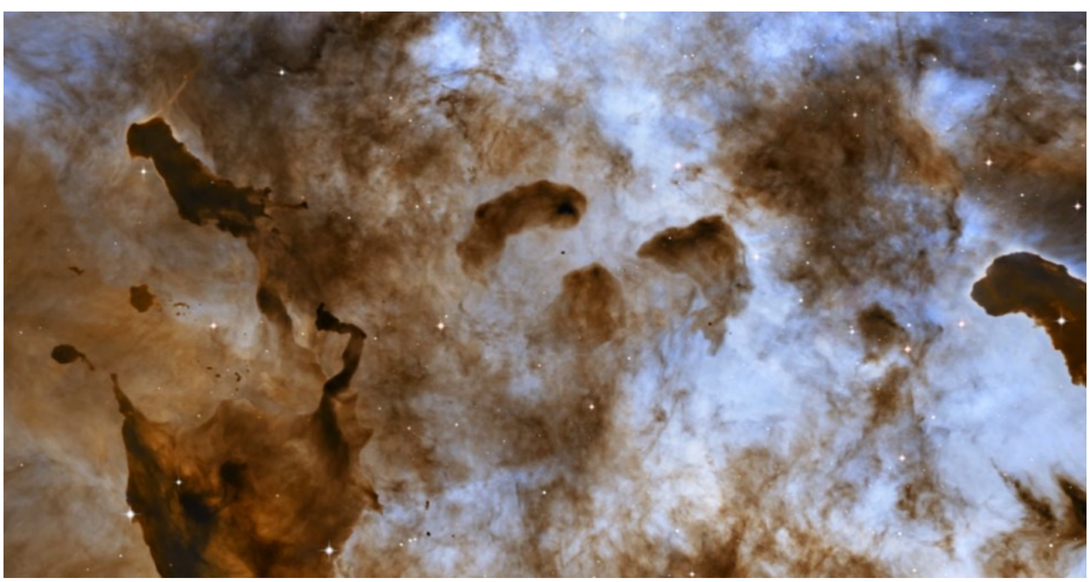
NGC 3324 is located at the northwest corner of the Carina Nebula. The glowing nebula has been carved out by intense ultraviolet radiation and stellar winds from several hot, young stars. The image also reveals dramatic dark towers of cool gas and dust that rise above the glowing wall.

Jet in the Carina Nebula – 7,500 light years

This image from Hubble shows the tip of a 3-light-year-long pillar, bathed in the glow of light from hot, massive stars off the top of the image. Scorching radiation and fast stellar winds are sculpting the pillar and causing new stars to form within it. Although the stars themselves are invisible, one of them is providing evidence of its existence. Thin jets of material can be seen traveling to the left and to the right of a dark notch in the center of the pillar. Astronomers estimate that the jets are moving at speeds of up to 1.4 million km/hr (that's 850,000 miles per hour).

Carina Nebula dust clouds – 7,500 light years

These one-light-year-tall pillars of cold hydrogen and dust are created by violent stellar winds and powerful radiation from massive stars.



Carina Nebula pillars – 7,500 light years

Here's a three-light-year-tall pillar of gas and dust that is being eaten away by the brilliant light from nearby bright stars. The pillar is also being assaulted from within, as infant stars buried inside it fire off jets of gas that can be seen streaming from towering peaks.

Heart Nebula, IC 1805 and Soul Nebula IC 1848 – 7,500 light years

The Heart nebula's intense red output and its configuration are driven by the radiation emanating from a small group of stars near the nebula's center. The Soul nebula is the eastern neighbor of the Heart Nebula and the two are often mentioned together as the "Heart and Soul".

The Statue of Liberty Nebula – 9,000 ly

Here are two nebulae drifting through the Sagittarius arm of our Milky Way Galaxy. The nebula on the right is called the Statue of Liberty, or Torch Bearer. It's 9,000 light years away.

The nebula on the left, NGC 3603, is actually 11,000 light years further away than that. It is classified as a giant HII Region. In fact, it's the largest nebula in the Milky Way! We'll cover it in more detail at the end of this segment.

NGC 3576's delicate loops around the statue are approximately 100 light years wide and are caused by material being blown outwards by the intense radiation pressure from young stars in the center of the nebula. Most of these stars are hidden from our view in the bright area at the base of the loops.

RCW 34 – 10,100 light years

Here we are zooming into the glowing nebula called RCW 34. Its central gas is heated dramatically by young stars and expands through the surrounding cooler gas. Once the heated hydrogen reaches the borders of the gas cloud, it bursts outwards into the vacuum like the contents of an uncorked champagne bottle — this process is referred to as champagne flow.

NGC 2467 – 13,000 light years

Like the familiar Orion Nebula, NGC 2467 is a huge cloud of gas — mostly hydrogen — that serves as an incubator for new stars. The huge clouds of gas and dust are sprinkled with bright blue, hot young stars.

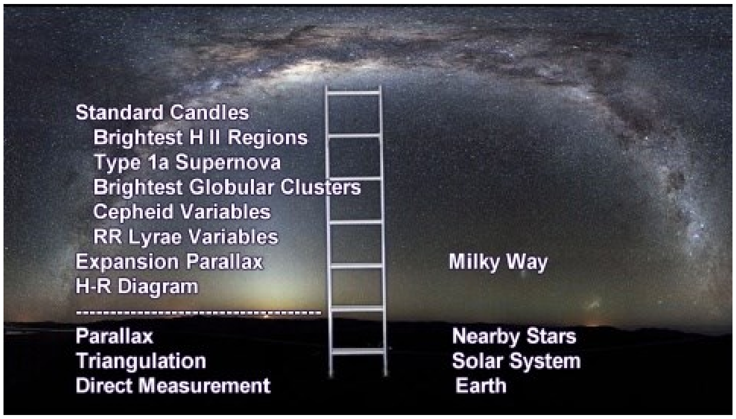
NGC 3603 – 20,000 light years

Here we're zooming into the giant nebula NGC 3603 - a prominent star-forming region, about 20,000 light-years away. As we said earlier, it is the largest H II Region in the galaxy, and it's the last H II reagion we'll cover in this segment.

The star cluster HD 97950 is nestled within the nebula. It contains three of the most massive and luminous stars known. Ultraviolet radiation and violent stellar winds from these stars have blown out an enormous cavity in NGC 3603's gas and dust enveloping the cluster. These winds have created the unobstructed view we see here.

Distance Ladder

Like Globular Star Clusters, HII regions come in a wide variety of sizes and luminosities, but just like with globular clusters, observations have shown that the brightest HII regions all have a common luminosity. This makes them an important standard candle because, just like the brightest globular clusters, they are bright enough to be seen out to great distances. So we can add them to our distance ladder.



The Milky Way

*{**Abstract** – In this segment of our "How far away is it" video book, we cover the structure of the Milky Way galaxy.*

We start with a high-level description of the three main components: the galactic center with its black hole, the galactic disk with its spiral arms, and the galactic halo stretching far out in all directions using the European Space Agency spacecraft Gaia's findings. We also show how full images of the Milky Way can be created from within the galaxy.

Using the full power of the Hubble, Spitzer, and Chandra space telescopes, we take a deep dive into the center of our galaxy with its central bulge. We detail the evidence for the existence of a supermassive black hole, Sagittarius A, at the very center of the galaxy's core. We cover and illustrate the work done by the UCLA Galactic Centre Group in conjunction with the new Keck observatory on top of the Mauna Kea volcano in Hawaii, and the Max Plank Institute for Extraterrestrial Physics in Germany and more recently and the European Southern Observatory with its array of Very Large Telescopes in Chile. This includes a look at how close the star S2 approached Sgr A* and what that black hole might look like. In addition, we cover stellar interferometry with ducks on a pond to see how these measurements were done.*

Next, we go a level deeper into the nature of a Black Hole singularity. We cover the Schwarzschild radius, event horizon, accretion disk, gravitational lensing, and gamma-ray jets. We then actually build Sgr A. In addition to the supermassive black hole, we take a look at a solar mass black hole.*

We then cover the structure of the galactic disk including: the bar core, the two 3 Parsec arms, Scutum-Centaurus, Perseus, Sagittarius with its Orion Spur, Norma and the Outer Arm. We review the locations of various celestial objects we've seen in previous Milky Way segments, to show how close to us they are. We also cover the disk's rotation and the Sun's orbit. We look at our solar system's Ecliptic Plane with respect to the galactic plane. And we cover the galaxy's dust clouds and how we see them with radio astronomy. We also cover the galaxy's rotation curve and its connection with dark matter.

Next, we cover the galactic halo. We start with Shapley's globular cluster map that first showed that we were not at the center of the galaxy. We cover the size of the halo, the inner and outer halos orbital motion, and the newly discovered galaxy within our galaxy called Gaia-Enceladus. We end with recent discoveries of massive amounts of Hydrogen in the halo and this finding's impact on the Dark Matter debate. And we end with a calculation of the entire Milky Way's mass.

*We end our galaxy coverage by illustrating how far one would have to go to take a picture that would include what we see in our illustrations. We conclude the chapter with another look at the distance ladder that took us across the galaxy.**}***

<u>Introduction</u> ***[Music:*** *@00:00 Beethoven, Ludwig van: Symphony No.9 in D minor Op.125, 'Choral' : III Adagio molto e cantabile; Daniel Barenboim & Staatskapelle Berlin; from the album "Beethoven : Symphonies Nos 1 - 9 & Overtures" 2004****]***

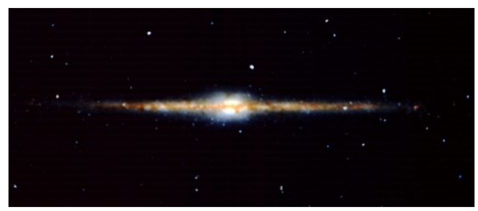
Welcome to our final segment on the Milky Way. In this segment:

- We'll go over our current understanding about the structure and size of the Milky Way as a whole, and our place in it.
- We'll examine the galactic center with its supermassive black hole. We'll go a little deeper into the nature of a black hole and show a few of the black hole candidates we have found.
- We'll explore the galactic disk with its spiral arms.
- And we'll cover the latest information on the galactic halo.

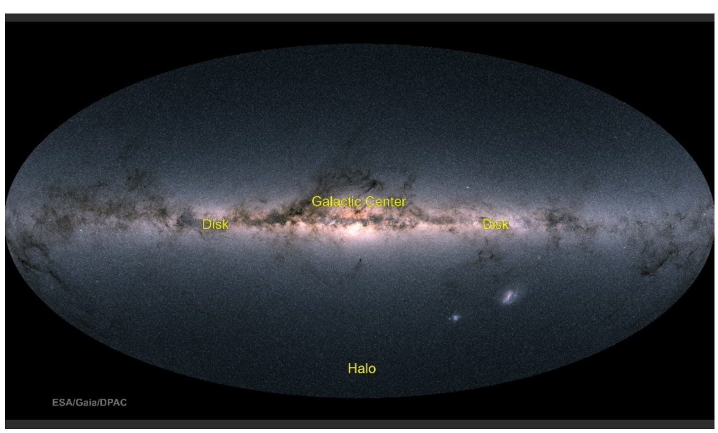
And, as usual, we'll discuss how we came to know these things from our viewpoint deep inside the galaxy itself.

Galaxy Overview

On January 1st, 1990, from its orbit around Earth, the Goddard Space Flight Center's Cosmic Background Explorer created this edge-on view of our Milky Way galaxy in infrared light.



Here's a newer inside image of our galaxy. In fact, it's the most detailed map ever made. It was released in 2018 by Gaia the European Space Agency spacecraft that recorded the position and brightness of 1.7 billion stars, as well as the parallax, proper motion and color of more than 1.3 billion stars. The map shows the density of stars in each portion of the sky. The galaxy has a center with a central bulge, a disk of rotating stars and dust and a halo without dust clouds, and peppered with globular star clusters. The disk is at least 100,000 light years in diameter, and the halo is much larger than that. We'll go into each of these galaxy components, starting with the galactic center.



We'll cover how images like these are created from inside the galaxy, and how impossible it is to get an image from outside the galaxy later in this segment.

Galactic Center - 26,000 light years

The world's Great Space Observatories — the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory — have collaborated to produce this unprecedented look at the central region of our galaxy.

- Hubble documented vast arches of gas, heated by stellar winds from very large stars.
- Spitzer's infrared picked up the pervasive heat signals of all these stars.
- Chandra detected x-ray sources from ultra dense neutron stars and small black holes.

Together, they produced this spectacular image.

[Additional info: Observations using infrared light and X-ray light see through the obscuring dust and reveal the intense activity near the galactic core.

Note that the center of the galaxy is located within the bright white region to the right of and just below the middle of the image.

Each telescope's contribution is presented in a different color:

- Yellow represents the near-infrared observations of Hubble.

- Red represents the infrared observations of Spitzer.

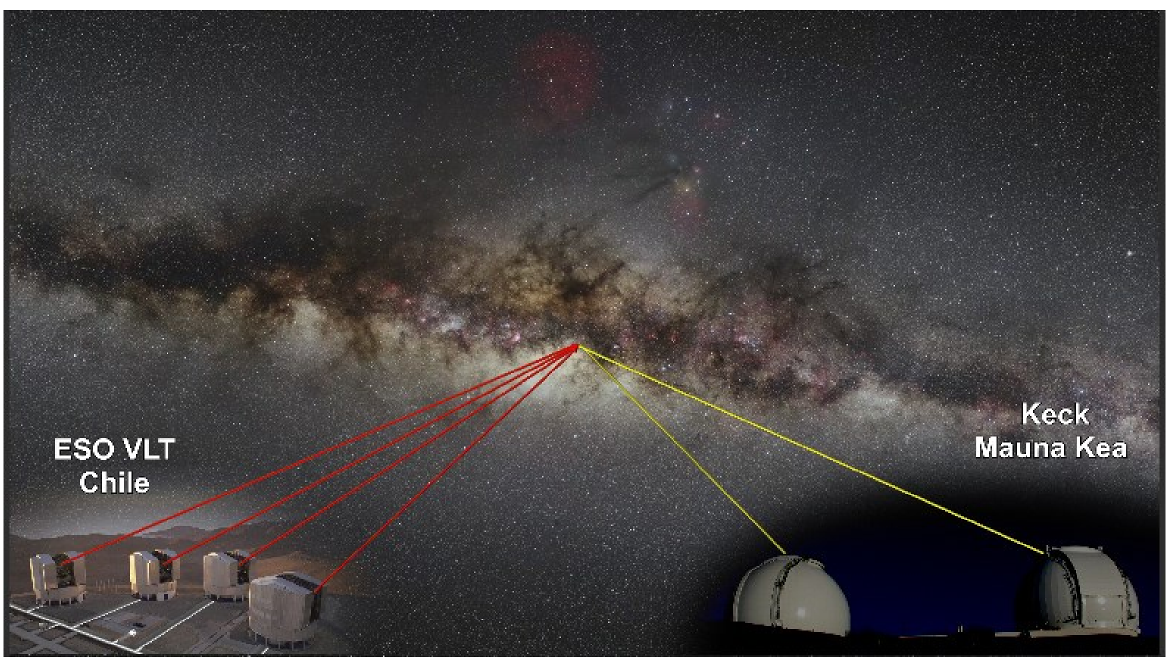
- Blue and violet represent the X-ray observations of Chandra.

When these views are brought together, this composite image provides one of the most detailed views ever of our galaxy's core.**]**

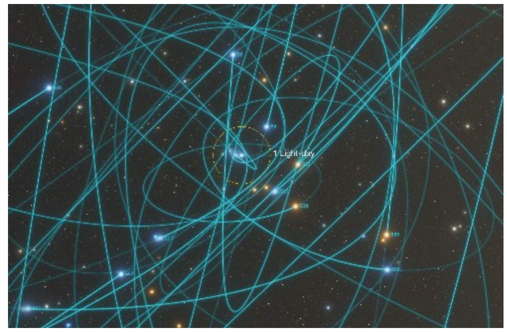
The central object in the Milky Way is known as Sagittarius A* or Sgr A* for short. It lies approximately 26,000 light-years away. It is surrounded by so many stars and gas and dust that it is extremely difficult to see.

[Additional info: Our first look at Sgr A* came with the advent of broadcast radio in the 1930s. Karl Jansky was asked to locate the radio interference to Bell Labs early trans-Atlantic transmissions. He built the first radio antenna and located the source at the center of the galaxy. He named it Sagittarius and is credited with starting the entire field of radio astronomy. Flashing forward – we now have the Hubble space telescope which was designed in part to study what we now call Sagittarius A*.**]**

Teams of astronomers and astrophysicists have been working on understanding Sgr A* for over 25 years. The UCLA Galactic Centre Group along with the Keck observatory on top of the Mauna Kea volcano in Hawaii, and the European Southern Observatory with its array of Very Large Telescopes in Chile, and the Max Plank Institute for Extraterrestrial Physics in Germany and many others have made dramatic progress in advancing our understanding of this critically important part of our galaxy.



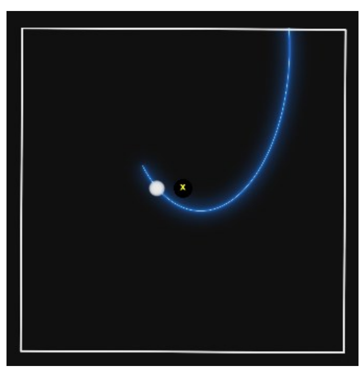
After decades of carful observations, the speeds and orbits of around 45 stars around Sgr A* have been calculated. This enabled measuring the precise location of the point they are all orbiting around. The measured orbits also identified the gravitational pull from this point which in turn gave us its mass at 4 million times the mass of our Sun.



But, when we look at this point, we don't see anything. This was strong evidence that Sgr A* was a black hole because stars are known to be unstable at much smaller masses.

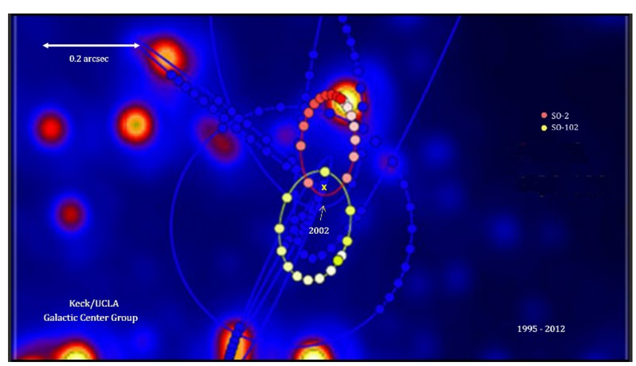
The star S2 is of particular interest because it passes closer to Sgr A* than any other. It's a single main sequence star with 10 to 15 times the mass of our Sun.

Observations of the star showed that its orbit took it to within 20 light hours of Sgr A* in 2002 without bumping into anything. That puts Sgr A*'s 4 million solar mass into a very small place.

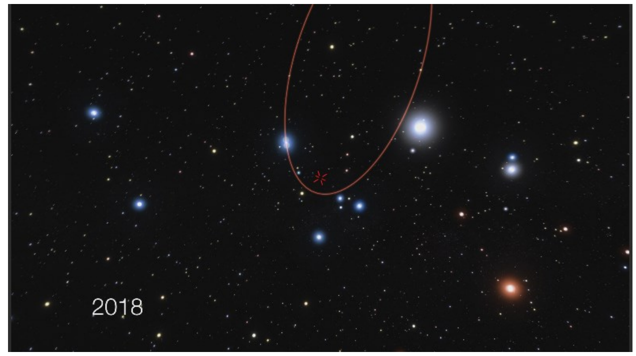


For many astrophysicists, this constituted proof that it was indeed a supermassive black hole. But others pointed out that an extremely dense dim star cluster could produce these results.

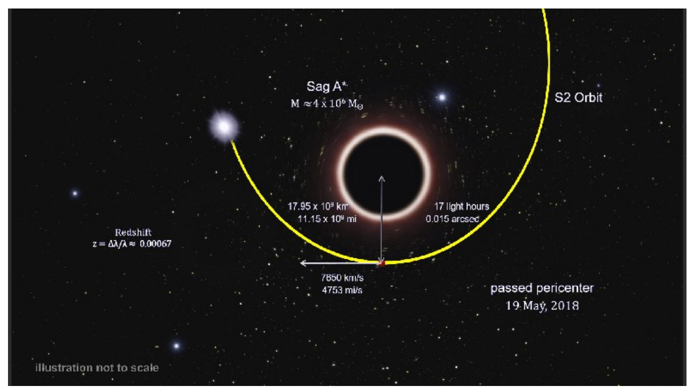
But if Sgr A* were a cluster, S2's orbit would have wobbled. It did not wobble. This was persuasive evidence that the object S2 is orbiting is a Super Massive Black Hole (or SMBH for short). 500 years after Copernicus put the sun at the center of our solar system, we have identified Sagittarius A* as a supermassive black hole at the center of our galaxy.



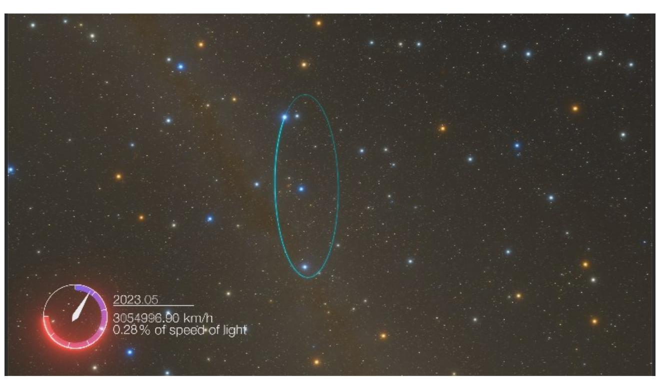
But we weren't done with S2. Its orbital period is 16 years. Following the 2002 passing, a major effort was mounted to upgrade ESO's VLT array of telescopes to enable the precision needed to reveal the true geometry of space and time near this object and test Einstein's theory of general relativity.



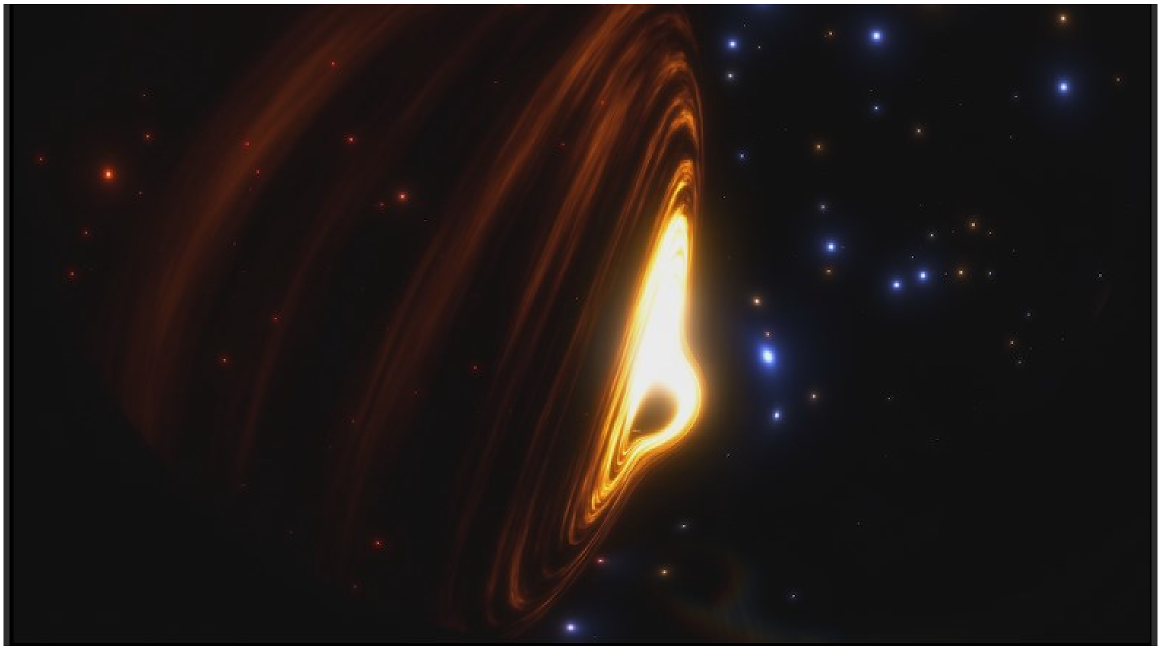
These new instruments followed S2 very closely. At the start of 2018 it was accelerating towards Sgr A* reaching relativistic speeds. On May 19th, it reached its closest approach. At that point, it was traveling at 7650 km/s (or 4753 mi/s). That's almost 3% of the speed of light. Its distance from the black hole was just 18 billion kilometers (or 11 billion miles). That's only 120 times our distance from the Sun. The separation on the sky between the two points was just 15 mas. It was also reddening in color as the black hole's gravitational field stretched its light to longer wavelengths. The color change in this illustration is exaggerated for effect. The reddening is quite small and would not be visible to the naked eye.



S2's velocity changes close to the black hole were in excellent agreement with the predictions of general relativity. In addition, the change in the light wavelength agreed precisely with what Einstein's theory predicted. But understanding what is happening this far away is always prone to errors. I remember when we thought there was a gas cloud G2 that would be entering the black hole in 2014. This never materialized. In our current case, some astronomers point out that massive, non-luminous objects, such as stellar mass black holes, might be present and could affect the orbital dynamics of S2. More research is needed to rule out this possibility.

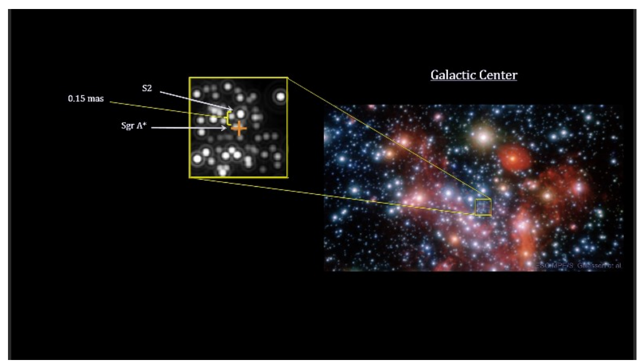


Here's a Fulldome illustration that shows how Sgr A* might look to viewers on a planet orbiting S2 as it orbits the black hole. We'll cover black holes and why our super massive black hole might look like this, but first we'll cover how the ESO VLT actually measured the minute distances associated with S2 and Sgr A* 26,000 light years away.

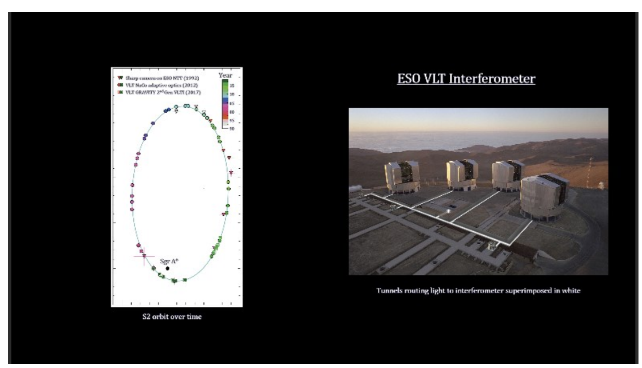


Stellar Interferometers

The Hubble space telescope can resolve angles on the sky as small as 50 milliarcsec. The angular distance between S2 and Sgr A* at pericenter was just 15 milliarcsec. That's 42 billionths of one degree and 3 times smaller than Hubble can resolve.

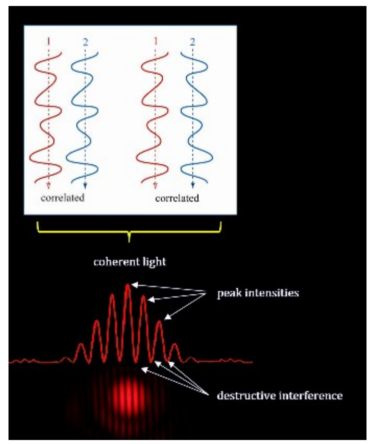


To follow S2 as closely as they did, astronomers had to use a stellar interferometer. These kinds of telescopes can resolve images 30 to 40 times smaller than optical telescopes. This makes them extremely important tools for studying the galactic center as well as exoplanets. They can even resolve sunspots on nearby stars. So, to understand how we know how close S2 got to Sgr A*, we need to understand how these stellar interferometer telescopes work.



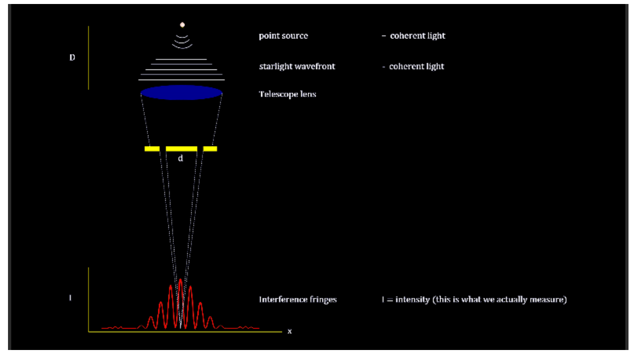
In the "Speed of light" chapter of the "How fast is it" video book, we covered the Michelson Interferometer used to measure minute distances in a lab. Interferometers can measure distances on the order of a few nanometers. Michelson and Morley used it to show that the speed of light was a constant.

In order to create light interference, Michelson illuminated his interferometer with fully coherent light. Coherent light has a common frequency and phase. It always produces interference patterns on the far side of a double slit. Fully coherent light (like the kind that lasers create) will produce regions of fully destructive interference. That is, the dark regions have no light falling on them. Partially coherent light will produce regions of partially destructive interference – meaning some light falls in the dark regions. And incoherent light will not produce interference patterns at all.

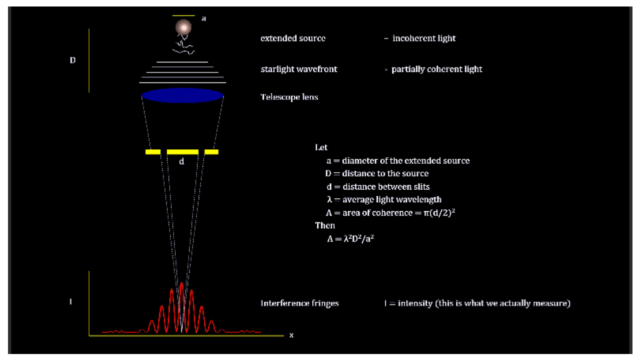


We find in nature that waves can start out as incoherent and become partially coherent as the waves spread out. Watch how these ducks start with a chaotic mix of water waves as they enter the pond. But as the waves move out, they become quite orderly. This is a geometrical effect. The farther away one travels from the source, the less significant the distance between the individual wave generators becomes.

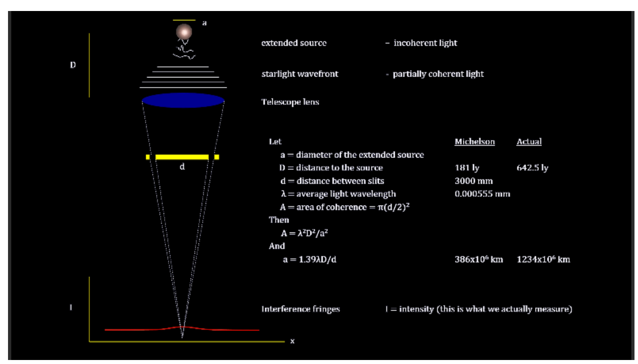
[A point source for starlight would produce coherent light. And at any distance from the source, the light would create interference patterns. But there are no point sources in nature.



Stars have a diameter on the sky. An extended thermal light source would start out with incoherent light. But as the light moves away from the source, its coherence increases just like with the ducks on the pond. The relationship between the diameter of the source, its distance from the interferometer, and the distance between the two slits was determined in the lab. The area of coherence is the area at the telescope that contains coherent enough light from the source to create interference patterns. It goes up with the distance from the source and it goes down with the diameter of the source.



Michelson used this property to measure the diameter of Betelgeuse in 1921. [He added optics to make an interferometer on the Mt. Wilson 100” Hooker Telescope. He determined the aperture spacing that produced fringes (2,000 mm or 6 feet) and the largest spacing that didn't (3,000 mm or 10 feet). That gave him the area of coherence. In his day, they thought Betelgeuse was 181 ly away. So, from that he calculated the diameter of the star to be 386 million km or 240 million miles. Today we know that Betelgeuse is 642 ly away with a diameter 3 times larger than Michelson calculated. But it was a good start for stellar interferometry.



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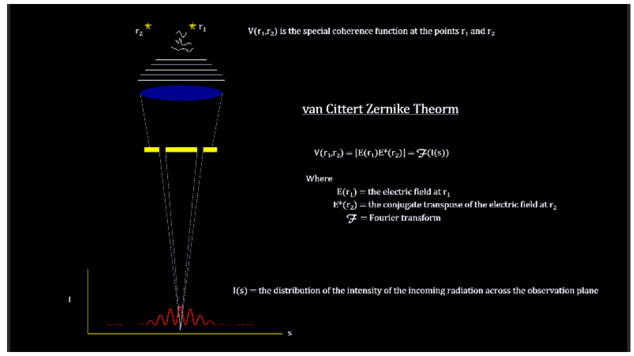
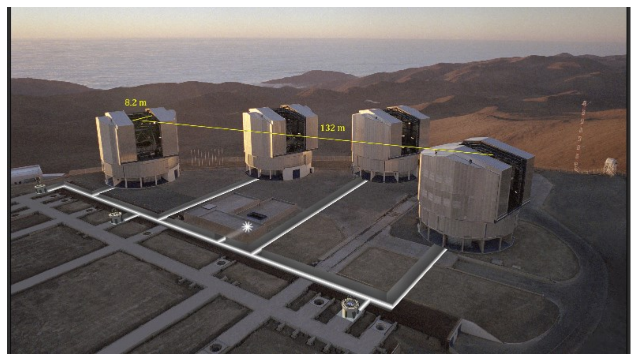
It is fascinating to note that incoherent light waves created by exited atoms in stars 20 billion km apart can travel for 26,000 years and still carry the remnants of that starting condition. A large enough stellar interferometer can use the visibility dimming of the interference patterns created by that light to detect the original star separation. See how the amount the image fads is greater the further apart the two stars are. The math involved was developed independently by Dutch physicists P.H. van Cittert in 1934 and F. Zernike in 1939. It's known as the van Cittert-Zernike theorem.



It has taken 80 years to extrapolate the basic physics of interferometry into the working instruments we have today. There are currently over 20 stellar interferometers in operation around the globe. [It was the four 8.2-meter ESO VLT optical telescopes with an attached 4-way interferometer called GRAVITY that covered the S2 pericenter passage around Sgr A*. The diameter of the observation baseline is the 130 meters between the two outermost telescopes, not the 8.2 meters on any one of the telescopes. This gives the interferometer over 15 times the telescopes' resolving power.]



Black Holes

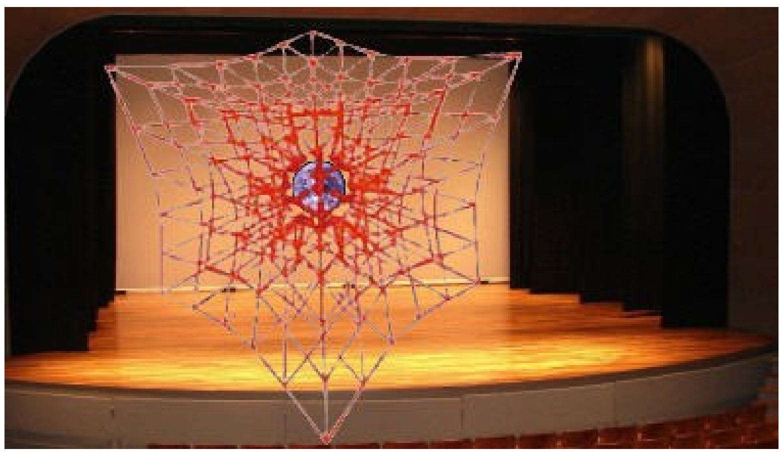
From antiquity into the eighteenth century, it was believed that the idea of empty space is a conceptual impossibility.

Space is nothing but an abstraction we use to compare different arrangements of the objects. Concerning time, it was believed that there can be no lapse of time without change occurring somewhere. Time is merely a measure of cycles of change within the world.

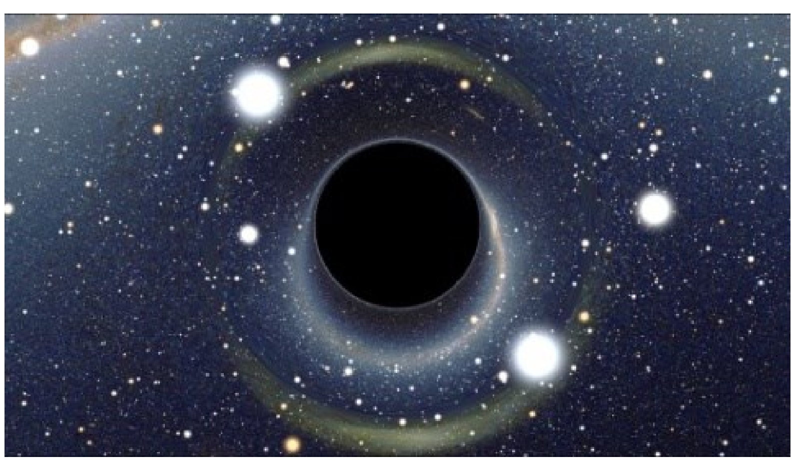
Then, in 1686, Isaac Newton founded classical mechanics on the view that *space* is real and distinct from objects and that *time* is real and passes uniformly without regard to whether anything moves in the world.

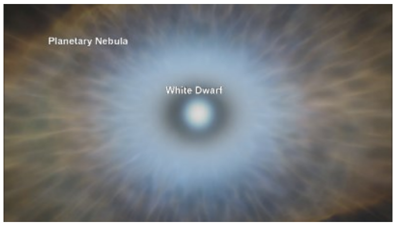
He spoke of *absolute space* and *absolute time* as a stage within which matter existed and moved as time flowed at a constant rate. It was understood that space and time tell matter how to move, but matter has no effect on space and time.

The idea that space and time act on matter, but that matter does not act on space and time, troubled Einstein. Noting that light curved in a gravitational field, Einstein proposed that the mass of an object does indeed act on the space and time it exists in. Specifically, he proposed that the presence of matter curves space-time.



This led Einstein to his theory of general relativity which predicts the existence of black holes as objects so massive that light itself cannot escape their gravity. [The star goes dark for distant observers – hence the name Black Hole.]



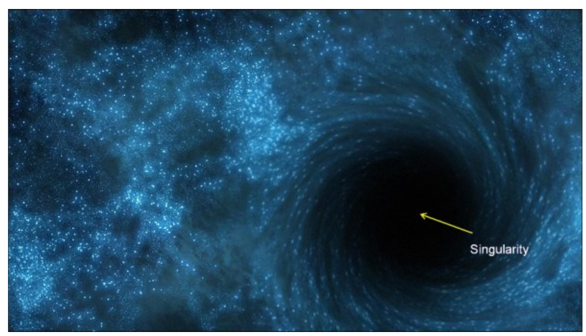


You'll recall that explosions at the end of life for stars less than 5 times the mass of the sun create planetary nebula and leave behind white dwarfs. In these stars, electron exclusion pressure is enough to counteract the inward force of gravity.

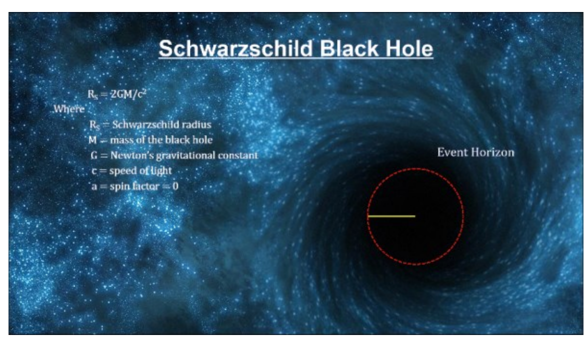
Supernova explosions at the end of life of stars more than 5 times the mass of the sun leave behind a neutron star. In these stars, electron pressure is insufficient to overcome the force of gravity, but neutron exclusion pressure is.

But if a star is greater than 30 times the mass of the sun, even neutron exclusion pressure won't do the trick. In fact, there is no known force that will counteract the inward force of gravity for such a supernova or hypernova exploding star.

According to Albert Einstein's general theory of relativity, the star will collapse into zero volume and infinite density – called a singularity. This defines a black hole. It gets its name from the fact that such a singularity would create a gravitational pull that not even light could escape. The object literally becomes invisible.

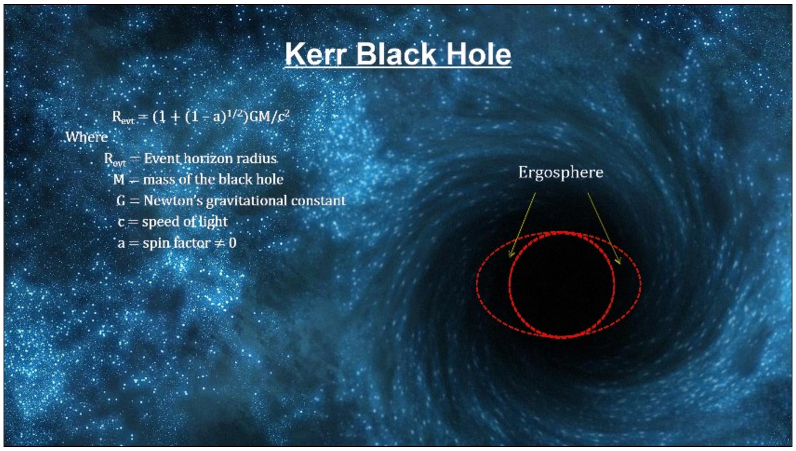


In 1916, Karl Schwarzschild, a contemporary of Einstein, solved his equation for the special case of a non-rotating sphere. He found that although the diameter of the singularity is zero, the radius at which light would be captured depends entirely on the mass of the black hole. This is called the Schwarzschild radius and it defines the Event Horizon.

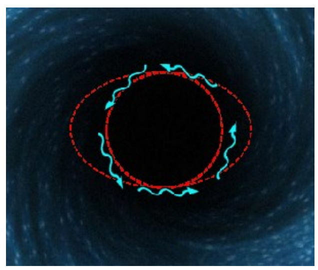


[For the Sun, the Schwarzschild radius is 3 km or 1.8 mile. That means that if the Sun were to shrink to a 6 km or 3.6 mile diameter, it would disappear!]

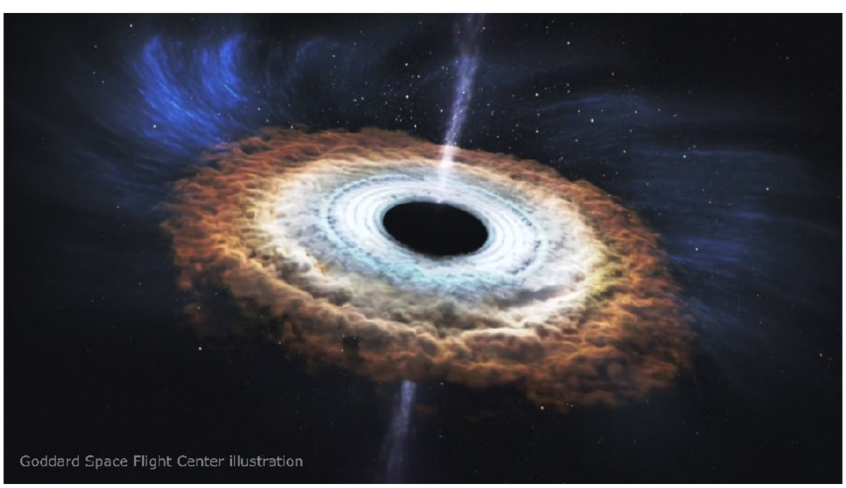
But it would be the rare black hole that doesn't spin. In 1963, Roy Kerr developed the general solution for spinning black holes. It showed that there is a second region beyond the event horizon that defines a volume around the black hole called the ergosphere.



In this region, space itself is dragged around by a black hole's spin. (It's called frame dragging.) Also, in this region, light can enter stable orbits around the black hole. This would produce a photon sphere shell incasing the black hole with light from all the stars in the universe accumulated over the entire age of the black hole. It would be a sight to see.

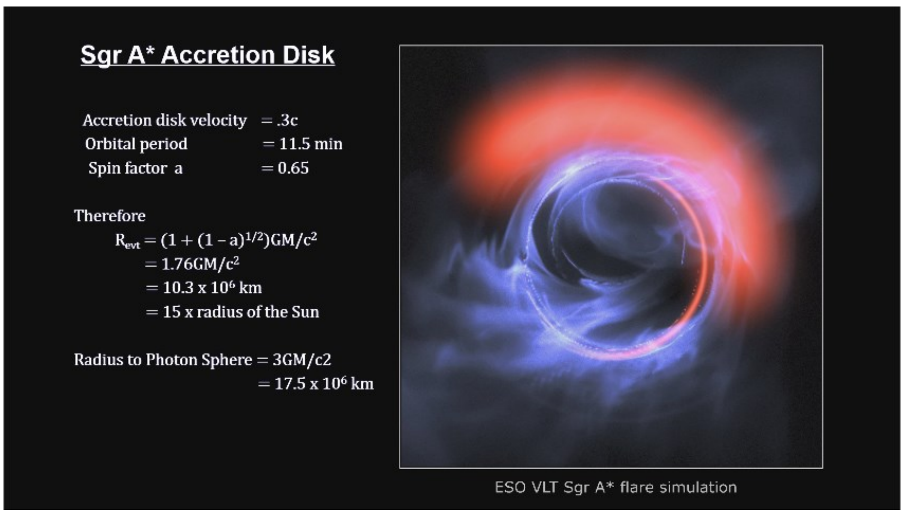


One thing all rotating black holes have in common besides the fact that we can't see them, is that matter flows in via an accretion disk. The exact mechanism is not yet fully understood, but we know that gamma-ray jets shoot out at the polls carrying a percentage of the falling matter with it at speeds approaching the speed of light.

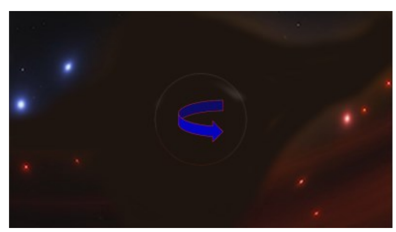


Black Hole Sagittarius A*

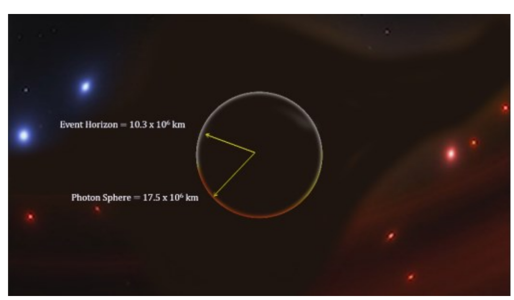
In late 2018, ESO's GRAVITY instrument observed flares of infrared radiation coming from the accretion disc around Sgr A*. These flares came from clumps of gas swirling around at about 30% of the speed of light on a circular orbit just outside its event horizon. [Light from objects moving closer to and across the event horizon is stretched into and beyond infrared wavelengths. This will create what looks like a flare.] They indicate that Sgr A* is spinning with a full rotation every 11.5 minutes. This makes the 4 million solar masses Sgr A* a supermassive Kerr black hole. This new information also enabled calculating the distance from Sgr A*'s center to its event horizon at round 10 million km or 15 times the radius of our Sun, and the distance to the photon sphere at around 17 million km.



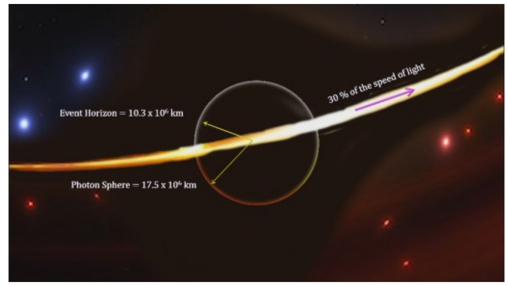
To illustrate how a black hole might look, we'll build Sgr A*. Here we are viewing it from the equatorial plane and the object is rotating in on the left an out on the right. Its center is dark out to the event horizon.



This thin ring around the black hole, just outside the event horizon, represents the cross section of Sgr A*'s ergosphere with shell of orbiting light. What we'd see is the light that leaks out in our direction.



The observed flares indicate that Sgr A* has the remnants of an accretion disk that is no longer feeding the black hole on a regular basis. If the disk were not gravitational lensed, the black hole would have looked like this.

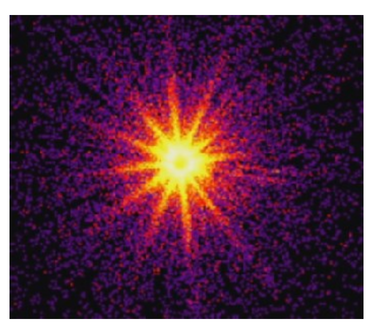


But, because of gravitationally lensing, the massive amount of light rays emitted from the disk's top face travel up and over the black hole, and light rays emitted from the disk's bottom face travel down and under the black hole. This combination gives us the full image of how the black hole would actually look.

Stellar Mass Black Hole MAXI J1820+070 – 10,000 ly

There are three classifications for black holes based on their mass: stellar - with masses up to ten times the mass of our sun; supermassive - with millions or even billions of times the mass of our sun; and intermediate - with masses somewhere in between. Sgr A*, the black hole at the center of our galaxy is a supermassive black hole.

Stellar-mass black holes form when the most massive stars supernova. Here's one called J1820 discovered by accident. In March, 2018, the Japanese's instrument MAXI aboard the international space station recorded an extremely strong x-ray outburst.



NASA's NICER neutron star instrument, also on the space station, focused on the outburst for days and watched it fade. In addition, the Gaia mission was able to locate the x-ray source companion star and determine its distance at 10,000 light years. Analysis showed that the x-ray object is a black hole with the mass of around 10 suns. The x-rays are generated as matter from the stare feeds the accretion disk around the black hole.

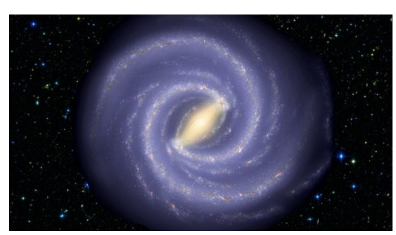
Some astronomers calculate that there are as many as 100 million stellar-mass black holes like this one in our galaxy. Most of these are invisible to us, and only about a dozen have been identified. For more information on Black Holes, see the "General Relativity Effects" segment of the "How fast is it" video book.

The Galactic Disk

[Music: *Tchaikovsky, Pyotr Ilyich: Symphony No. 5 in E minor, Op. 64; Bernard Haitink, Royal Concertgebouw Orchestra, Amsterdam, 2012***]**

The number of stars in the Milky Way is very difficult to determine. But, based on detailed analysis of star distances, star motions, neutral hydrogen radiation from spiral arms, galaxy rotation curves and mass (including dark matter) astronomers currently believe that the galaxy has a relatively flat rotating 100,000 to 120,000 light years wide and 1,000 ly deep disk of some 100 to 400 billion stars.

This image, out of the Spitzer Science Center and the University of Wisconsin, represents an attempt to synthesize over a half-century of work on the Galactic Disk's structure based on data obtained from the literature at radio, infrared, and visible wavelengths.



[Additional info: The Milky Way was dubbed as a spiral galaxy in 1951 when William Morgan of the Yerkes Observatory presented his results showing the galaxy's three arms of hot stars, which he named Perseus, Orion and Sagittarius.

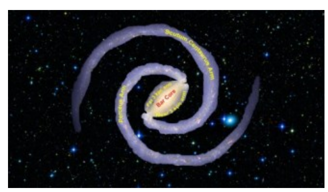
There were three methods traditionally used to map the disk structure of our Galaxy.

- Starting in 1958, the first method studied the density of the neutral hydrogen in the plane of the Galaxy.
- Starting in the 1960s the second method used radio astronomy to map out the Milky Way's structure.
- Starting in 1976, the third method plotted the giant HII regions. These were usually formed in the spiral arms.]

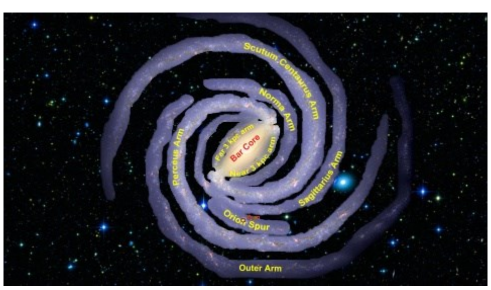
The galactic center itself, with the supermassive black hole that we discussed earlier, is shaped like a bar. Although most parts of the Milky Way galaxy are relatively uncrowded, roughly 10 million stars are known to orbit within just a single light-year of the galactic center in a region known as the central bulge.

Recent surveys discovered the two 3-kpc Arms, named for their length. They are now generally thought to be associated with gas flow roughly parallel to the central bar.

Using infrared images from Spitzer, scientists have discovered that the Milky Way's elegant spiral structure is dominated by just two arms wrapping off the ends of a central bar of stars. One is named Scutum-Centaurus and the other is named Perseus.



Each of these major arms consists of billions of both young and old stars.



Three thinner arms spiral out between the two giant main arms called Sagittarius, Norma and the Outer Arm. These are primarily filled with gas and pockets of star-forming activity.

There is also a spur off the Sagittarius arm called the Orion Spur.

- It's 3,500 light-years across; and approximately 10,000 light-years long.
- We are located on the inner edge half-way along this spur around 26,000 light years from the galactic center.

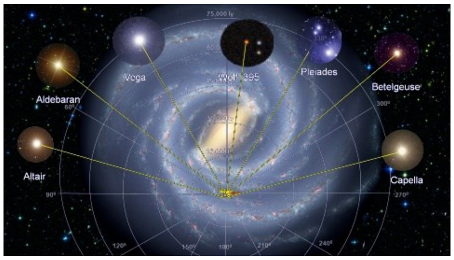
When we fill in the space between the arms, we get the full picture.

It's interesting to note that the number of stars per unit volume of space in the regions between arms is the same as the number in the arms themselves. What distinguished the arms is that they have a far greater number of younger stars. In fact, all the known H II star forming regions in the galaxy exist inside the arms. We don't find any in the area between the arms.

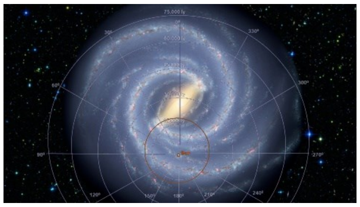
Our place in the Milky Way

If we lay a grid over the galaxy, we can locate some of the stars, nebula and H II regions we have seen in this chapter.

Actually, all the local neighborhood stars would fit into the red circle I used to locate our Solar System. That would be stars like Wolf 395, Altair, Vega, Polaris, Capella, Aldebaran, the Pleiades, and Betelgeuse. They are all with us in the **Orion Spur**, as is the Orion, Horsehead, Cone, Witch's Head, Veil and many other Nebulae.

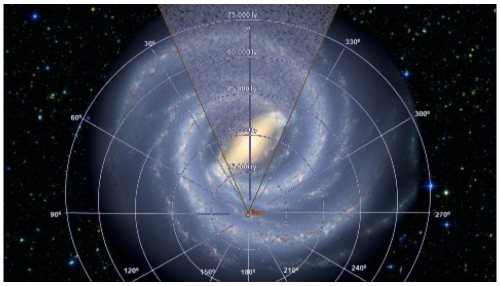


In **Sagittarius**, we see the Jewel Box star cluster and the Trifid, Omega, Lagoon, Eagle, and Cat's Paw nebulas among other. In **Perseus**, we see the Rosette, Heart and Soul Nebulae as well as the Crab Supernova to name just a few.

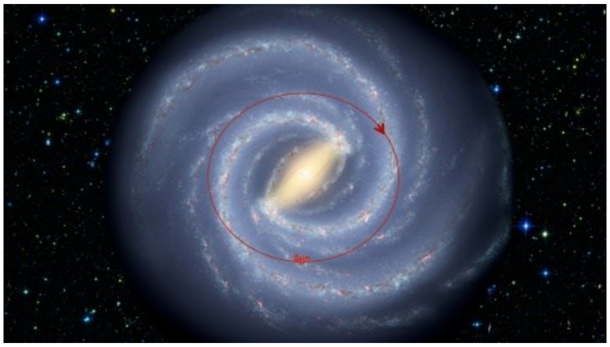


In fact, except for the hyper-velocity stars and a few of the supernova remnants, everything we have seen in this chapter is within this circle. As vast an area as we have covered, it is only a fraction of the Milky Way galaxy.

Another point that ought to be covered is that we cannot see through the galactic core into the other side. The core is simply too dense with stars and gas and dust to penetrate. So, this slice of the disk has not been seen or analyzed. But our understanding of spiral galaxies is that they are symmetric, so this picture makes that assumption and fills in the blanks accordingly.

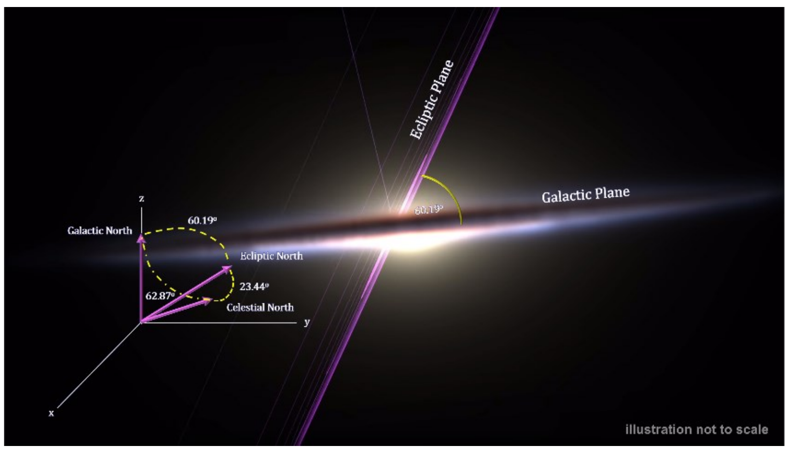


Viewed from "above" – what would be North on Earth – the Milky Way spins in the counter-clockwise direction. Of course, if you were to view it from the other side, it would spin clockwise.

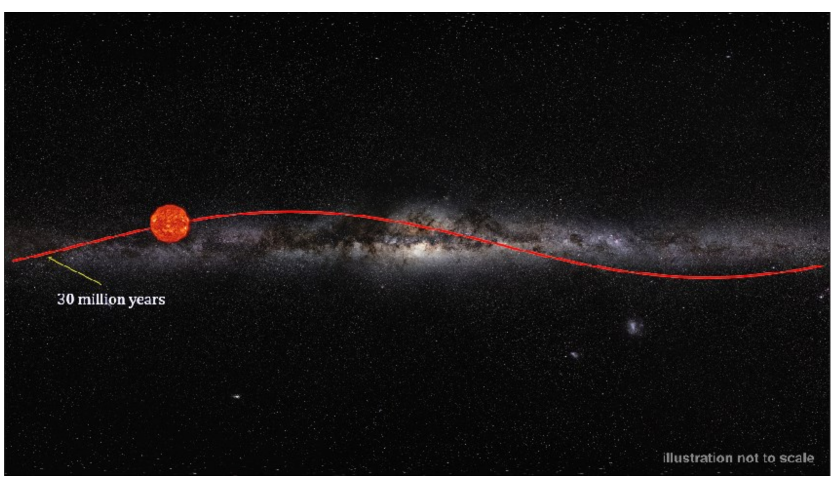


Here we see the Sun’s orbit around the galactic center. Our orbital speed is approximately 230 km/s or 143 miles per sec. That’s fast, but it takes us around 213 million years to complete one orbit around the galactic center. The last time we were in the same place in our orbit, dinosaurs were just starting to appear on the Earth. We have traveled around 1/1000th of a revolution since the origin of humans.

Here’s a look at our solar system’s Ecliptic Plane with respect to the galactic plane. It’s just over 60 degrees off. We see that the solar system is quite out of alignment with the galaxy’s disk. Earth’s 23-degree tilt to the solar plane puts us at an almost 63-degree tilt from the galactic plane. This is why the Milky Way appears at such a strange angle across the night sky.



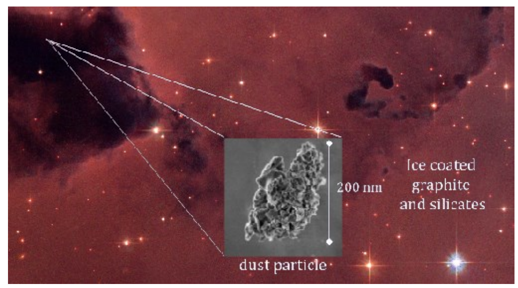
Also, as the Sun orbits the galaxy, it oscillates up and down relative to the plane of the galaxy. It does this approximately 2.7 times each time around. Astronomers estimate that we are currently at around 75 to 100 light years above the galactic plane and moving down. This estimate has us crossing the plane in approximately 30 million years!



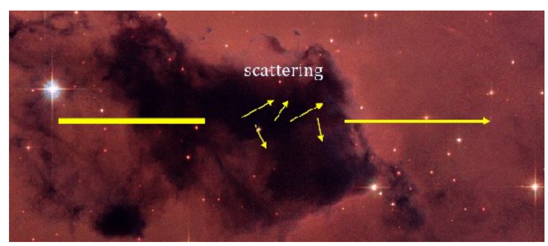
Dust

Before we leave the galaxy's dusty disk, we'll take a closer look at the dust itself. It's critically important for calculating intrinsic star luminosity, and it's the only galaxy content that we can use to accurately calculate the galaxy's rotation curve - that's star velocities as a function of their distance from the galactic center. The Milky Way's rotation curve is one of the reasons scientists have proposed the existence of dark matter.

The dust is made of thin, highly flattened flakes of graphite and silicate (that's carbon and rock-like minerals) coated with water ice. Each dust flake is roughly the size of the wavelength of blue light or smaller. The dust is probably formed in the cool outer layers of red giant stars and dispersed in the red giant winds and planetary nebulae.

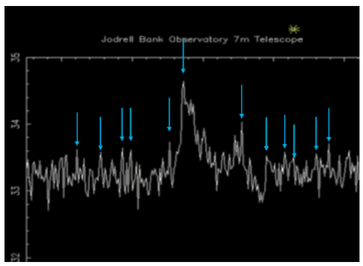


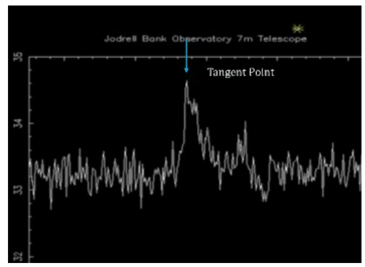
The dust absorbs and scatters the light that passes through it. The further the light has to travel, the more of this dust it encounters, and the dimmer it gets. Astronomers call this 'extinction'. Due to this extinction effect, stars in the galactic disc can lose half their luminosity every 3,000 light years. [It wasn't until we could measure the amount of dust between us and the stars that we could accurately use standard candles to determine how far away they were. It was the astronomer Robert Trumpler who first quantified this phenomenon in the 1930s.]



These clouds are best viewed using radio astronomy. This is because gas clouds radiate radio waves. And radio waves pass through dust particles untouched because their wavelength is much larger than the size of these particles. We can see these clouds all across the galaxy, including the hidden area behind the central bulge. What's more, the hydrogen in these regions emit a spectral line in the radio frequency band. And this spectral line exhibits Doppler shifts enabling us to measure the cloud's radial velocity relative to us.

In this line of sight reading, we see a number of peaks. Each one represents a cloud. The peaks have different frequencies because the clouds have different radial velocities. The maximum peak is from a cloud that's radial velocity is close to its total orbital velocity. **[Additional info:** In particular, in HI regions, neutral hydrogen has one at 21 cm from neutral hydrogen, and in HII regions, carbon monoxide has one at 2.6 and 1.3 mm.**]**





[Kinematic Distance

We can use the Doppler shift of dust clouds to find the kinematic distance to the object and calculate how fast it is rotating around the center of the galaxy. Kinematic distance is the distance to an object based on its motion.

Motion around the galactic center is generally circular, but all stars, including our own, have orbits that are perturbed by the presence of other stars. To calculate a baseline motion, we use a Local Standard of Rest (LSR) based on the average motion of all the stars in our vicinity. It is currently set at 220 km/s (V_0) at 26,100 ly (R_0) from the center. In addition, based on several Palomar Observatory Sky Surveys, we are 65.2 light years above the galactic plane.

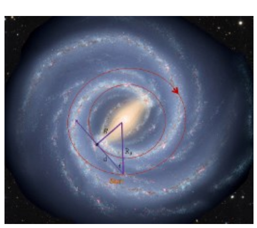
In order to convert this radial velocity information into rotational velocity and distance from the center of the galaxy, we use a technique called the Tangent Point Method. First, we take a line of sight look for clouds. Having found one, we adjust the longitude to get the maximum radial velocity based on the Doppler shift. This will mark the clouds closet approach to the center. At this tangent point, a line to the center will be perpendicular to the line of sight. Here, the radial velocity of the cloud will be equal to its rotational velocity around the center of the galaxy. We can calculate its distance from the center and its distance from us with a little trigonometry.

<u>Kinimatic Distance</u>

$$R = R_0 \boldsymbol{sin}(\ell)$$

$$d = R_0 \boldsymbol{cos}(\ell)$$

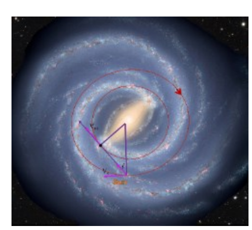
Where
R = object's distance to center
R_0 = Sun's distance to center
d = distance to the object
ℓ = galactic longitudinal angle



<u>Kinimatic Distance</u>

$$V_r = V_m + V_s \boldsymbol{sin}(\ell)$$

Where
V_r = rotaional velocity of object
V_m = measured radial velocity of object
V_s = rotaional velocity of the Sun
ℓ = galactic longitudinal angle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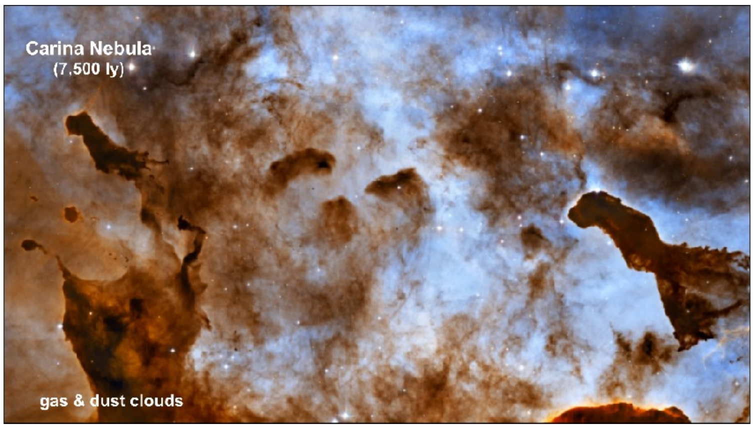
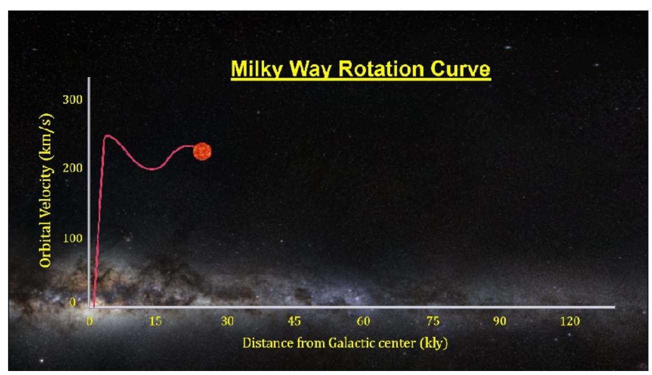
Milky Way Rotation Curve

The best way to map out the rotation curve for the galaxy's disk is to measure the orbital velocities and distances of gas clouds and star forming regions across the galaxy. These are the HI, HII, and molecular clouds we covered in our segment on "Star Birth Nebula". These are the best objects to analyze for three reasons:

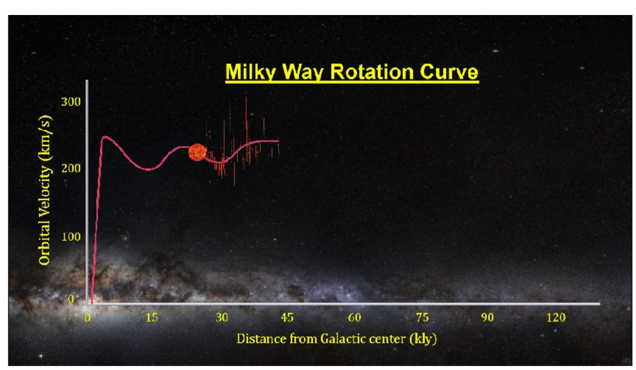
1) They trace out the spiral arms;
2) We can see them clearly at great distances using radio astronomy; and
3) There is a good way to calculate their distance for the inner part of the galaxy.



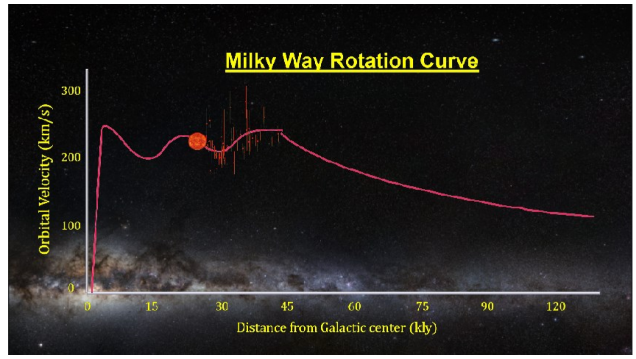
So, for clouds closer to the center than we are, we can scan the sky, bit by bit and create a map of the rotation velocity and distance for the inner galaxy. This map can then be used to find distances to all the clouds and the stars they contain as long as they are closer to the center of the galaxy than we are.



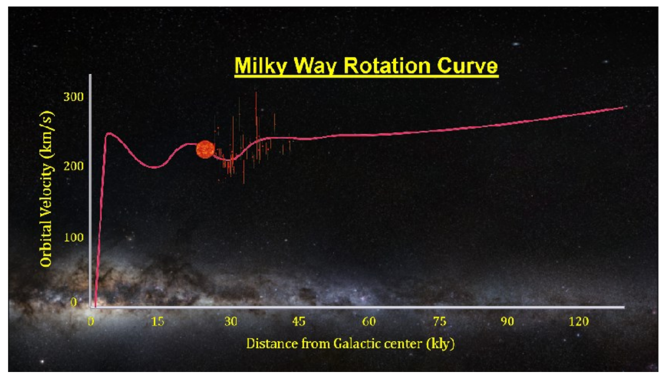
For clouds further out, there are no tangent points. For these, we have to use weaker methods for determining distance and rotational velocity. We then do a best fit line from the collected data. Here is a graphic superimposed on our galaxy curve that indicates the accuracy of methods used to provide the included data points. The vertical lines through each point represent the range of possible velocities for any given distance. Notice that these lines are quite long.



Rotation curves give us a measure of a system's mass. And, at the outer edges of the disk, the star mass density drops off dramatically. That's why, in the 1970s, everyone expected to see a rotation curve that looked like this.



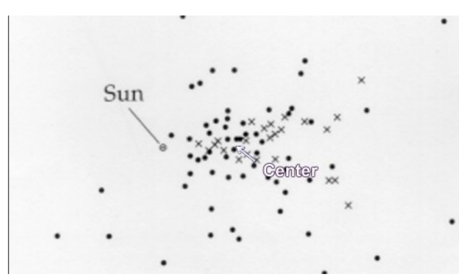
But what we found is that, where the velocities were expected to fall off, they remained relatively constant. If our current theory of gravity holds up over galactic distances, then this curve tells us that our model of the Milky Way is missing something. In order for objects far from the center of the Galaxy to be moving faster than predicted, there must be significant additional mass far from the Galactic Center exerting gravitational pulls on those stars.

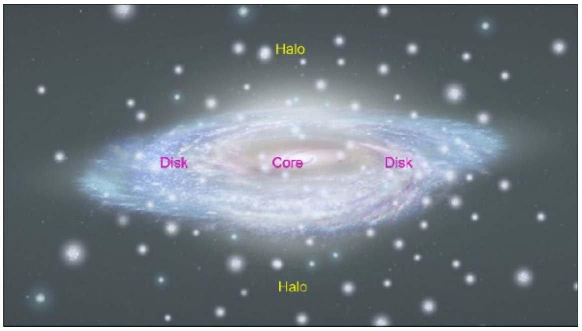


This means that the Milky Way must include an unseen component that is very massive and much larger than the galaxy's visible disk. Not knowing what it is, we call it Dark Matter and it extends way into the galaxy's halo.

The Milky Way Halo

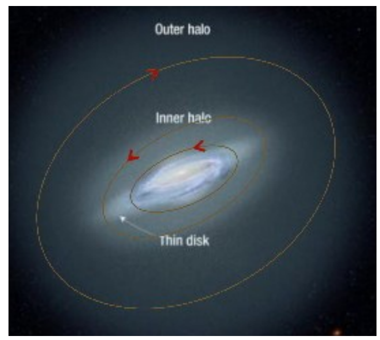
At the turn of the 20th century, astronomer Harlow Sharpley, studying a large number of RR Lyrae stars inside globular clusters, found that the center of the galaxy was far from the Sun. He mapped 93 globular clusters. They formed a spheroidal shape with their own center – not near the Sun. He concluded that these giant clusters formed the "bony frame" of the galaxy.



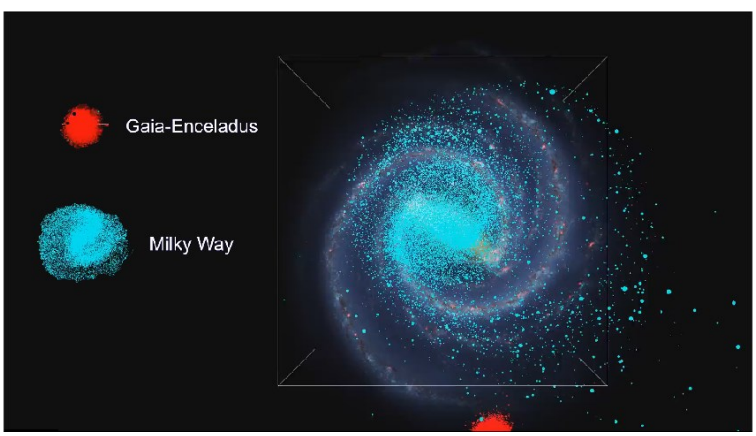


This area around the disk is called the galactic halo or corona. It holds a large number of old stars and 158 globular clusters. The Galactic halo itself has a diameter of at least 600,000 light years based on the locations of the globular clusters, although it may extend much further. [There is no star formation out in the halo.]

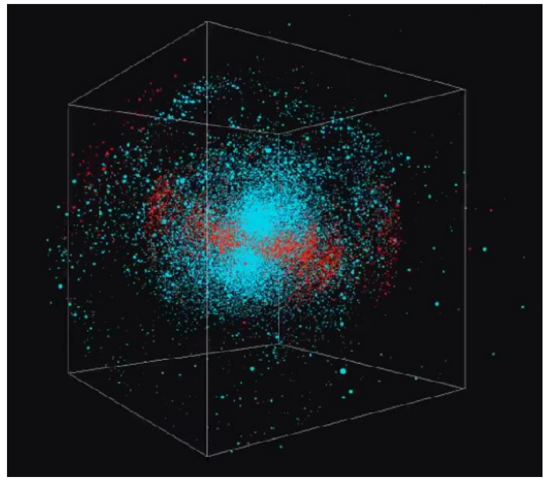
In 2007, using 20,000 stars observed by the Sloan Digital Sky Survey, an international team of astronomers discovered that the Milky Way halo is a mix of two distinct components rotating in opposite directions: the outer halo and the inner halo.



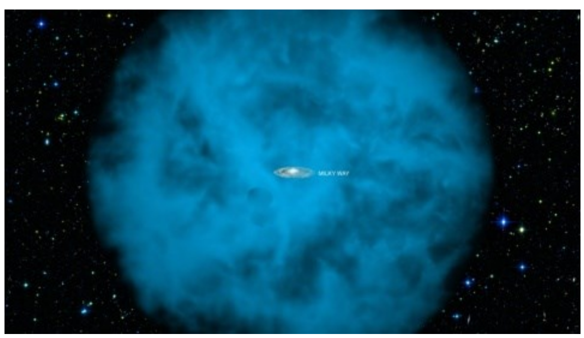
Then, in 2018, a team of astronomers analyzed seven million stars from the Gaia mission, and found that 30,000 of them were moving counter to the normal Milky Way flow. Star motion and composition profiles indicated that they came from a different galaxy. They called this new galaxy Gaia-Enceladus. Using computer models for galaxy collisions, they estimated that it collided with the Milky Way around 10 billion years ago.



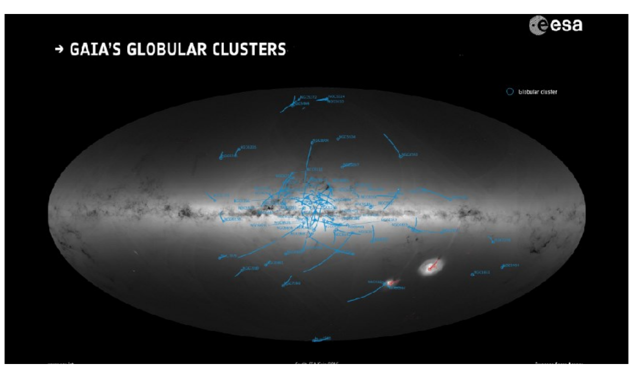
This is a computer simulation of the merger. Here we see that Gaia-Enceladus is now our galaxy's inner halo.



On September 24, 2012, Chandra found evidence that the Milky Way Galaxy is embedded with a large amount of hot gas in the halo. Counting this vast amount of gas, the mass of the halo is estimated to equal the mass of the stars in the galaxy! But, as massive as it is, the amount of matter in this hot gas is not nearly enough to explain the galaxy's rotation curves. Dark Matter or a new theory of gravity is still needed.



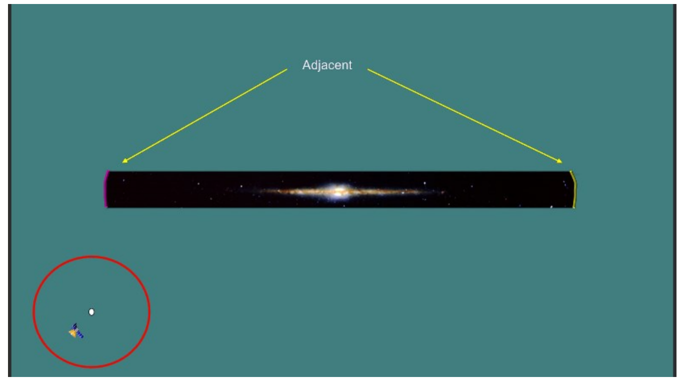
In 2018, using both Hubble and Gaia data on globular cluster sizes and velocities, the mass of our galaxy was estimated to be at least 1.5 trillion times the mass of our sun. This is more than previous estimates and indicates that the Milky Way is among the universe's larger galaxies.



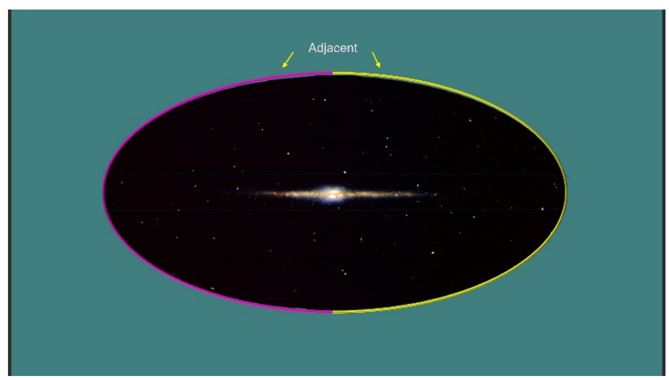
How to photograph our galaxy from the inside

But first let's take a closer look at how an image like this is created.

From orbit, we point the camera at the center of the galaxy, and turn it 180 degrees to face away from the center. We're now looking through the plane of the galaxy away from the center. Then we scan the camera clockwise taking hundreds of pictures along the way. We continue the rotation through the center and all the way back to the starting point. Note that the stars on the right edge of the image, taken at the end of the rotation, are adjacent to the stars on the left edge of the image, taken at the beginning. In other words, the entire right side of the image borders on the left.



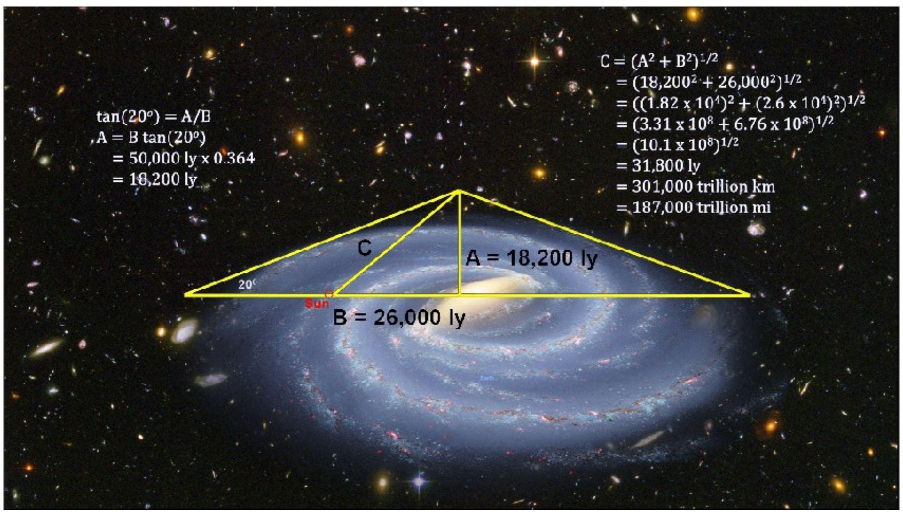
Now we rotate the camera up a bit and repeat the process. We do this over and over until the entire northern sky is covered. The last shot is taken with the camera pointing straight up perpendicular to the galactic plane. We then repeat the process for the southern sky and we have the entire picture.



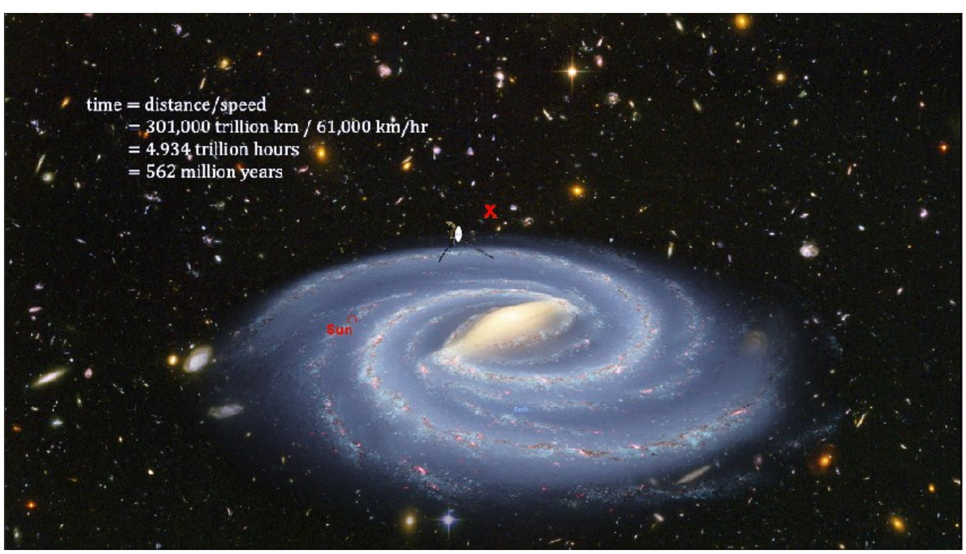
Once we have all the pictures covering the spherical surface of the sky all around us, we map it to a flat surface. There are a number of ways to do this. Astronomers use the elliptical projection method, because it maintains the relative size and distance between celestial objects. You may have seen maps of the Earth that use this technique.

Milky Way Photo Point

We started with an image of the Milky Way constructed from within the galaxy. Whenever you see any picture of the whole Milky Way from outside the galaxy, remember that it is an artist drawing. The size of the galaxy is so large, that the distance one must travel to see it all is way too far. Here's what I mean. If we assume that our field of view is 140 degrees, we can use trigonometry to find the distance to a point where such a picture could be taken. That point is approximately 301,000 trillion km or 187,000 trillion miles from the Sun's current location.



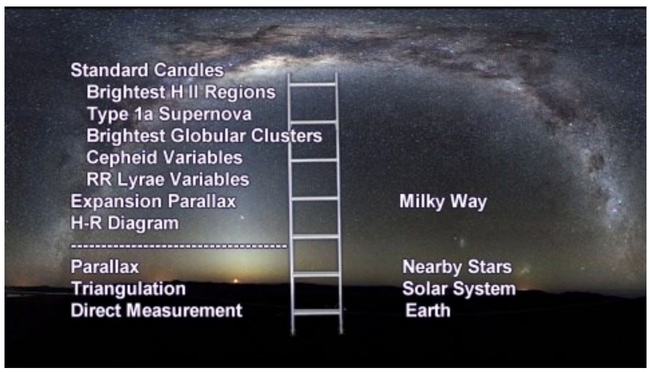
Voyager I left on its journey in 1977 and is traveling at 61,000 km/hr or 38,000 miles per hour. It has already gone 21.2 billion km or 13.2 billion miles. If we aim it at the photographic point, at its current velocity, Voyager won't reach this point for another 562 million years. If some future generation were to ever take such a picture, they would see our entire solar system as little more than a single pixel.



Chapter Conclusion

In our chapter on the Milky Way:

- We studied the nearby stars were parallax told us how far away they were.
- We developed the H-R diagram as a way to calculate luminosity based on temperature and spectral analysis.
- We covered key standard candles such as Cepheid and RR Lyrae Variables as well as Type 1a Supernovae
- And we examined star clusters; planetary nebula; and emission nebula for their beauty and value as standard candles.



This distance ladder took us all the way across the galaxy. In our next chapter, we'll use all these techniques to move out into intergalactic space.

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

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Andromeda and the Local Group

*{**Abstract** – In this segment of our "How far away is it" video book, we cover the Andromeda galaxy along with our local group of galaxies, including some of the dwarf galaxies orbiting the Milky Way.*

We begin with Edwin Hubble's discovery of a Cepheid variable star in what was thought to be a Milky Way nebula. The star was V1 and it changed the history of astronomy. We also take a deep dive into the galaxy's disk, and point out what was going on here on our planet when the light we see left Andromeda on its journey into our telescopes. We finish with a look at Andromeda's collision course with our Milky Way.

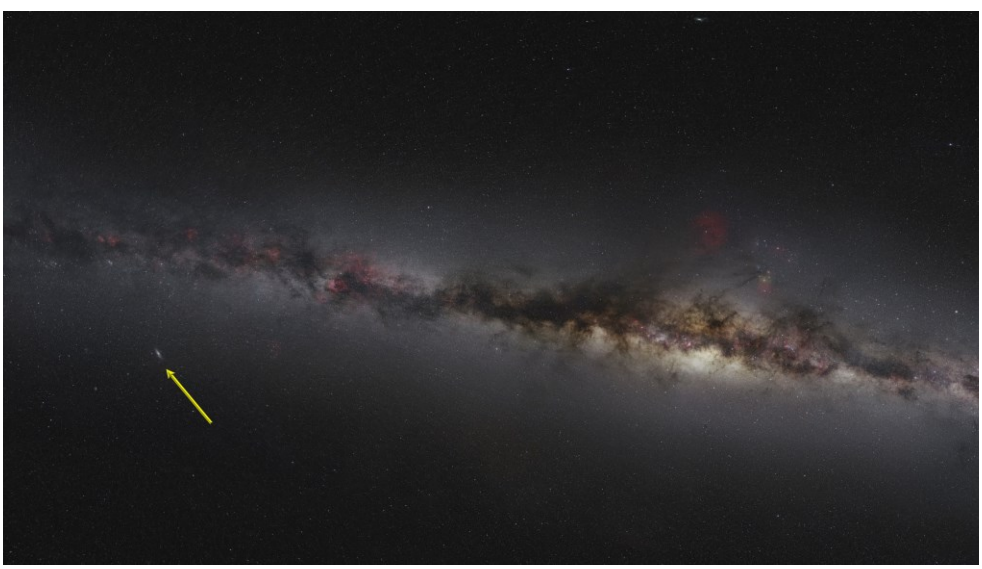
Next, we identify the local group of galaxies including: Triangulum with its great star birth H II region NGC 604; irregular galaxy NGC 6822 with its unique Hubble V H II region; the recently discovered galaxy IC 10; nearly edge on galaxy 3109; and Sextans A.

We then cover 5 of the dwarf galaxies orbiting the Milky Way including Sagittarius Dwarf, Sculptor Dwarf and Fornax Dwarf along with the Large Magellanic Cloud and the Small Magellanic Cloud. Then we examine some of the amazing nebula within these two dwarf galaxies including: Supernova Remnant N 63A, SN 0509-67.5, the Tarantula Nebula, 30 Doradus, Hodge 301, the Double Bubble, LH 95, NGC 2074, NGC 602, NGC 346 and others. We conclude with a review of the galaxies we covered marked on a map of the Local Group.}

Introduction

> **[Music:** @00:00 *Alexander Borodin – "Nocturne" –From the album The Most Relaxing Classical Music, 2003***]**

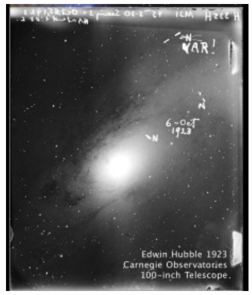
Visible to the naked eye and studied by Persian astronomers around 900 ADS, the Andromeda nebula was thought to be a part of the Milky Way. In fact, it was thought that all the stars in the Universe were in our Milky Way galaxy.



That changed in the early 1900s. In 1923, Edwin Hubble found a Cepheid variable in the nebula. This star altered the course of modern astronomy. The star goes by the name V1.

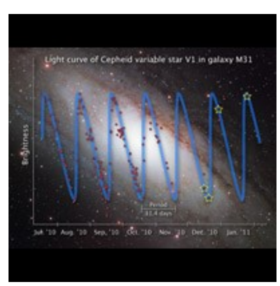
Andromeda, M31 – 2.65 mly

Here's Edwin Hubble's image of Andromeda, which was made on a 4 by 5-inch glass plate and dated Oct. 6, 1923. He originally identified three stars and marked each of them with an "N" for novae, a class of exploding star. Later, Hubble realized that the nova at the top right was actually a Cepheid variable. He crossed out the "N" and wrote "VAR" for variable.



He added an explanation point because he knew that this variable would allow him to calculate the distance. You may recall from our segment on distant stars, that we covered how Harriet Leavitt discovered the relationship between Cepheid variables frequency and their intrinsic luminosity. And once we know the intrinsic luminosity of a star, we can use the apparent luminosity and the inverse square law to determine how far away the star is.

And indeed, once the period was measured (at 31.4 days), he knew he had another galaxy! Before V1, distances to stars were measured in thousands of light years. After V1, the universe became a much bigger place. V1 was over two and a half million light years away.

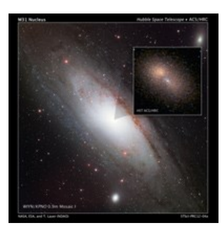


Andromeda is a beautiful barred spiral galaxy with two spiral arms that glow with a massive number of new stars. This is very much like our Milky Way. But Andromeda's disk is 220,000 ly wide. That's more than twice the width of the Mikey Way. But recent studies of star escape velocities indicate that both galaxies have the mass of 800 billion Suns counting stars, gas, dust and Dark matter.

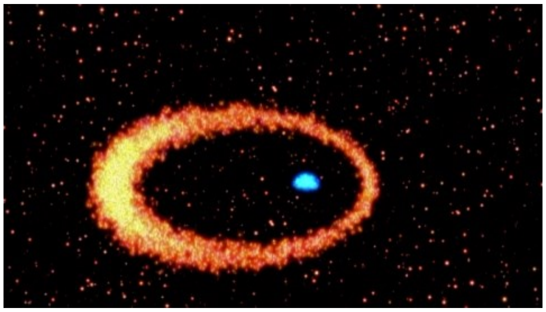
Light from this magnificent galaxy left its stars just over two and a half million years ago. When the light that entered Hubble's telescope left Andromeda, there were no humans on Earth. While the light traveled towards Earth: we came into being; we created and lost great civilizations; and we built the telescopes that caught that light when it finally reached our planet.

[Andromeda's Central Black Hole

Here we see the 100-million-solar-mass black hole at the Andromeda's core. This is the sharpest visible-light image ever made of the nucleus of an external galaxy. There is a blue glow at the center of what appears to be a double nucleus.



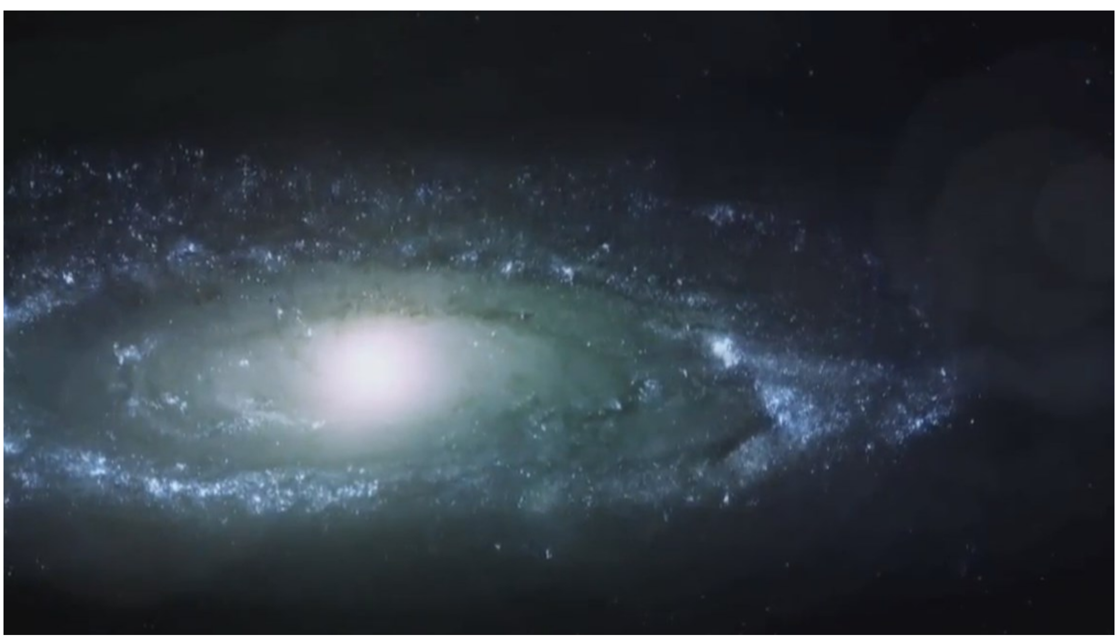
Astronomers using the Hubble Space Telescope have identified the source of the blue light surrounding this supermassive black hole in Andromeda's core.



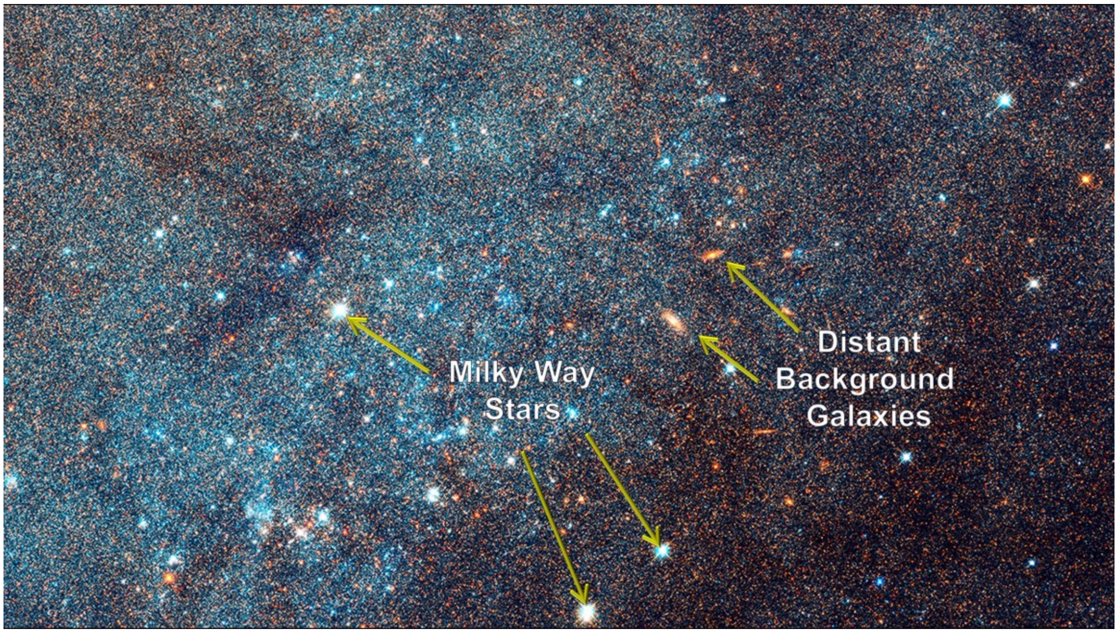
New spectroscopic observations reveal that the blue light consists of more than 400 stars. The stars are tightly packed in a disk that is only one light-year across. The disk is nested inside an elliptical ring of older, cooler, redder stars. When the stars are at the farthest point in their orbit, they move slower and give the illusion of a second nucleus.

[Additional info: Astronomers are trying to understand how apparently young stars were formed so deep inside the black hole's gravitational grip and how they survive in such an extreme environment. The fact that young stars are also closely bound to the central black hole in our Milky Way galaxy suggests this may be a common phenomenon in spiral galaxies.**]**

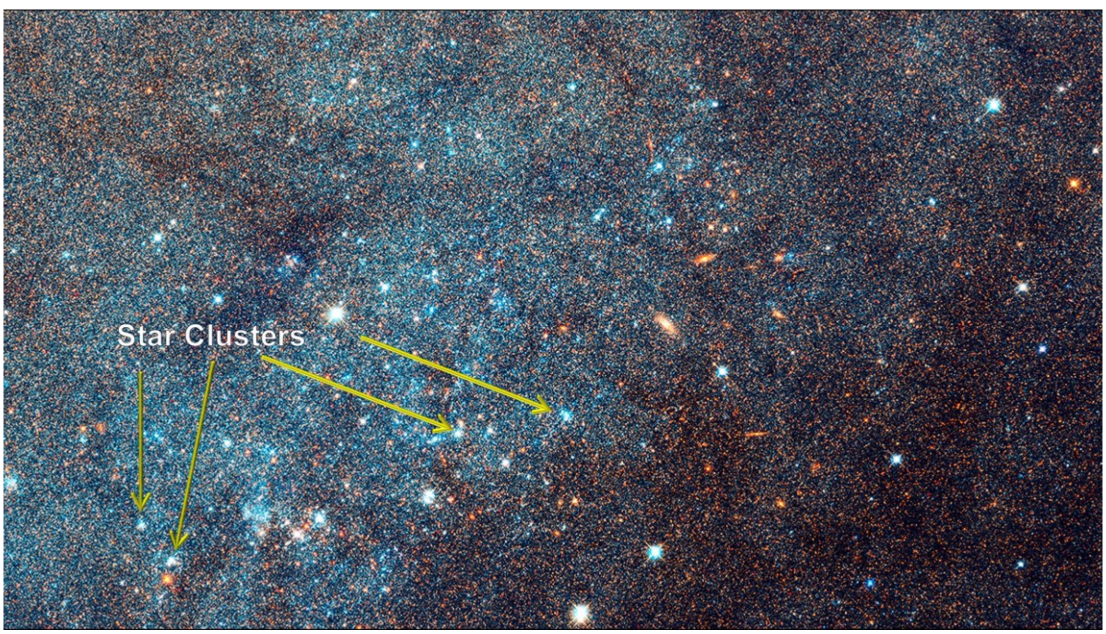
The Hubble Space Telescope has captured the sharpest and most detailed image ever taken of the galaxy. It shows over 100 million stars and thousands of star clusters embedded in a section of the galaxy's disc stretching across over 48,000 light-years. It traces the galaxy from its central galactic bulge on the left, where stars are densely packed together, across lanes of stars and dust to the sparser outskirts of its outer disc on the right.



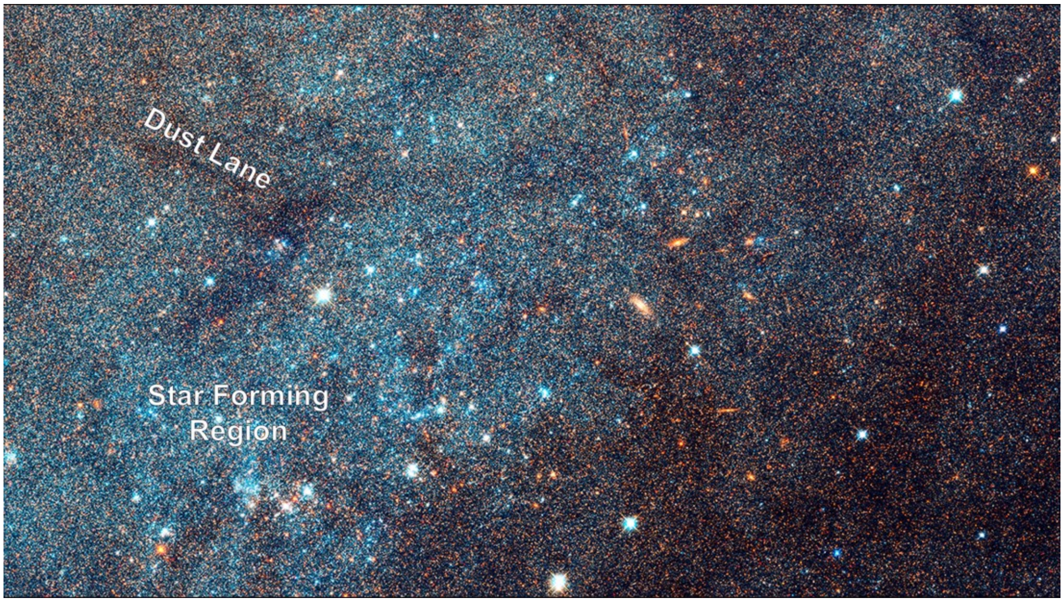
Zooming into the boxed field, we see some foreground Milky Way stars in the line of sight to Andromeda and a couple of distant spiral galaxies shining through Andromeda's disk.



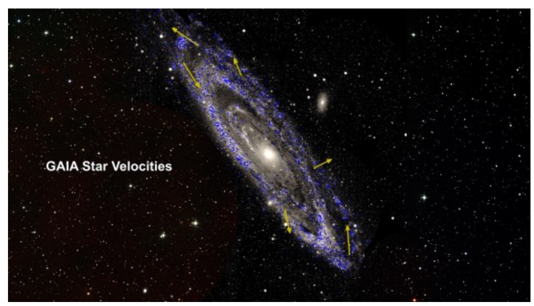
A large number of star clusters can be seen in this analysis of Andromeda.



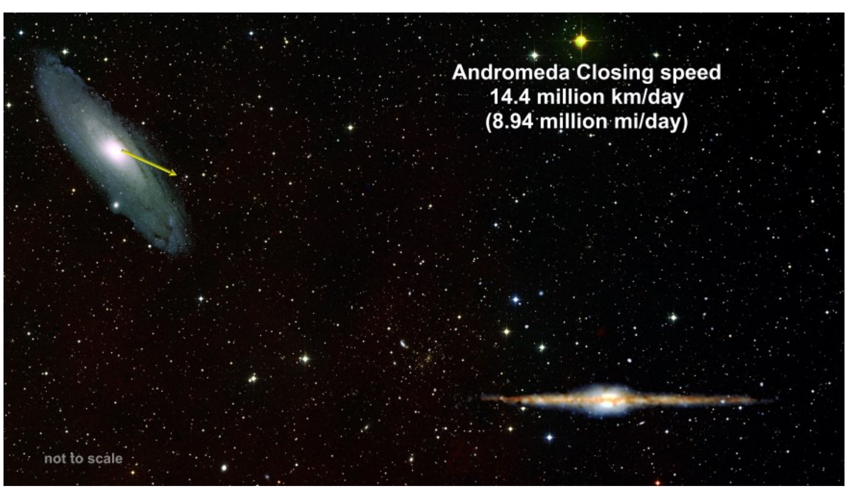
The large groups of blue stars in the galaxy indicate star-forming regions in the spiral arms, whilst the dark silhouettes of obscured regions trace out complex dust structures. Underlying the entire galaxy is a smooth distribution of cooler red stars that trace Andromeda's evolution over billions of years.



We'll conclude our coverage of Andromeda with a look at its closing velocity. Careful analysis of Andromeda's proper and radial motion indicates that it is on a collision course with our Milky Way.



It's closing at 14.4 million km/day. That's almost 9 million miles per day. But, given the 2.5 million light years between us, it won't get here for around 4 to 4.5 billion years. We cover this in depth in a subsequent segment on colliding galaxies.

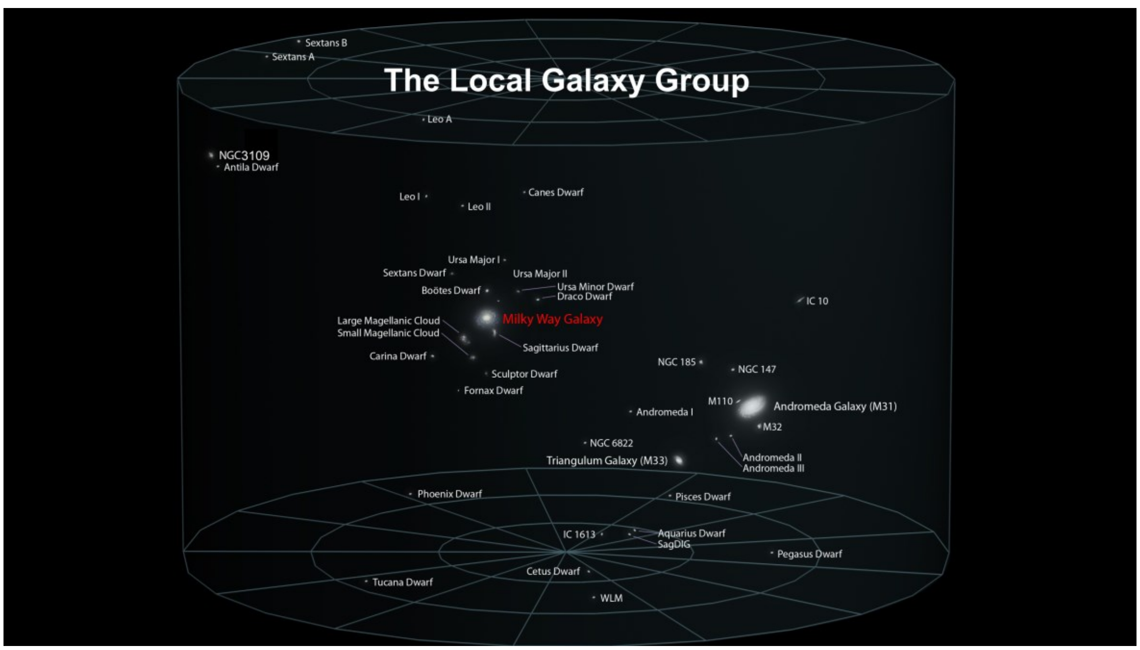


The Local Group

> **[Music:** @06:54 *Edward Elgar – "Enigma Variations" – from the album The Most Relaxing Classical Music, 1997.***]**

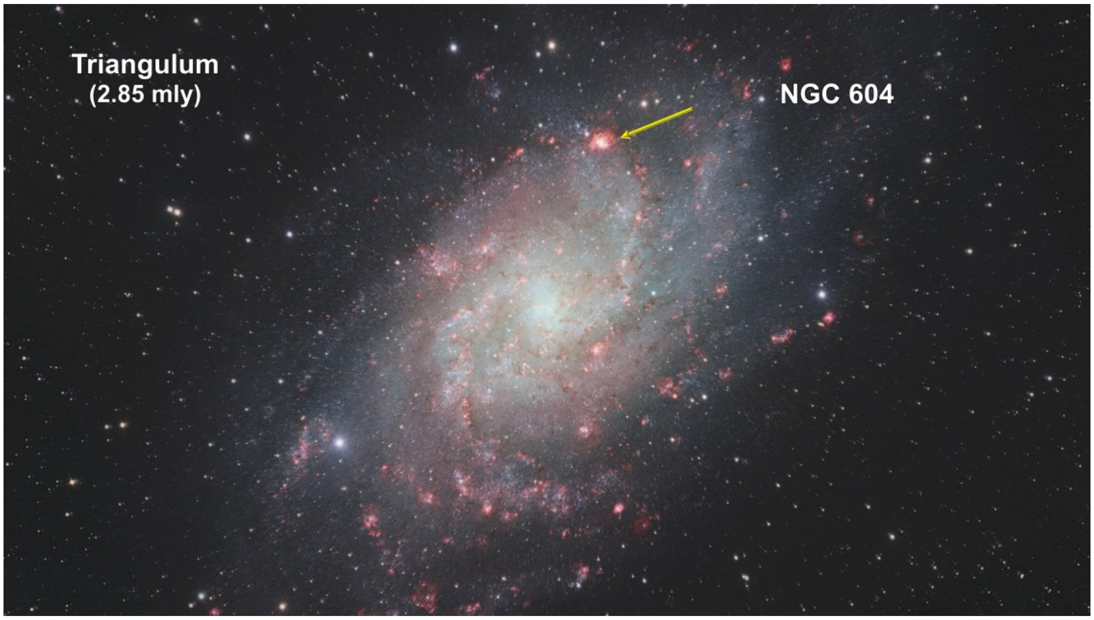
There are over 30 galaxies in the local group. Andromeda is the largest. The Milky Way is second and Triangulum is third. All the rest are dwarf galaxies, and most of these are obiting one or the other of the three big ones.

As of 2020, we have discovered 59 dwarf galaxies orbiting the Milky Way. Andromeda has at least 34. The Triangulum Galaxy has one. The other members of the group are gravitationally not orbiting any of these three larger galaxies. We'll take a look at some of these and then move closer to home, and have a good look at some of our orbiting dwarf galaxies.



Triangulum M33 – 2.85 mly

Here we are zooming into the Triangulum Galaxy. It's the third-largest member of the Local Group, with a diameter of about 60,000 light years. Triangulum is home to around 40 billion stars. That's small compared to our two to four hundred billion and Andromeda's trillion. The Galaxy doesn't have a bright bulge at its center, but it does contain a huge amount of gas and dust, giving rise to rapid star formation. New stars form at a rate of approximately one every two years.



This Hubble image contains 10 to 15 million individual stars. The mosaic of the Triangulum Galaxy showcases the central region of the galaxy and its inner spiral arms. Millions of stars, hundreds of star clusters and bright nebulae are visible.

NGC 604 in Triangulum – 2.85 mly

NGC 604 is among the largest known star formation regions in the Local Group. It lies in an outer Triangulum spiral arm. This star-birth region and contains more than 200 brilliant blue stars within a cloud of glowing gases some 1,500 light-years across. That's nearly 100 times the size of the Orion Nebula. By contrast, the Orion Nebula contains just four bright central stars. The bright stars in NGC 604 are extremely young by astronomical standards, having formed a mere 3 million years ago.

NGC 6822 – 1.6 MLY

The small, irregular galaxy is one of the Milky Way's closest neighbors and is considered prototypical of the earliest fragmentary galaxies that inhabited the young universe. What's striking about NGC 6822 is its unusually high abundance of HII region emission nebulae. These are visible surrounding the small galaxy, particularly toward the upper right.

Hubble V Nebula inside NGC 6822

This is one of them. The glowing gas cloud, called Hubble-V, has a diameter of about 200 light-years. A faint tail of nebulosity trailing off the top of the image sits opposite a dense cluster of bright stars at the bottom of the irregularly shaped nebula.

IC 10 – 2.2 mly

IC 10 is another irregular galaxy. [It's the closest-known starburst galaxy. Starburst galaxies are galaxies undergoing a furious pace of star formation fueled by an ample supplies of cool hydrogen gas.] Edwin Hubble suspected it might belong to the Local Group of galaxies, but its status remained uncertain for decades. Its membership in the group was finally confirmed in 1996 by direct measurements of its distance based on observations of Cepheids. The reason it took so long is that, despite its closeness, the galaxy lies near the plane of the Milky Way and is therefore heavily obscured by our galaxy's interstellar matter.

NGC 3109 – 4.7 mly

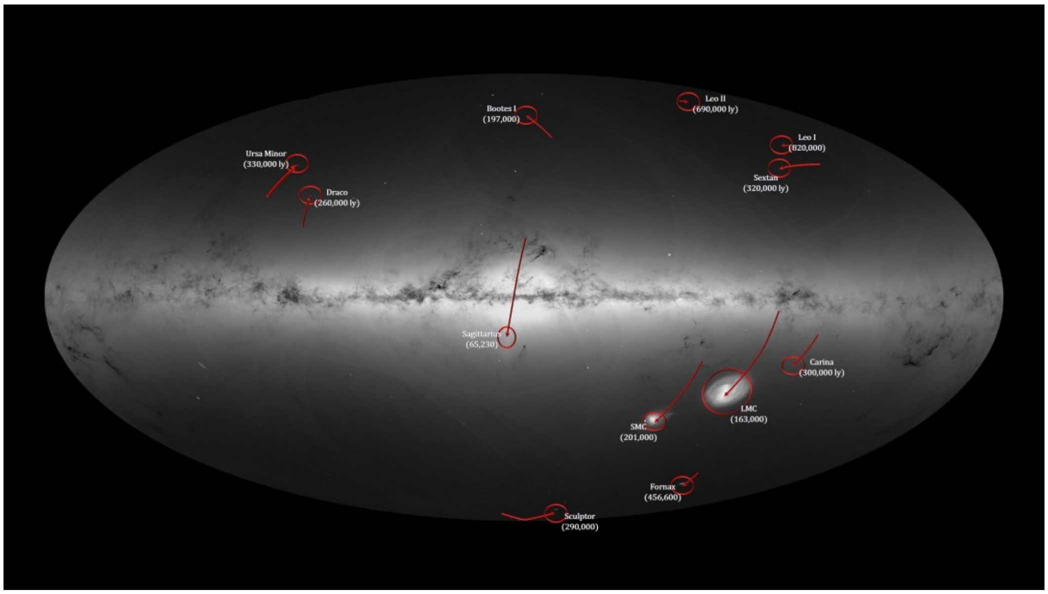
NGC 3109 looks like a small spiral galaxy. If it is a spiral galaxy, it would be the smallest in the Local Group. It is oriented edge-on from our point of view, and may contain a disk and a halo. It does not appear to possess a galactic nucleus. But it does seem to contain an unusually large number of planetary nebulae. [The disk appears to be composed of stars of all ages, whereas the halo contains only very old stars.]

Sextans A – 4.3 mly

Young blue stars and older yellow and red stars shine against a dark sky in this image of Sextans A from Japan's Subaru telescope. The galaxy is a small peculiar square-shaped dwarf galaxy 5,000 light years across 4.3 million light years from Earth. The bright foreground yellowish stars are in the Milky Way.

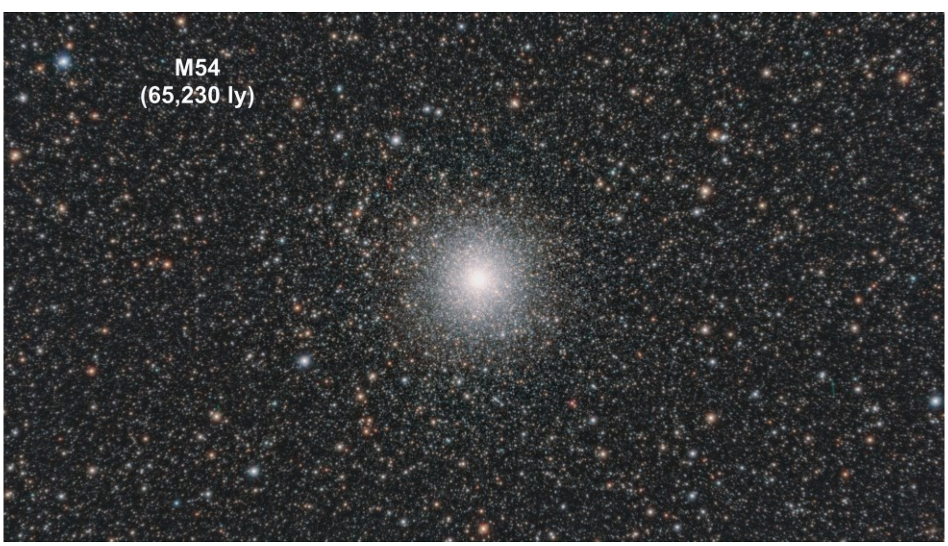
Dwarf galaxies Orbiting the Milky Way

Here we take a look at a few of the dwarf galaxies orbiting our Milky Way. Gaia's all sky star density map picked up a few of the closer ones and calculated their orbits. The lines represent the orbital track traveled over the past few millions of years. The further away the galaxy, the longer its orbital period. It can take billions of years for the satellites further out to complete a single orbit. Compare that to the 230 million years it takes us to make one revolution.



Sagittarius Dwarf – 65,230 ly

Sagittarius Dwarf is our closest orbiting galaxy. It is so close, that it is being ripped apart by the Milky Way. It will be fully integrated as part of the Milky Way within the next billion years. It can take a much as 770 million years to orbit the Milky Way. Here we are zooming into globular cluster M54 at its center.



Sculptor Dwarf **[Music:** @14:13 Tchaikovsky – "Symphony No 5" – from the album A Calendar of Classics – A 12 C …, 2007.**]**

Sculptor Dwarf is a dwarf spheroidal galaxy. These are very common. They contain an old stellar population with large separations between stars. They are also devoid of gas and dust, so there is no new star formation. A team of astronomers used data from both the Hubble Space Telescope and the Gaia satellite to directly measure the 3D motions of individual stars in Sculptor. Their results show that the galaxy's orbit is quite elongated. Currently at 290,000 ly, Sculptor Dwarf is near to its closest point to the Milky Way. But its orbit will take it as far out as 725,000 light-years.

Fornax Dwarf - 460,600 ly
Fornax Dwarf is one of our furthest orbiting galaxies. It's of interest to astronomers because its globular clusters don't fit current globular cluster formation theory because there aren't enough old stars in the clusters as theorized that there should be. Research continues.

Large and Small Magellanic Clouds

But the two dwarfs of the most interest can be seen in the southern night sky. They are the Large Magellanic Cloud 160 to 170 thousand light years away and the Small Magellanic Cloud a bit further at 200,000 light years from us. These companion galaxies were named for the Portuguese navigator Ferdinand Magellan, whose crew discovered them during the first voyage around the world (1519 to 1522).

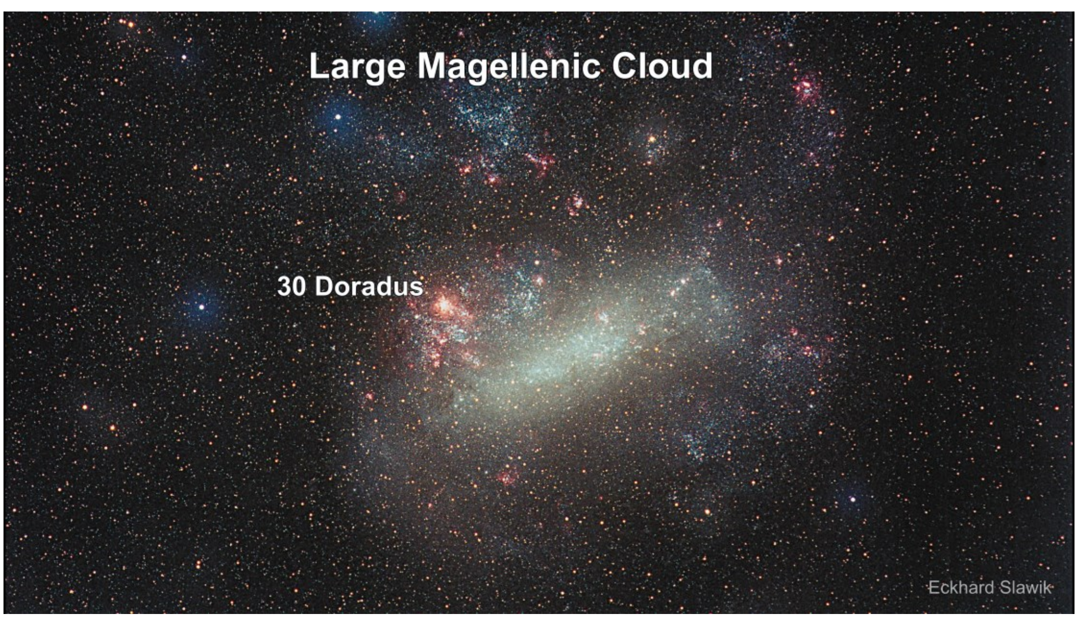
The Large Magellanic Cloud or LMC for short is the brightest galaxy in the sky. It contains several billion stars and many stars are still forming in it.

The Small Magellanic Cloud or SMC for short contains at least several hundred million stars. Like the LMC, there is still a lot star formation taking place within it.

[Music: *We return to and conclude with the exotic and lush melodies in Alexander Borodin's "Nocturne".* **]**

30 Doradus

Here we'll take a look at some of the amazing nebula in the LMC. This stellar region is called 30 Doradus. It contains millions of young stars including the most massive stars ever seen, weighing more than 100 times the mass of our Sun. No known star-forming region in our galaxy is as large or as prolific as 30 Doradus.



Tarantula Nebula

With this closer look, we see the Tarantula Nebula. Early astronomers nicknamed the nebula because its glowing filaments resemble spider legs. The image reveals the stages of star birth, from embryonic stars a few thousand years old still wrapped in their eggs to behemoths that die young in supernova explosions.

R136 – 170,000 ly

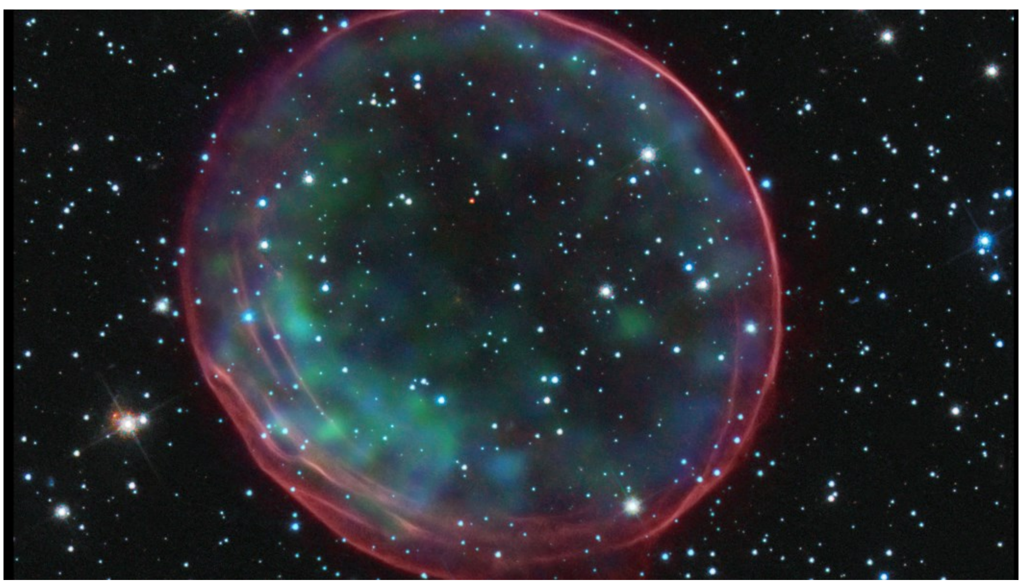
Astronomers using the unique ultraviolet capabilities of the Hubble Space Telescope have identified nine monster stars with masses over 100 times the mass of the Sun in the star cluster R136. This makes it the largest sample of very massive stars identified to date. The detected stars are not only extremely massive, but also extremely bright. Together these nine stars outshine the Sun by a factor of 30 million.

Hodge 301

Hodge 301, seen in the lower right-hand corner of this image, lives inside the Tarantula Nebula. Many of the stars in Hodge 301 are so old that they have exploded as supernovae. These exploded stars are blasting material into the surrounding region at speeds of almost 320 km/s (that's 200 miles per second). The high-speed matter is plowing into the surrounding Tarantula Nebula, shocking and compressing the gas into a multitude of sheets and filaments, seen in the upper left portion of the picture.

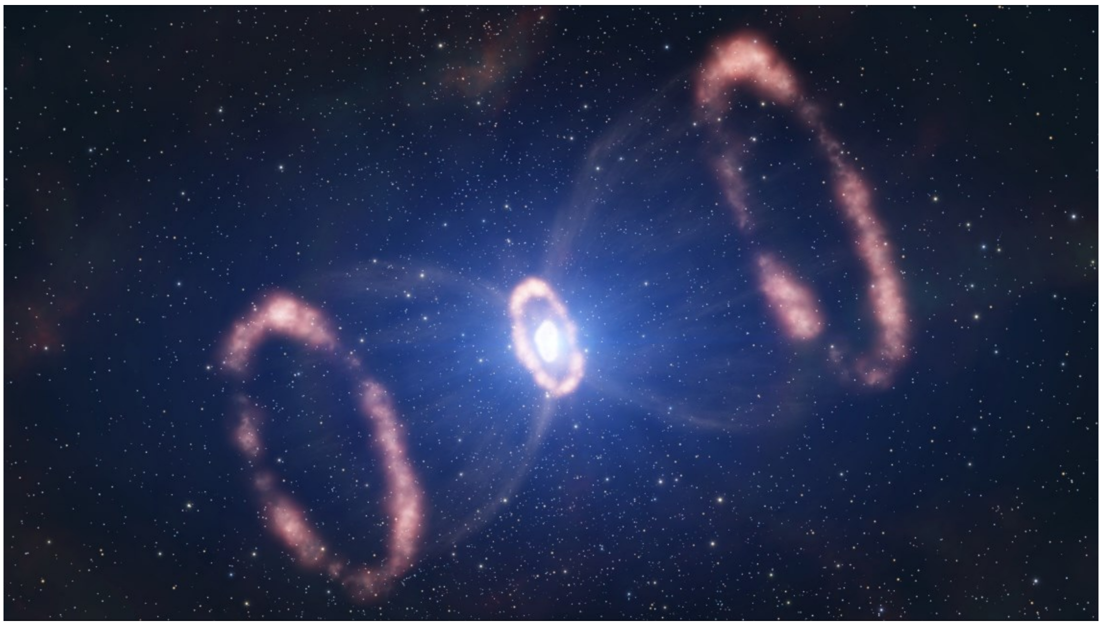
SNR 0509-67.5 – 170,000 light years

This image of supernova remnant 0509-67.5 was made by combining data from two of NASA's Great Observatories: Hubble and the Chandra X-ray Observatory. The result shows soft green and blue hues of heated material from the X-ray data surrounded by the glowing pink optical shell, which shows the ambient gas being shocked by the expanding blast wave from the supernova.

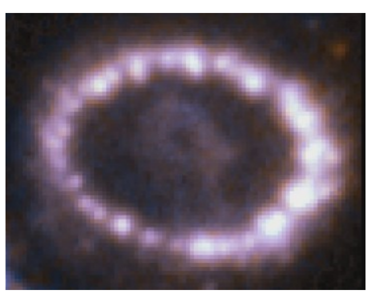


SN 1987A – 163,000

Three decades ago, astronomers spotted one of the brightest exploding stars in more than 400 years. The titanic supernova, called 1987A (SN 1987A) in the Large Magellanic Cloud, blazed with the power of 100 million Suns for several months following its discovery **[**on Feb. 23, 1987**]**. A dense ring of gas around the supernova is glowing in optical light, and has a diameter of about one light-year. A flash of ultraviolet light from the explosion energized the gas in the ring, making it glow for decades. [The ring was created when the star was a red giant - around 20,000 years before the star exploded.]



This time-lapse video sequence of Hubble images shows the effects of the shock wave from the supernova blast smashing into the ring. The ring begins to brighten as the shock wave hits it. [The ring is about one light-year across.] In the past few years, the ring's X-ray light has stopped getting brighter. And, the bottom left part of the ring has started to fade. These changes provide evidence that the explosion's blast wave has moved into the region beyond the ring. This represents the end of an era for this supernova. We expect to learn more about this new region as the blast wave impacts its contents.



Double Bubble DEM L 106 and N30B – 160,000 light years

A unique peanut-shaped reflection nebula surrounds a cluster of young, hot stars in this view from Hubble. The "double bubble - N30B" is inside a larger nebula. The very bright star at the top of the picture, called Henize S22, illuminates the dusty cocoon like a flashlight shining on smoke particles. This searing supergiant star is only 25 light-years from the N30B nebula.

LH -95

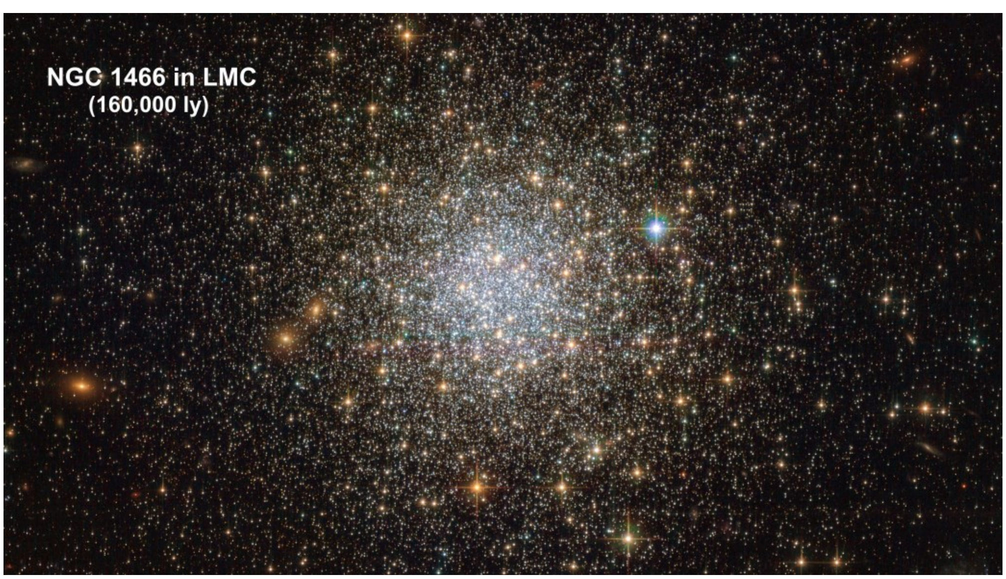
Swirls of gas and dust reside in this ethereal-looking region of star formation. It reveals a region where low-mass, infant stars and their much more massive stellar neighbors reside. This is just one of the hundreds of star-forming systems, located in the LMC.

Star Cluster NGC 2074 – 170,000 light years

This region is a firestorm of raw stellar creation, perhaps triggered by a nearby supernova explosion. The three-dimensional-looking image reveals dramatic ridges and valleys of dust, serpent-head "pillars of creation," and gaseous filaments glowing fiercely under torrential ultraviolet radiation. The region is on the edge of a dark molecular cloud that is an incubator for the birth of new stars.

NGC 1466 - 160,000 ly

In 2019 I released the "How Old are Stars" video where we covered HR Diagram turnoff points to find the age of star clusters. Here's NGC 1466, a very old globular cluster in the Large Magellanic Cloud (LMC)160,000 ly away. It has a mass equivalent to roughly 140,000 Suns and a turnoff point that indicates its age as around 13.1 billion years - making it almost as old as the Universe itself.



[All high mass blue stars would have moved into their Giant and Super Giant phases by now. But we do see blue stars in this and many other clusters of similar age.

These massive hot blue stars are a special type of re-invigorated stars called blue stragglers. Under certain circumstances, stars receive extra fuel that bulks them up and substantially brightens them. This can happen if one star pulls matter from a neighbor, or if two stars collide. Blue stragglers are so called because of their blue color, and the fact that their evolution lags behind that of the rest of the stars in the cluster.

]

NGC 602

Now let’s take a look at a couple of objects in the Small Magellanic Cloud.

At the heart of the SMC, lies star cluster NGC 602. The high-energy radiation blazing out from the hot young stars is sculpting the inner edge of the outer portions of the nebula, slowly eroding it away and eating into the material beyond. Elephant trunk-like dust pillars point towards the hot blue stars and are tell-tale signs of their eroding effect.

NGC 346

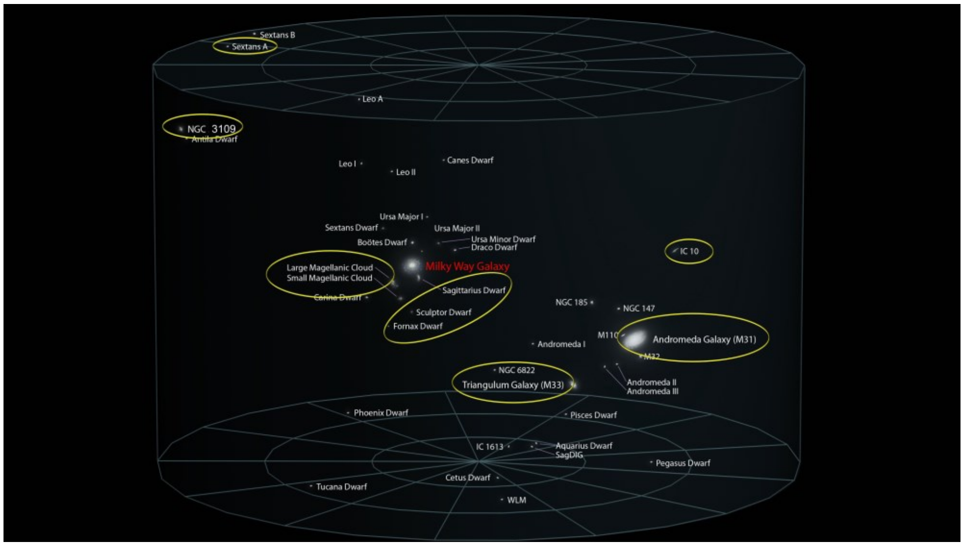
The NGC 346 cluster, at the center of this Hubble image, is resolved into at least three sub-clusters and collectively contains dozens of hot, blue, high-mass stars, more than half of the known high-mass stars in the entire SMC galaxy. A myriad of smaller, compact clusters is also visible throughout the region.

NGC 248 – 200,000 ly

Hubble captured two nebulas inside the Small Magellanic Cloud, situated so as to appear as one. Intense radiation from the brilliant central stars is heating hydrogen in each of the nebulas, causing them to glow red. This is part of a study to understand how interstellar dust is different in galaxies that have a far lower supply of heavy elements. The Small Magellanic Cloud has between a fifth and a tenth of the amount of heavy elements that the Milky Way does. Because it is so close, astronomers can study its dust in great detail, and learn about what dust was like earlier in the universes' history.

Conclusion

Here are the Local Group galaxies we saw in this segment. The Local Group is part of a larger structure known as the Local Volume. We'll explore this Local Volume in our next segment.



The Local Galaxy Volume

*{**Abstract** – In this segment of our "How far away is it" video book, we cover the local galaxy volume compiled by the Spitzer Local Volume Legacy Survey team.*

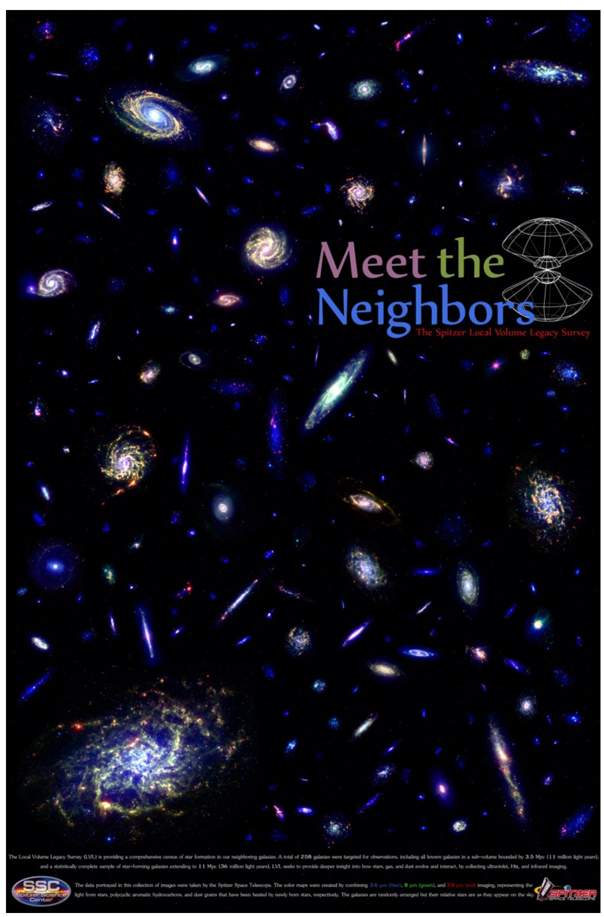
The survey covered 258 galaxies within 36 million light years. We take a look at just a few of them including: NGC 4214, Centaurus A, NGC 5128 Jets, NGC 1569, majestic M81, Holmberg IX, M82, NGC 2976,the unusual Circinus, M83, NGC 2787, the Pinwheel Galaxy M101, NGC 6503, the Fireworks Galaxy and its disappearing star, M106, NGC 3344, NGC 4485, the Sombrero Galaxy M104 including Spitzer's infrared view, NGC 1512, the Whirlpool Galaxy M51, M74, M66, and M96. In addition, we cover the Density Wave theory that attempts to explain how spiral arms in spiral galaxies exist as they do.

We end with a look at the tuning fork diagram created by Edwin Hubble with its description of spiral, elliptical, lenticular and irregular galaxies.}

Introduction

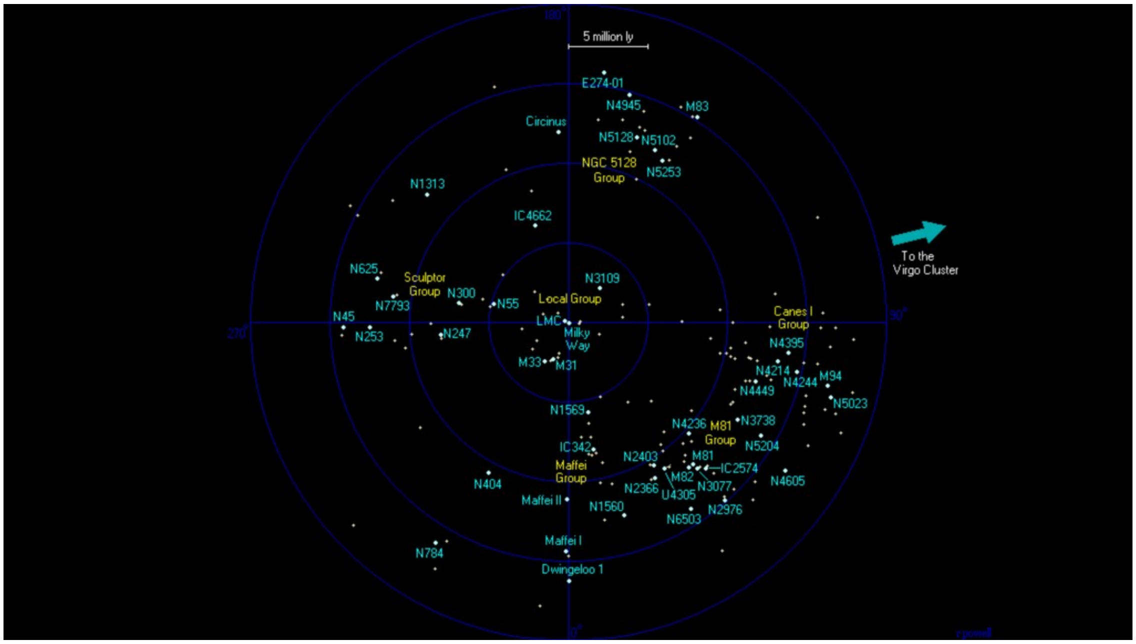
[Music: @00:00 Johann Pachelbel, "Canon in D"; from the album The Most Relaxing Classical Music, 1997**]**

The Local volume is the set of galaxies covered in the Local Volume Legacy survey or LVL, for short, conducted by the Spitzer team. It is a complete sample of 258 galaxies within 36 million light years. This montage of images shows the ensemble of galaxies as observed by Spitzer. The galaxies are randomly arranged but their relative sizes are as they appear on the sky.



[Additional info: The broad goal of LVL is to provide critical insight into two of the primary processes that shape the growth of galaxies: star formation and its interaction with the interstellar medium.**]**

Here we have the galaxies laid out by distance from us. We'll take a look at a number of them.

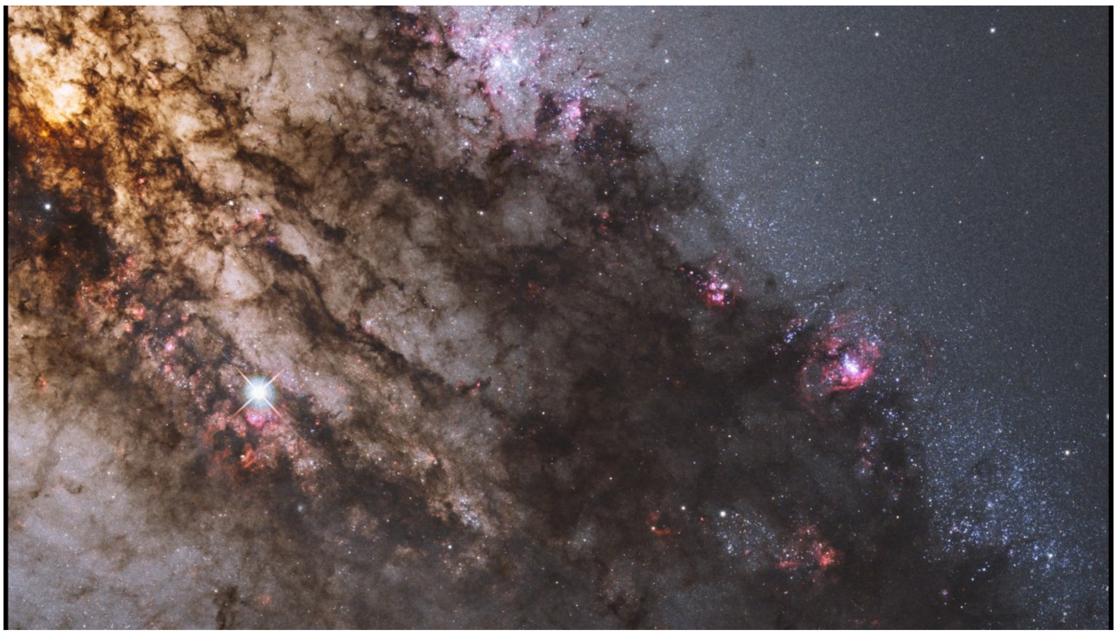


NGC 4214 – 10 mly

The dwarf galaxy NGC 4214 is ablaze with young stars and gas clouds. The galaxy's close proximity, combined with the wide variety of evolutionary stages among the stars, make it an ideal laboratory to research the triggers of star formation and evolution. Intricate patterns of glowing hydrogen formed during the star-birthing process, cavities blown clear of gas by stellar winds, and bright stellar clusters of NGC 4214 can be seen in this optical and near-infrared image.

NGC 5128, Centaurus A – 11 mly

Resembling looming rain clouds on a stormy day, dark lanes of dust crisscross the giant elliptical galaxy Centaurus A. Hubble's panchromatic vision, stretching from ultraviolet through near-infrared wavelengths, reveals the vibrant glow of young, blue star clusters and a glimpse into regions normally obscured by the dust. warped shape of Centaurus A's disk of gas and dust is evidence for a past collision and merger with another galaxy. The resulting shockwaves cause hydrogen gas clouds to compress, triggering a firestorm of new star formation. These are visible in the red patches in this Hubble close-up.



At a distance of just over 11 million light-years, Centaurus A contains the closest active galactic nucleus to Earth. The center is home for a supermassive black hole that ejects jets of high-speed gas into space, but neither the supermassive black hole nor the jets are visible in this image.

But they are in this one. This Color composite image of Centaurus A reveals the lobes and jets emanating from the active galaxy's central black hole.

NGC 1569 – 11 mly

This image showcases the brilliant core of one of the most active galaxies in our local neighborhood. The entire core is 5,000 light-years wide. NGC 1569 sparkles with the light from millions of newly formed young stars. It is pumping out stars at a rate that is 100 times faster than the rate observed in our Milky Way Galaxy. This frenzied pace has been almost continuous for the past 100 million years.

M81 – 11.6 mly

This beautiful galaxy is tilted at an oblique angle on to our line of sight, giving us a "birds-eye view" of this "grand design" spiral galaxy. It is similar to our Milky Way, but this favorable view provides a better picture of the typical architecture of spiral galaxies. The spiral arms, which wind all the way down into the nucleus, are made up of young, bluish, hot stars formed in the past few million years. A number of sinuous dust lanes also wind all the way into the nucleus of M81. The galaxy's central bulge is significantly larger than the Milky Way's bulge. A black hole of 70 million solar masses resides at the center. This is about 15 times the mass of the Milky Way's black hole. Hubble research shows that the size of the central black hole in a galaxy is proportional to the mass of a galaxy's bulge.

Holmberg IX – 12 mly

> **[Music:** @04:54 Mozart: Flute Quartet in G major; from the album Meditation: Classical Relaxation, 2010**]**

This loose collection of stars is actually a dwarf irregular galaxy, called Holmberg IX. It resides just off the outer edge of M81. Holmberg IX is of the so-called Magellanic type of galaxy, as its size and irregularity in structure are similar to the Small Magellanic Cloud. A close encounter with M81 may have triggered the newer star formation that has occurred. By understanding how Holmberg IX was formed, scientists hope to understand their role as building blocks for large galaxies.

M82 – 12 mly

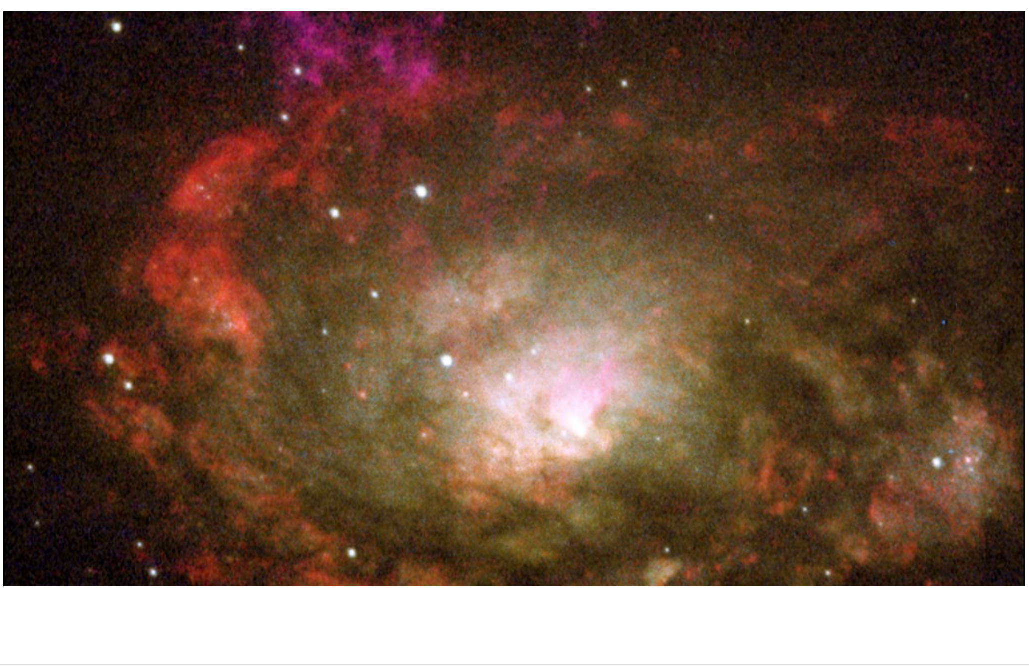
Here we are zooming into M82. The galaxy is remarkable for its bright blue disk, webs of shredded clouds, and fiery-looking plumes of glowing hydrogen blasting out of its central regions. Throughout the galaxy's center, young stars are being born 10 times faster than they are inside our entire Milky Way Galaxy. A huge concentration of young stars has carved into the gas and dust at the galaxy's center. The fierce galactic superwind generated from these stars compresses enough gas to make millions of more stars. Young stars are crammed into tiny but massive star clusters. These, in turn, congregate by the dozens to make the bright patches, or "starburst clumps," in the central parts of M82. The clusters in the clumps can only be distinguished in the sharp Hubble images. Most of the pale, white objects sprinkled around the body of M82 that look like fuzzy stars are actually individual star clusters about 20 light-years across that contain up to a million stars each.

NGC 2976 – 12

NGC 2976 does not look like a typical spiral galaxy. In this view of the galaxy's inner region, there are no obvious spiral arms. Dusty filaments running through the disk show no clear spiral structure. Although the gas is centrally concentrated, the galaxy does not have a central bulge of stars. What look like grains of sand in the image are actually individual stars. Studying the individual stars allowed astronomers to determine their color and brightness, which provided information about when they formed.

Circinus Galaxy – 13 mly

This galaxy is called Circinus. Much of the gas in its disk is concentrated in two specific rings — a larger one 1,300 light-years wide, and a previously unseen ring 260 light-years wide. Both rings are home to large amounts of gas and dust as well as areas of major "starburst" activity. At the center of the starburst rings is the supermassive black hole that is accreting surrounding gas and dust. The black hole and its accretion disk are expelling gas out of the galaxy's disk and into its halo. The detailed structure of this gas is seen as magenta-colored streamers extending towards the top of the image. near the plane of our own Milky Way Galaxy, the Circinus galaxy is partially hidden by intervening dust along our line of sight. As a result, the galaxy went unnoticed until 1999.



M83, the Southern Pinwheel – 15 mly

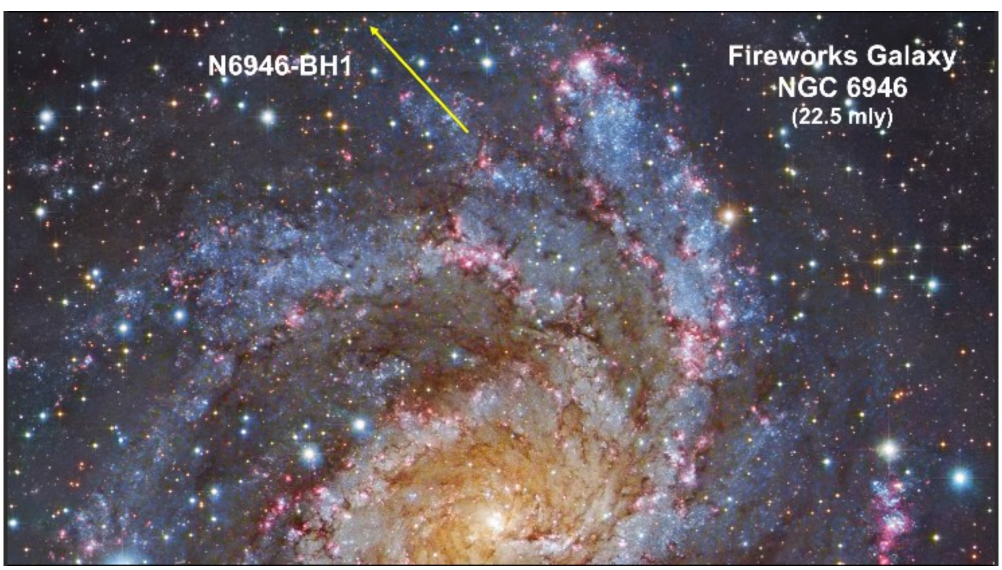
Nicknamed the Southern Pinwheel, M83 is undergoing more rapid star formation than our own Milky Way galaxy, especially in its nucleus. This Hubble close-up has captured hundreds of young star clusters, ancient swarms of globular star clusters, and hundreds of thousands of individual stars, mostly blue supergiants and red supergiants. The remains of about 60 supernova blasts can be seen in the image.

NGC 6503 18 mly

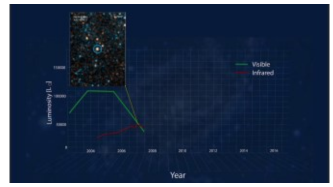
Hubble has taken a beautiful picture of NGC 6503. It spans some 30,000 light-years. In this image, bright red patches of gas can be seen scattered through its swirling spiral arms, mixed with bright blue regions that contain newly-forming stars, with dark brown dust lanes snaking across the galaxy's bright arms and center.

NGC 3344 – 20 mly
This beautiful bared spiral galaxy is about half the size of the Milky Way. Astronomers estimate that two-thirds of all spiral galaxies have a bar structure at its center. That including our own Milky Way. The swirling spiral arms are the birthplace of new stars. Their high temperatures make them shine blue. Clouds of dust and gas distributed through the spiral arms — glowing red in this image — are reservoirs of material for even more stars. The bright stars on the left are Milky Way stars in the line of sight to NGC 3344.

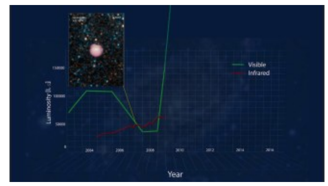
Fireworks Galaxy – 22 mly
The Large Binocular Telescope (LBT for short) in Arizona was scanning the Fireworks Galaxy 22 million light years away looking for supernova candidates. [The galaxy is known for having large numbers of supernova explosions.] They examined the star named N6946-BH1 – a star 25 times more massive than our Sun. Stars that size usually end in a supernova explosion – leaving behind a neutron star or a black hole.



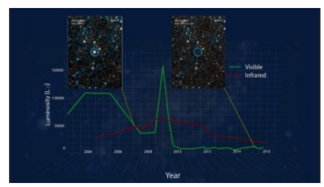
Here's a graph of the star's luminosity in visible and infrared light over time. In 2007, Hubble took this picture of the star.



In 2009, the star shot up in brightness to become over 1 million times more luminous than our sun for several months. The expectation was that it was about to supernova.



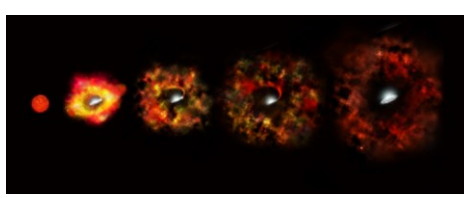
But it didn't. It just seemed to vanish, as seen in this image from 2015. After the LBT turned up the star, astronomers aimed the Hubble (for visible light) and Spitzer (for infrared light) space telescopes to see if the star was still there. All the tests came up negative. The star was no longer there. The researchers eventually concluded that the star must have become a black hole - without a supernova.



[This illustration shows the possible final stages in the life of a supermassive star that fails to explode as a supernova but instead implodes under gravity to form a black hole.

- The massive star evolves into a red supergiant.
- The outer envelope of the star is ejected and expands, producing a cold, red transient source surrounding the star.
- Gravity pulls the rest of the star to within its Schwarzschild radius creating a newly formed black hole.
- Some residual material falls into the black hole, as illustrated by the stream and the disk, potentially powering some optical and infrared emissions years after the collapse.]

It has been estimated that up to 30% of all massive stars form black holes this way with the remaining 70% taking the supernova path.



M106 – 23.5 mly

Here's the magnificent spiral galaxy M106. It is a class of galaxy called a Seyfert galaxy. Seyfert galaxies account for about 10% of all galaxies and are some of the most intensely studied objects in astronomy, as they are thought to be powered by the same phenomena that occur in quasars, although they are closer and less luminous than quasars. These galaxies have supermassive black holes at their centers which are surrounded by accretion discs of in-falling material. The accretion discs are believed to be the source of the observed ultraviolet radiation.

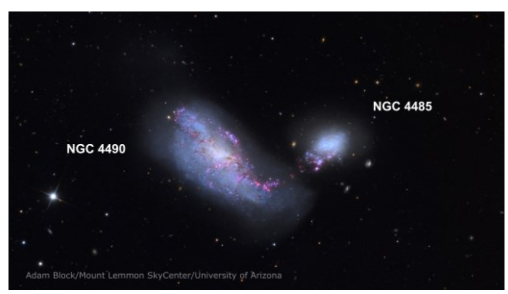
NGC 2787 – 24 mly

Tightly wound, almost concentric, arms of dark dust encircle the bright nucleus of galaxy NGC 2787. This lens-shaped galaxy shows little or no evidence of any grand spiral arms. Also visible in the image are about a dozen globular clusters hovering around the galaxy. What appear to be stars are, in fact, gravitationally bound families of 100,000's of ancient stars orbiting the center of NGC 2787.

NGC 4485 – 25 mly

The irregular galaxy NGC 4485 shows all the signs of having been involved in a collision with another galaxy. The right side of the galaxy is ablaze with star formation, shown in the large number of young blue and pinkish star berth nebulas. The left side, however, looks intact. It contains hints of the galaxy's previous spiral structure, which, at one time, was undergoing normal galactic evolution.

Here's the other colliding galaxy NGC 4490. The two galaxies sideswiped each other millions of years ago and are now 24,000 light-years apart. The gravitational tug-of-war between them created rippling patches of higher-density gas and dust within both galaxies.



<u>Pinwheel Galaxy M101 – 25 mly</u>

Here we are zooming into the Pinwheel galaxy, M101. This is the largest and most detailed photo of a spiral galaxy that has ever been released from Hubble. The galaxy's portrait is actually composed of 51 individual Hubble exposures, in addition to elements from images from ground-based photos. The giant spiral disk of stars, dust, and gas is 170,000 light-years across or nearly twice the diameter of our galaxy. M101 is estimated to contain at least one trillion stars. Approximately 100 billion of these stars could be like our Sun in terms of temperature and lifetime.

Sombrero Galaxy M104 – 28mly

This is the Sombrero galaxy. The galaxy's hallmark is a brilliant white, bulbous core encircled by the thick dust lanes comprising the spiral structure of the galaxy. It is 50,000 light-years across. M104's rich halo system of nearly 2,000 globular clusters is 10 times as many as orbit our Milky Way galaxy. Embedded in the bright core of M104 is a smaller disk, which is tilted relative to the large disk. X-ray emission suggests that there is material falling into the compact core, where a 1-billion-solar-mass black hole resides.

Here's what it looks like in inferred from Spitzer.

NGC 1512 – 30mly

NGC 1512 is a barred spiral galaxy spanning 70,000 light-years. The galaxy's core is unique for its stunning 2,400 light-year-wide circle of infant star clusters, called a "circumnuclear" starburst ring.

In this view of the center of the magnificent barred spiral galaxy NGC 1512, Hubble's broad spectral vision reveals the galaxy at all wavelengths from ultraviolet to infrared. The colors (which indicate differences in light intensity) map where newly born star clusters exist in both "dusty" and "clean" regions of the galaxy.

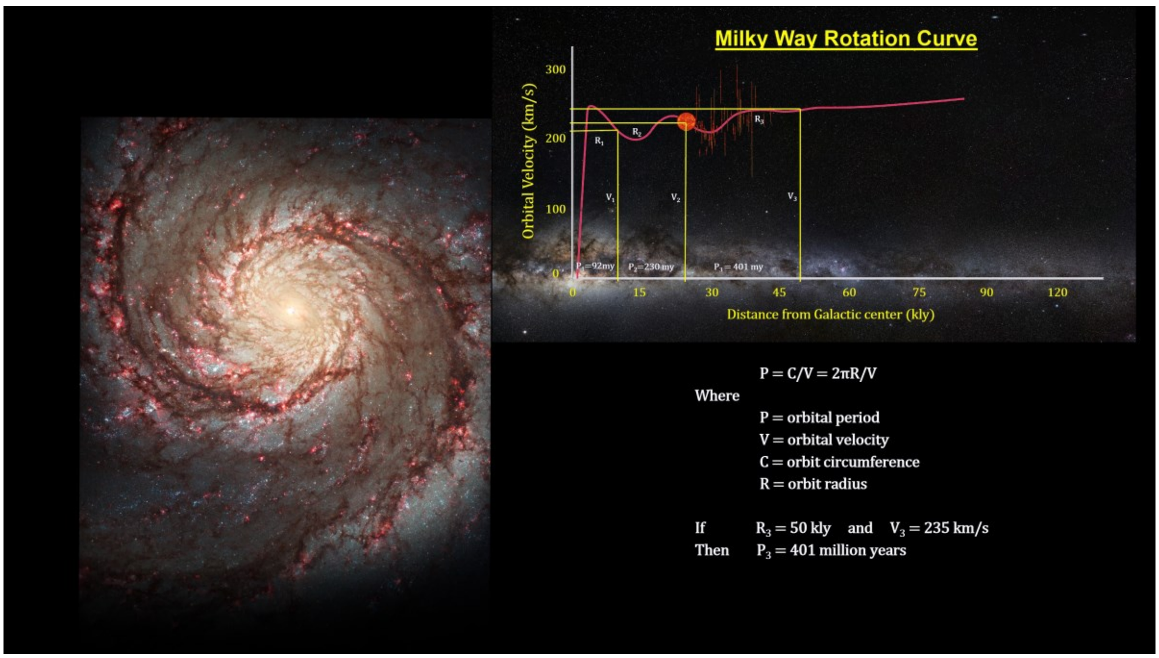
<u>Whirlpool Galaxy M51 – 31 mly</u>

[Music:** @17:14 Schubert: Impromptu in A-Flat; Pianist Evelyne Dubourg; from the album Meditation: Classical Relaxation, 2010**]

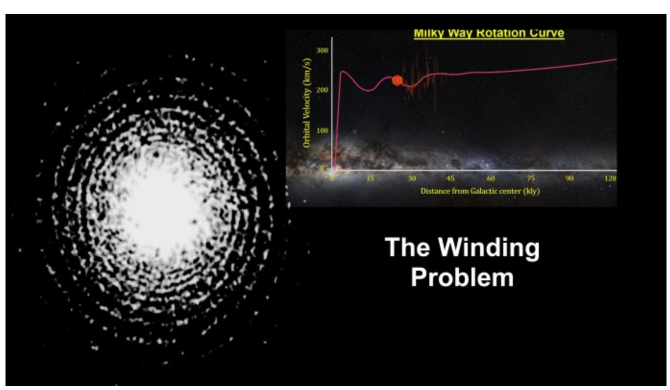
Here's a deep dive into the Whirlpool galaxy, M51. These images of the Whirlpool galaxy highlight the attributes of a typical spiral galaxy, including graceful, curving arms, pink star-forming regions, and brilliant blue strands of star clusters.

Spiral Arms – Density Waves

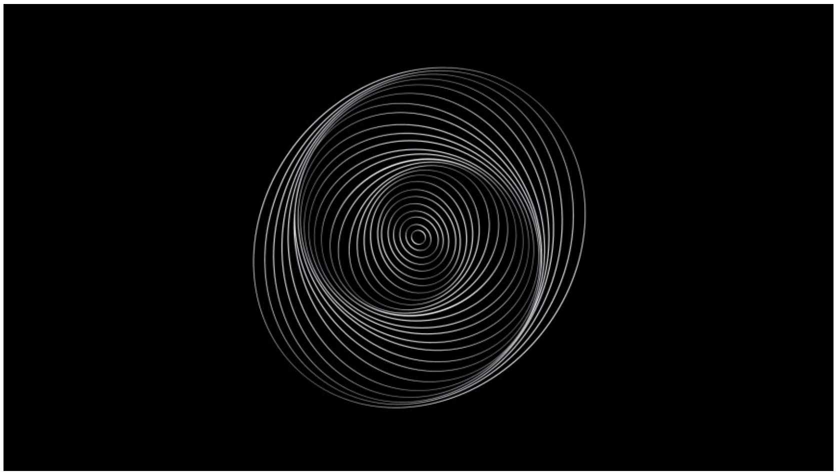
In the early days, when knowledge of spiral arms around galaxies was relatively new, astronomers thought that they were made of material and orbited the center of their galaxy just like stars, dust and gas. Our whirlpool galaxy is a good model for this. But as star motion within galaxies became better understood, we found that the stars nearer the center have a much shorter orbital period than the stars further way from the center. For example, in our Milky Way, stars near the central bulge can complete a revolution around the central bulge in around 90 million years. Out here 26,000 ly away it takes 230 million years. And in the outskirts, it can take over 400 million years.



It followed that if the spiral arms were rotating with the stars, its structure would be lost in just a few rotations. You can see in this simulation that even after just one rotation, the arms would change significantly with the inner galaxy areas being stretched more than the outer galaxy areas. In astronomical terms, we would see spiral arm structure disappear in short order. But, from all we see from spiral galaxies of all ages, the spiral arm structure does persist over billions of years. This disconnect is called the 'Winding Problem". Clearly, the spiral arms do not rotate with the stars, dust and gas.

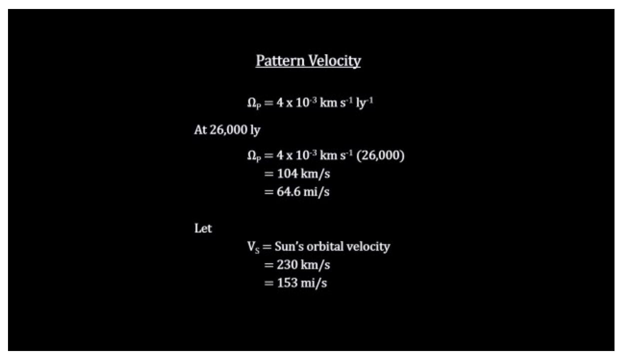


The density wave theory was proposed by C.C. Lin and Frank Shu in the mid-1960s to explain the spiral arm structure of spiral galaxies. The theory holds that spiral arms are not material in nature, but instead made up of areas of greater density. The stars, gas and dust in a galaxy move around the center in elliptical orbits. If we simply assume that an orbit's major axis shifts slightly as the distance from the center goes up, we can reconstruct the spiral arms as we see them in real galaxies.

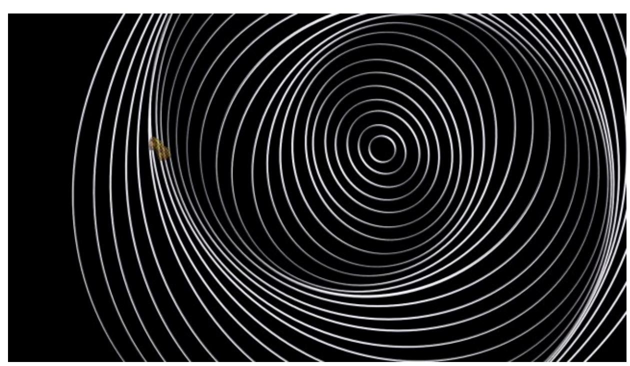


Lin and Shu, examining magnetic fields, gas distributions and star velocities, showed that this kind of grand design spiral pattern could persist indefinitely if the pattern also rotated, but with the outer portion of the arms rotating faster than the inner portions.

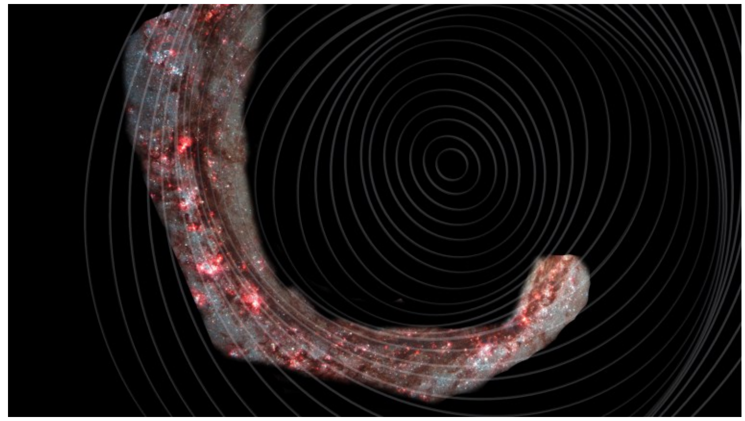
By their calculations, a typical pattern velocity is around .004 km s^{-1} ly^{-1}. That is the velocity of the pattern goes up .004 km/s for each ly the pattern location is from the center. For our star 26,000 ly from the center of the Milky Way, we have a pattern velocity for the Orion Spur at around a hundred km/s or 65 mi/s. Our velocity around the center is more than twice that much. I expect we'll be leaving the Orion spur in a few million years.



Here's a look at a gas cloud orbiting around the galaxy in the spiral patten's frame of reference. As it approaches a spiral arm, it gets compressed as the orbiting molecules within the cloud move closer to each other. This compression effect is thought to trigger cloud collapse. This in turn creates new stars. The most massive blue stars don't burn long enough to make it through the spiral arm before they run out of hydrogen fuel and supernova.



That explains why we only see these giant blue stars in the trailing edge of spiral arms. Normal yellow and lower mass red stars exist for much longer and exit the spiral arm and orbit the galaxy for billions of years. It's important to note that just how these spiral arm structures form in the first place is still unknown.



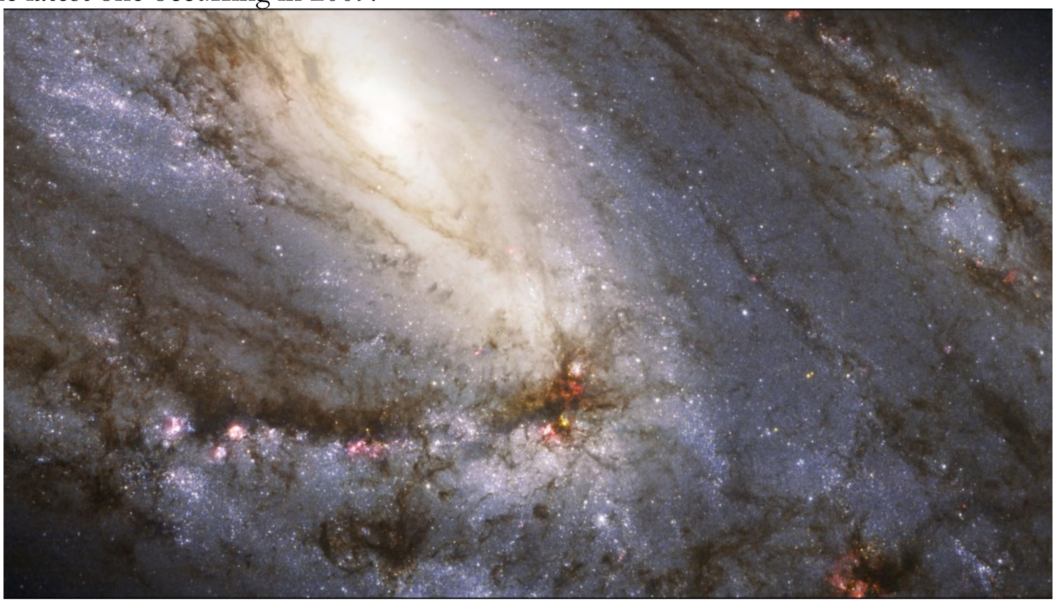
M74 – 32 mly

[Music:** @22:51 Tchaikovsky: Suite No. 1 - Intermezzo; from the album Meditation: Classical Relaxation, 2010**]

Here we are zooming into Messier 74, a stunning example of a "grand-design" spiral galaxy that is viewed by Earth observers nearly face-on. Its perfectly symmetrical spiral arms emanate from the central nucleus and are dotted with clusters of young blue stars and glowing pink H II regions of ionized hydrogen Tracing along the spiral arms are winding dust lanes that also begin very near the galaxy's nucleus and follow along the length of the spiral arms.

M66 – 35 mly

Here's a deep look into M 66, the owner of unusually asymmetric spiral arms which seem to climb above the galaxy's main disc and a displaced nucleus. Astronomers believe that M66's once orderly shape has most likely been distorted by the gravitational pull of its two neighbors. M66 boasts a remarkable record of supernovae explosions. The spiral galaxy has hosted three supernovae since 1989, the latest one occurring in 2009.

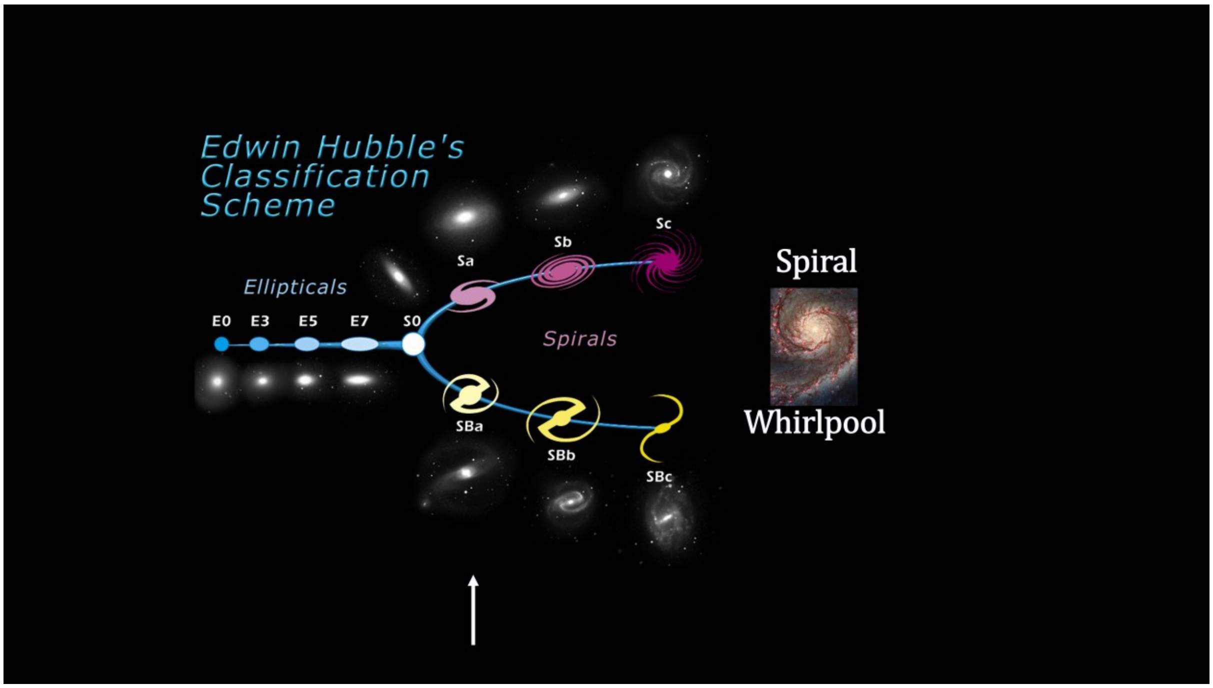


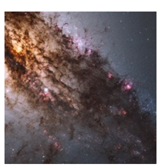
M96 – 35 mly

M96's core is also displaced from the galactic center. Its gas and dust are distributed asymmetrically and its spiral arms are ill-defined. But this portrait, taken with the ESO's Very Large Telescope, shows that imperfection can be beautiful. The galaxy's core is compact but glowing, and the dark dust lanes around it move in a delicate swirl towards the nucleus. And the spiral arms, patchy rings of young blue stars, are like necklaces of blue pearls. Its graceful imperfections likely result from the gravitational pull from nearby galaxies. spans some 100,000 light-years in diameter — about the size of our Milky Way.

Galaxy Classifications

In 1926, there were enough galaxies known for Edwin Hubble to create a morphological classification scheme. This is his diagram. His students called it the "Hubble tuning-fork". The scheme divides galaxies into 3 broad classes based on their visual appearance.





Elliptical galaxies have smooth, featureless light distributions and appear as ellipses in images like Centaurus A. They are denoted by the letter E, followed by an integer n representing their degree of ellipticity on the sky.

Spiral galaxies consist of a flattened disk, with stars forming a spiral structure, and a central concentration of stars known as the bulge like the Whirlpool galaxy. They are given the symbol S or SB if it has a bar core followed by a letter a through c. The spiral arm structure becomes more open from a to c; the amount of dust and young stars decreases from a to c; and the central bulge of the galaxy decreases in size relative to the disc size from a to c.

Lenticular galaxies also consist of a bright central bulge surrounded by an extended, disk-like structure but, unlike spiral galaxies, the disks of lenticular galaxies have no visible spiral structure and are not actively forming stars in any significant quantity. NGC 2787 is an example of these. They are designated S0.

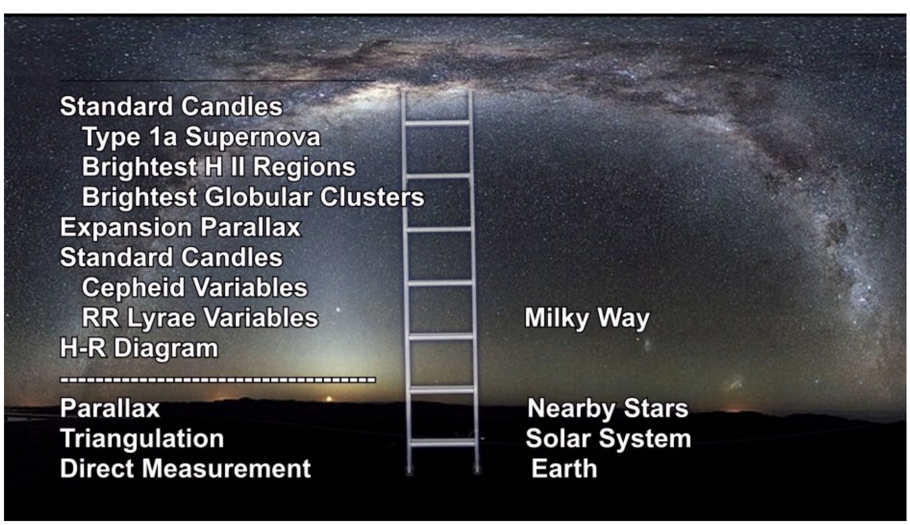
These broad classes can be extended to enable finer distinctions of appearance and to encompass other types of galaxies, such as **irregular galaxies**, which have no obvious regular structure (either disk-like or ellipsoidal). The Large Magellanic Cloud is an excellent example of this.

Since then, others have added characteristics such as Bars, Rings, and Spiral arm characteristics.

Distance Ladder

[Additional info: We've seen a wide variety of shapes and sizes as we toured the Local Volume of stars studied by the Spitzer LVL team. In each galaxy, it was not to hard to find at least one Cepheid Variable, RR Lyrae Variable, Type 1a Supernova, Bright HII and/or Globular cluster. Star spectra and the H-R diagram were also useful for red supergiants which are abundant in many of these galaxies. These were used to calculate galaxy distances.**]**

We lost parallax when we went beyond the nearby stars. But, so far, the rest of our distance ladder has taken us through the local group and the local volume. But at the outer reaches, RR Lyrae variables leave our list. They are just not bright enough to be seen well beyond 20 million light years. But Cepheids, H II Regions, Globular Clusters, and Type 1a Supernova are still going strong. They will take us well into the Virgo Supercluster, our next segment.



The Virgo Supercluster

*{**Abstract** – In this segment of our "How far away is it" video book, we cover our local supercluster, the Virgo Supercluster.*

We begin with a description of the size, content and structure of the supercluster, including the formation of galaxy clusters and galaxy clouds. We then take a look at some of the galaxies in the Virgo Supercluster including: NGC 4314 with its ring in the core, NGC 5866, I Zwicky 18, the beautiful NGC 2841, NGC 3079 with is central gaseous bubble, M60, M100, M77 with its central supermassive black hole, NGC 3949, NGC 3310, NGC 4013, the unusual NGC 4522, NGC 4710 with its "X"-shaped bulge, NGC 1052, Hanny's Voorwerp, *NGC 3256 and NGC 4414. Then we continue with galaxy gazing with: NGC 1427A, NGC 3982, NGC 1300, NGC 5584, the dusty NGC 1316, NGC 4639, NGC 4319, NGC 3021 with is large number of Cepheid variables, NGC 3370, NGC 1309, and 7049.*

*At this point, we have enough distant galaxies to formulate Hubble's Law and calculate Hubble's Red Shift constant. From a distance ladder point of view, once we have the Hubble constant, and we can measure red shift, we can calculate distance. So, we add Red Shift to our ladder. We end with a review of the distance ladder now that Red Shift has been added.**}***

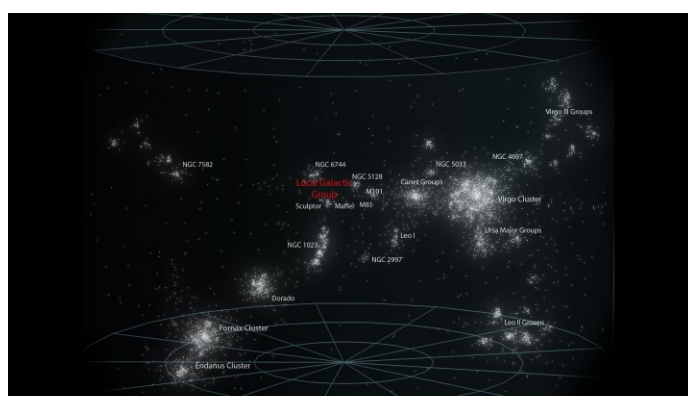
Introduction

> **[Music:** *Antonio Vivaldi: Four Seasons - Winter Concerto in F Minor – Largo; from the album The Most Relaxing Classical Music, 1997***]**

Superclusters are among the largest structures in the known Universe. The Virgo Supercluster, also known as the Local Supercluster, is 110 million light-years diameter. It contains 4,000 luminous galaxies, organized into 100 galaxy groups and galaxy clusters. The Virgo Supercluster's volume is approximately 7,000 times larger than our Local Group and 100 billion times larger than the Milky Way.

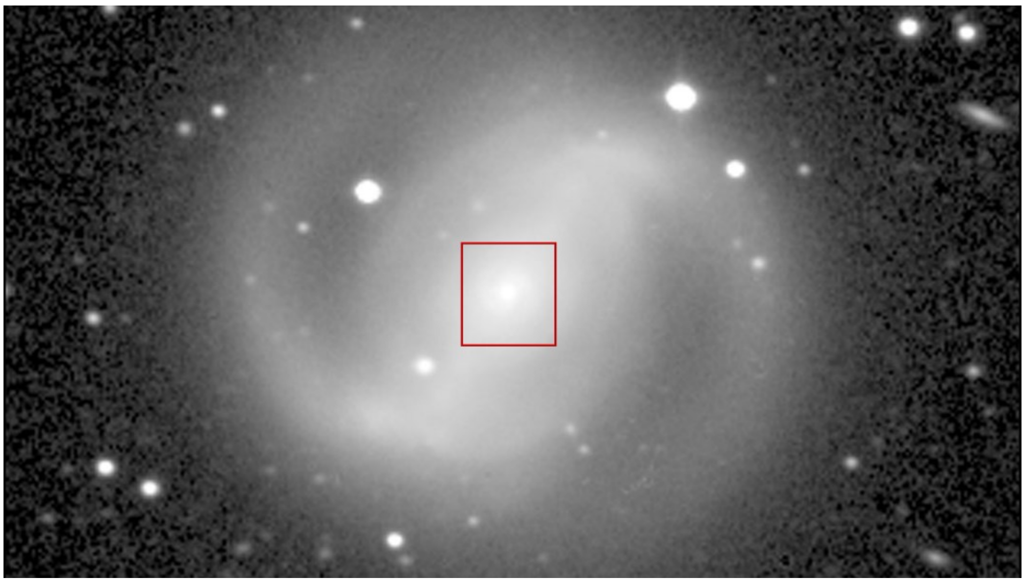
For the first time, we are at a distance where we can see that galaxies are not just evenly distributed throughout space.

In this picture, each galaxy is a point of light. And these points are crowded together into galaxy clusters. And these clusters are crowded together into galaxy clouds. And these clouds of galaxy clusters are grouped up into the supercluster. Let's take a look at some of the galaxies in the Virgo Supercluster.



NGC 4314 – 30 mly - 672 km/s

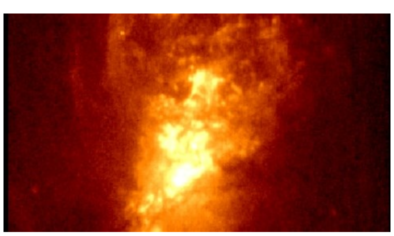
This ground-based image of the barred-spiral galaxy NGC 4314 was taken by the McDonald Observatory in Texas. It shows the entire galaxy, including the bar of stars bisecting the core and the outer spiral arms, which begin near the ends of this bar. That's normal enough.



But this Hubble image reveals clusters of infant stars that formed in a ring around the core. This close-up view by Hubble also shows other interesting details in the galaxy's core: dust lanes, a smaller bar of stars, dust and gas embedded in the stellar ring, and an extra pair of spiral arms packed with young stars. These details make the center resemble a miniature version of a spiral galaxy.

M77, NGC 1068 – 35 mly - 784 km/s

Messier 77 is a spiral galaxy containing a supermassive black hole. The X-ray images and spectra obtained using Chandra's Spectrometer show that a strong wind is being driven away from the center of the galaxy at a rate of about 1.6 million km/hr that's a million miles per hour. This wind is likely generated as surrounding gas is accelerated and heated as it swirls toward the black hole. A portion of the gas is pulled into the black hole, but some of it is blown away.



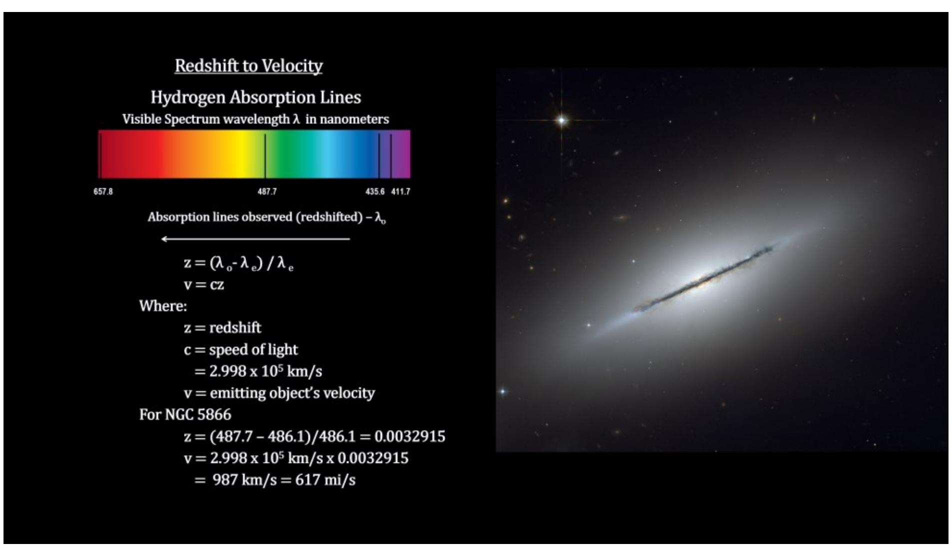
High energy X-rays produced by the gas near the black hole heat the ouflowing gas, causing it to glow at lower X-ray energies. These results help explain how an "average"-sized supermassive black hole can alter the evolution of its entire host galaxy.

Music: *Saint-Saëns: "The Carnival of the Animals - The Swan"; from the album he "Most Relaxing Classical Music" 1997*]

<u>NGC 5866 – 45 mly – 987 km/s</u>

This is a unique view of a galaxy tilted nearly edge-on to our line-of-sight. The image highlights the galaxy's structure: a subtle, reddish bulge surrounding a bright nucleus, a blue disk of stars running parallel to the dust lane, and a transparent outer halo. The dust lane is slightly warped compared to the disk of starlight. This warp indicates that NGC 5866 may have undergone a gravitational tidal disturbance in the distant past, by a close encounter with another galaxy.

We'll use this galaxy along with several others in the Virgo Supercluster to develop our final Cosmic Distance Ladder rung – Redshift. You may recall that we covered redshift in our segment on Planetary Nebula where we used the shift in hydrogen spectral lines to determine the radial velocity of a celestial object. NGC 5866's redshift [0.0032915] indicates that it is moving away from us at just under 1,000 km/s (that's 617 miles/s).



M100 – 50 mly – 1120 km/s

This is a 1993 image of the grand-design spiral galaxy M100 taken with Hubble's Wide Field/Planetary Camera 1, which was part of an original suite of instruments launched aboard Hubble in 1990. Because of a manufacturing flaw, the galaxy appears blurred because it cannot be brought into a single focus.

In celebration of the 25th anniversary of the first astronaut mission to service the Hubble Space Telescope in orbit, a comparison photo made by Hubble's Wide Field Camera 3 was released. The improvement was both critically important for Hubble’s science mission, it made for significantly better pictures.

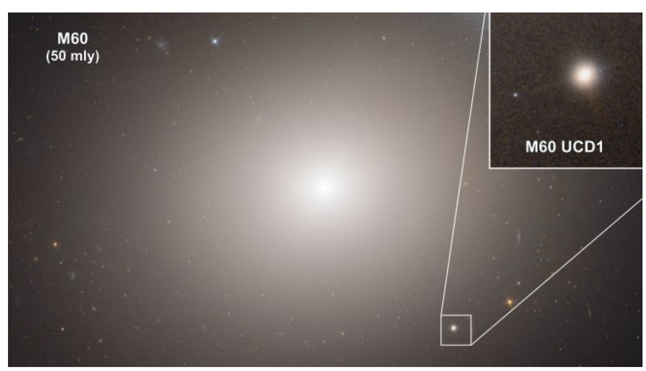
NGC 3949 – 50 mly – 1120 km/s

One of the ways we construct the form of our home Milky Way galaxy is to examine galaxies that are similar in shape and structure. Spiral galaxies like NGC 3949, pictured in this Hubble image, fit the bill. Like our Milky Way, this galaxy has a blue disk of young stars peppered with bright pink star-birth regions. In contrast to the blue disk, the bright central bulge is made up of mostly older, redder stars.

M60-UCD1 50 mly

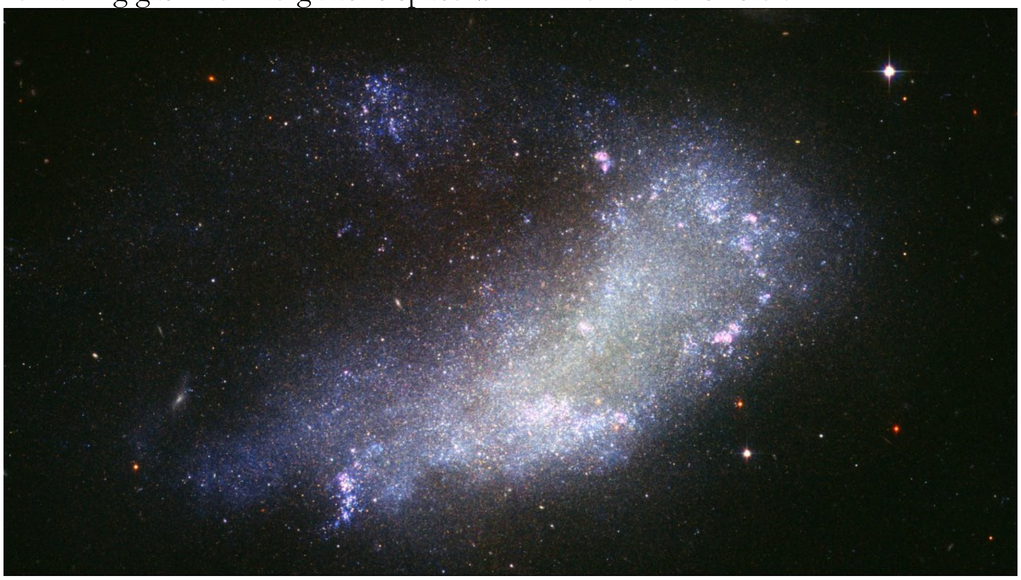
Here's a look at a pair of galaxies: NGC 4647 is the spiral galaxy in the upper right; M60 is the large elliptical galaxy. On the edge of M60, there is an Ultra-Compact galaxy known as M60-UCD1.

New Hubble observations have found a supermassive black hole with the mass of 20 million Suns at its center, making this tiny galaxy the smallest ever found to host such a black hole. M60-UCD1 is a tiny galaxy with a diameter of 300 light-years, containing some 140 million stars. This is 500 times smaller than the Milky Way, but its supermassive black hole is 5 times more massive than ours. This shows just how significant this black hole is and it leaves open the question about just how a black hole this large could have been created in the first place, given the small number of stars in its galaxy.



NGC 1427A – 50 mly

NGC 1427A is a bright dwarf irregular galaxy on the outskirts of the Fornax cluster. It is similar to the Large Magellanic Cloud orbiting our Milky Way. It is plunging headlong into the cluster at nearly 600 km/s (that's nearly 400 miles per second). 1427A will not survive long as an identif1able galaxy passing through the cluster. Within the next billion years, it will be completely disrupted, spilling its stars and remaining gas into intergalactic space within the Fornax cluster.



NGC 3310 – 55 mly

Most galaxies form new stars at a fairly slow rate, but members of a rare class known as "starburst" galaxies blaze with extremely active star formation. The galaxy NGC 3310 is forming clusters of new stars at a prodigious rate. There are several hundred star clusters visible in this image as the bright blue diffuse objects that trace the galaxy's spiral arms. Each of these star clusters represents the formation of up to about a million stars.

NGC 4013 – 60 mly

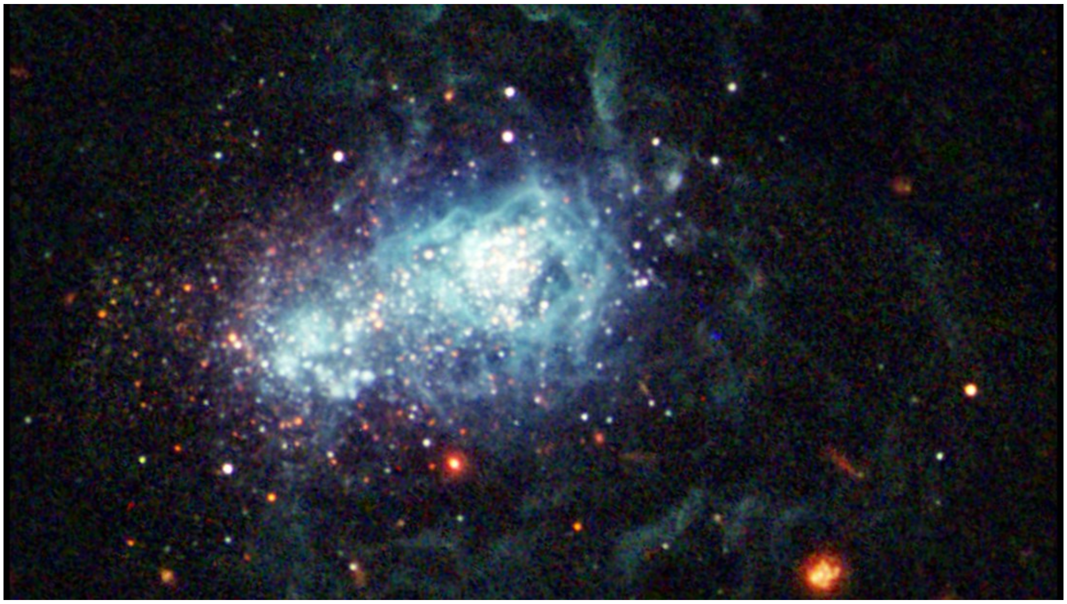
[Music: *Mascagni: "Intermezzo"; Philharmonia Orchestra - from the album "The Most Relaxing Classical Music" 1988***]**

NGC 4013 is a spiral galaxy, similar to our own Milky Way. This Hubble picture reveals, with exquisite detail, huge clouds of dust and gas extending along, as well as far above, the galaxy's main disk. Viewed pole-on, it would look like a nearly circular pinwheel. Even at 55 million light-years, the galaxy is larger than Hubble's field of view, and the image shows only a little more than half of the object.

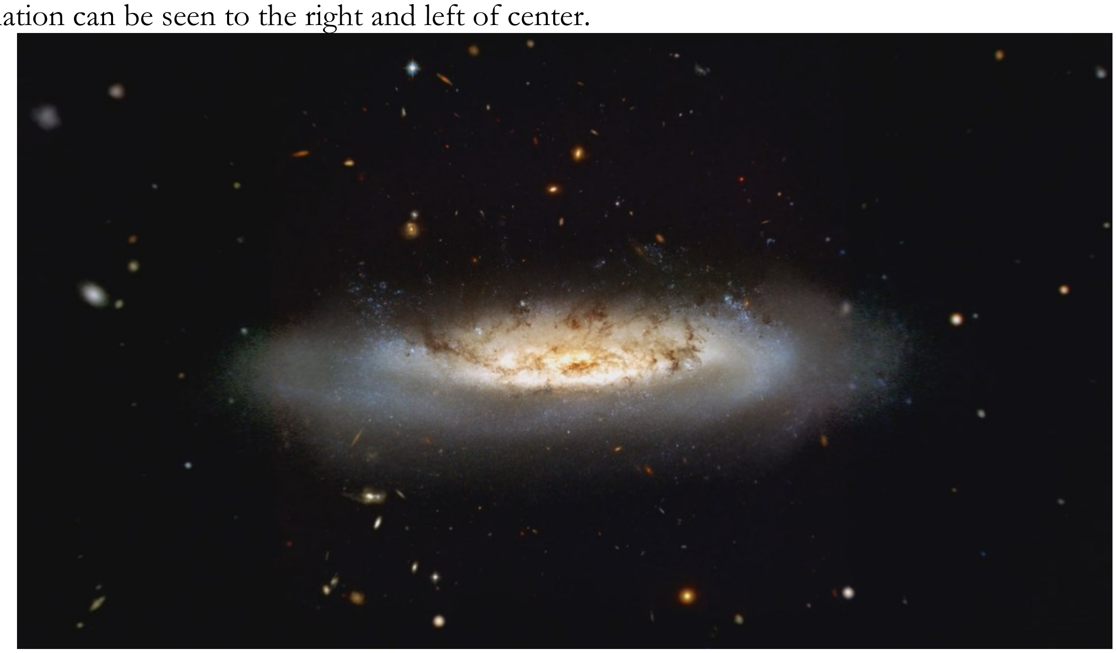
[Additional info: When light passes through a volume containing small particles, it becomes fainter and redder. By studying the color and the amount of light absorbed by these distant clouds in NGC 4013, astronomers can estimate the amount of matter in them. Individual clouds contain as much as one million times the amount of mass in our Sun.**]**

I Zwicky 18 – 60 mly

I Zwicky 18 is classified as a dwarf irregular galaxy and is much smaller than our Milky Way. The concentrated bluish-white knots embedded in the heart of the galaxy are two major starburst regions where stars are forming at a significant rate. The wispy blue filaments surrounding the central starburst regions are bubbles of gas that have been blown away by stellar winds and supernovae explosions from a previous generation of stars. This gas is now heated by intense ultraviolet radiation from hot, young stars. Besides the bluish-white young stars, white-reddish stars also are visible. These stars are thought to be around 10 billion years old.

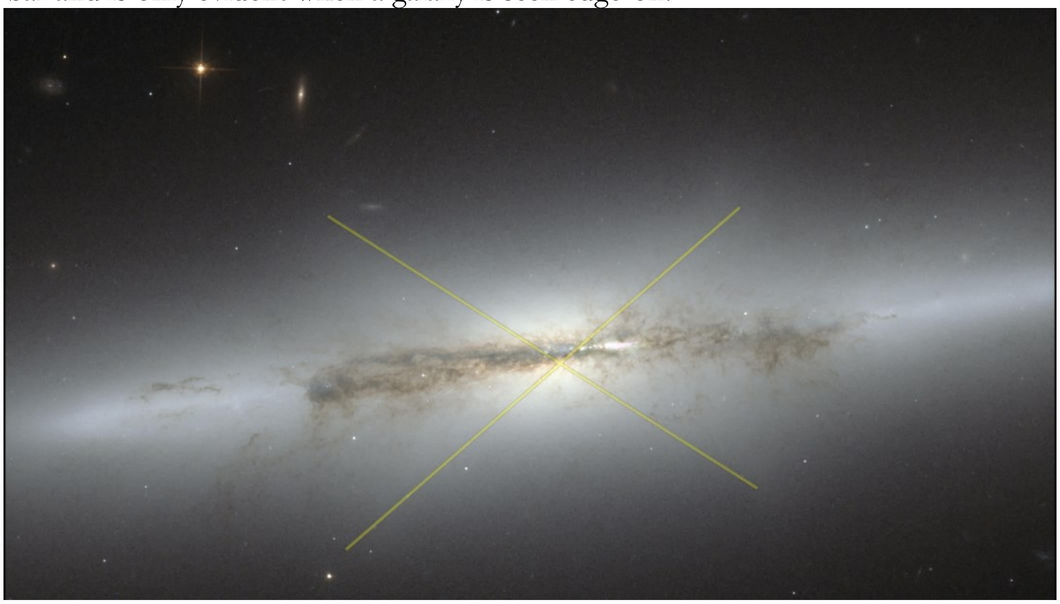


NGC 4522 – 60 mly – 1336 km/s
NGC 4522 is a spectacular example of a spiral galaxy that is currently being stripped of its gas content by its strong central winds. Scientists estimate that the galaxy is moving at more than 6 million miles per hour. A number of newly formed star clusters that developed in the stripped gas can be seen in the Hubble image. The picture highlights the dramatic state of the galaxy with an especially vivid view of the ghostly gas being forced out of its center. Bright blue pockets of new star formation can be seen to the right and left of center.



NGC 4710 – 60 mly

Here we are zooming into NGC 4710 in the Virgo Cluster. This magnificent giant galaxy is tilted nearly edge-on to our view from Earth. This perspective allows astronomers to easily distinguish the central bulge of stars from its pancake-flat disk of stars, dust, and gas. When staring directly at the center of the galaxy, one can detect a faint, ethereal "X"-shaped structure. Such a feature, which astronomers call a "boxy" or "peanut-shaped" bulge, is due to the vertical motions of the stars in the galaxy's bar and is only evident when a galaxy is seen edge-on.



NGC 1316 – 60 mly

NGC 1316 is one of the brightest ellipticals in the Fornax galaxy cluster. The Hubble Space Telescope enabled uniquely accurate measurements of a class of red star clusters inside the galaxy. Astronomers conclude that these star clusters constitute clear evidence of the occurrence of a major collision of two spiral galaxies that merged together a few billion years ago to shape NGC 1316 as it appears today.

NGC 4414 – 62 mly

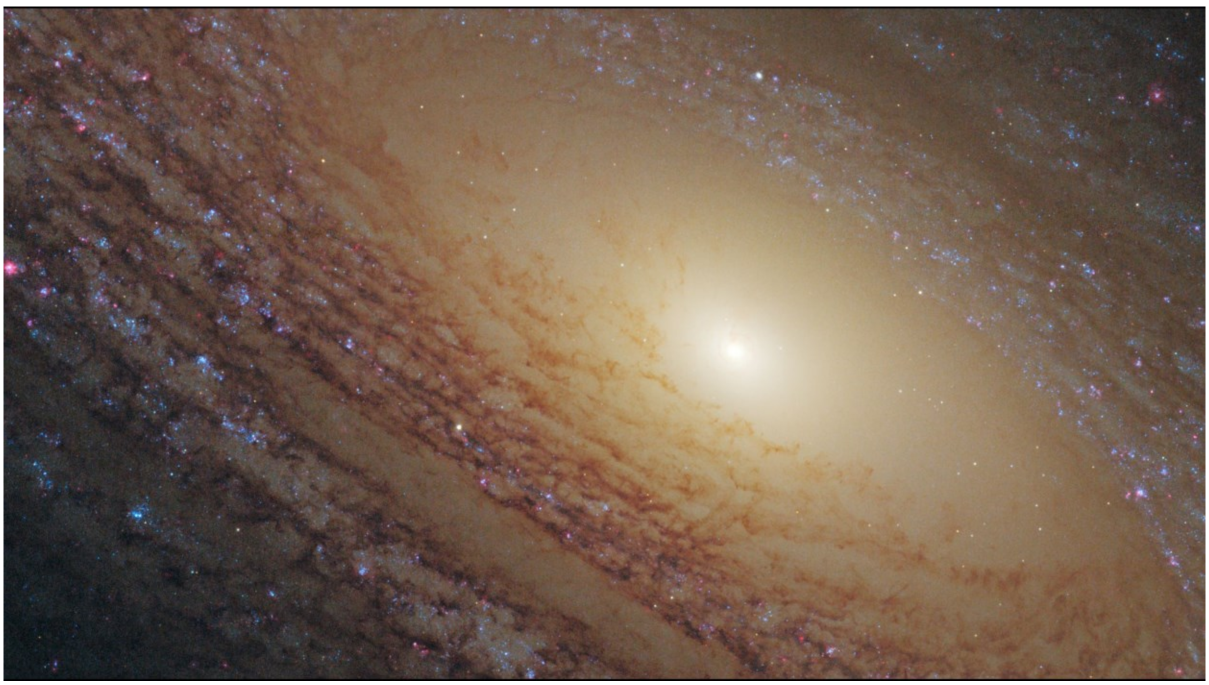
In 1995, the majestic spiral galaxy NGC 4414 was imaged by the Hubble as part of the Key Project on Extragalactic Distance Scales. An international team observed this galaxy on 13 different occasions over the course of two months. Based on their discovery and careful brightness measurements of Cepheid variable stars in NGC 4414, the Key Project astronomers were able to make an accurate determination of the distance to the galaxy - 62 million light-years.

NGC 1300 – 62 mly

The Hubble telescope captured a display of starlight, glowing gas, and silhouetted dark clouds of interstellar dust in this image of the barred spiral galaxy NGC 1300 - a prototypical barred spiral galaxy. Blue and red supergiant stars, star clusters, and star-forming regions are well resolved across the spiral arms, and dust lanes trace out fine structures in the disk and bar.

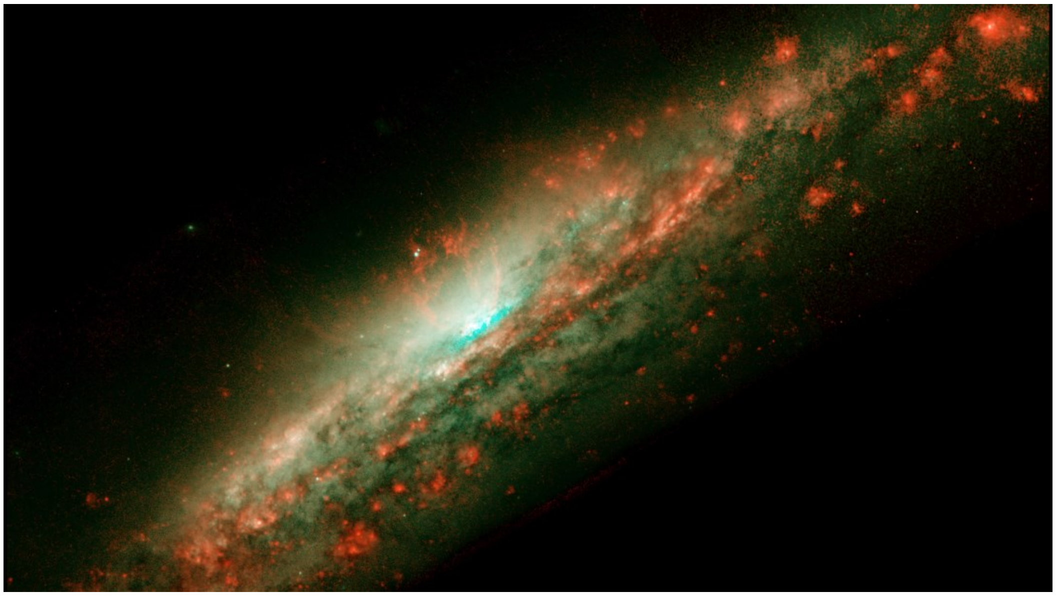
NGC 2841 – 65 mly

Hubble reveals a majestic disk of stars and dust lanes in this view of the spiral galaxy NGC 2841. A bright cusp of starlight marks the galaxy's center. Spiraling outward are dust lanes that are silhouetted against the population of whitish middle-aged stars. Much younger blue stars trace the spiral arms. Notably missing are pinkish emission nebulae indicative of new star birth. It is likely that the radiation and supersonic winds from fiery, super-hot, young blue stars cleared out the remaining gas, and hence shut down further star formation in the regions in which they were born.

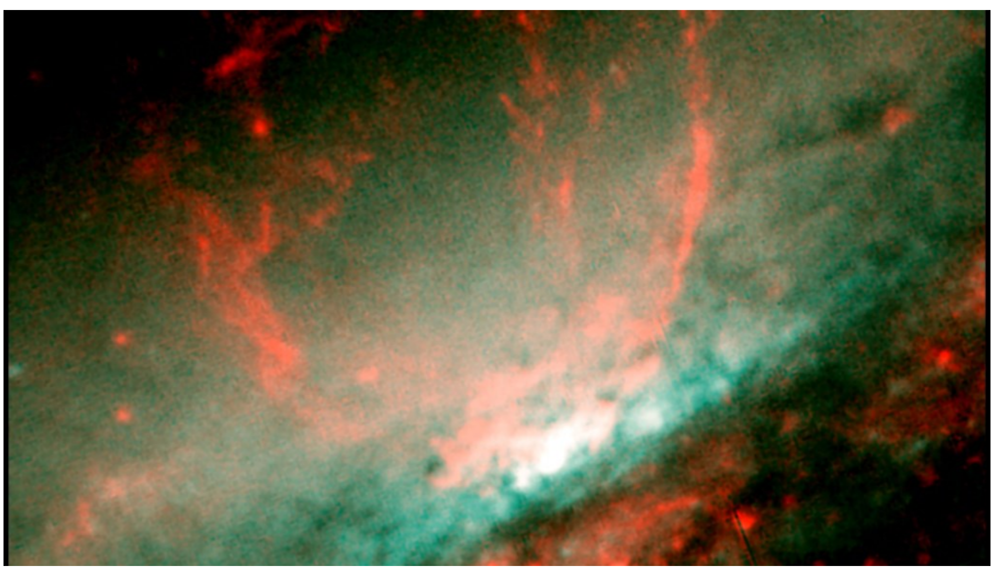


NGC 3079 – 65 mly

This picture shows a bubble in the center of the galaxy's disk. The structure is more than 3,000 light-years wide and raises 3,500 light-years above the galaxy's disk.



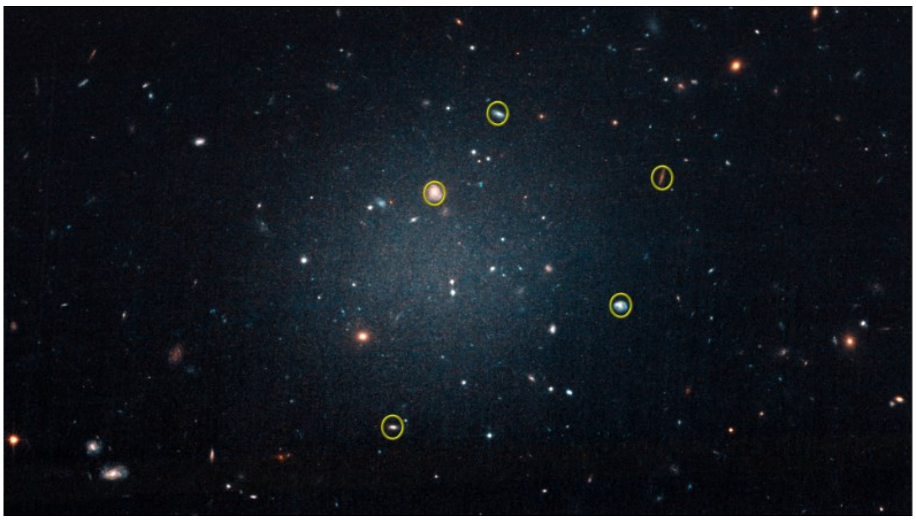
This is a close-up view of the bubble. Gaseous filaments at the top of the bubble are whirling around in a vortex and are being expelled into space. Eventually, this gas will rain down upon the galaxy's disk where it may collide with gas clouds, compress them, and form a new generation of stars.



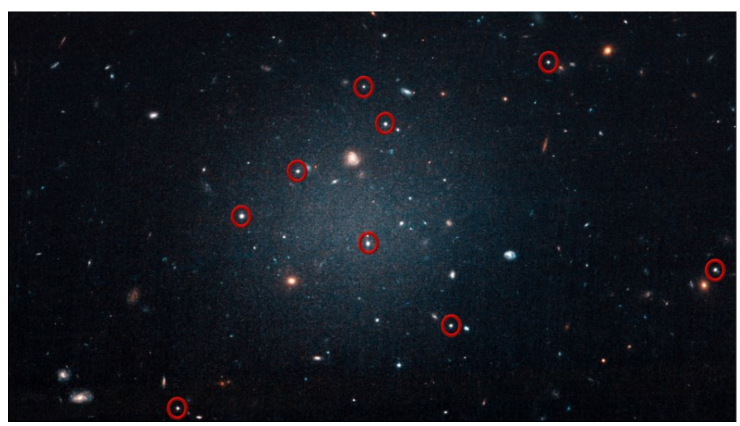
NGC 1052-DF2 – 65 mly

> [**Music:** *Puccini - Le Villi - Opera in 2 Acts _ Act 1 – Prelude; Radio-Symphonie-Orchester Berlin and Riccardo Chailly; from the album "Puccini Without Words" 2006*]

Here's a very interesting galaxy. It is as large as our Milky Way, but it contains only 1/200th the number of stars. Given the object's large size and faint appearance, astronomers classify it as an ultra-diffuse galaxy. Note the galaxies behind it and further away. This is literally a see-through galaxy.

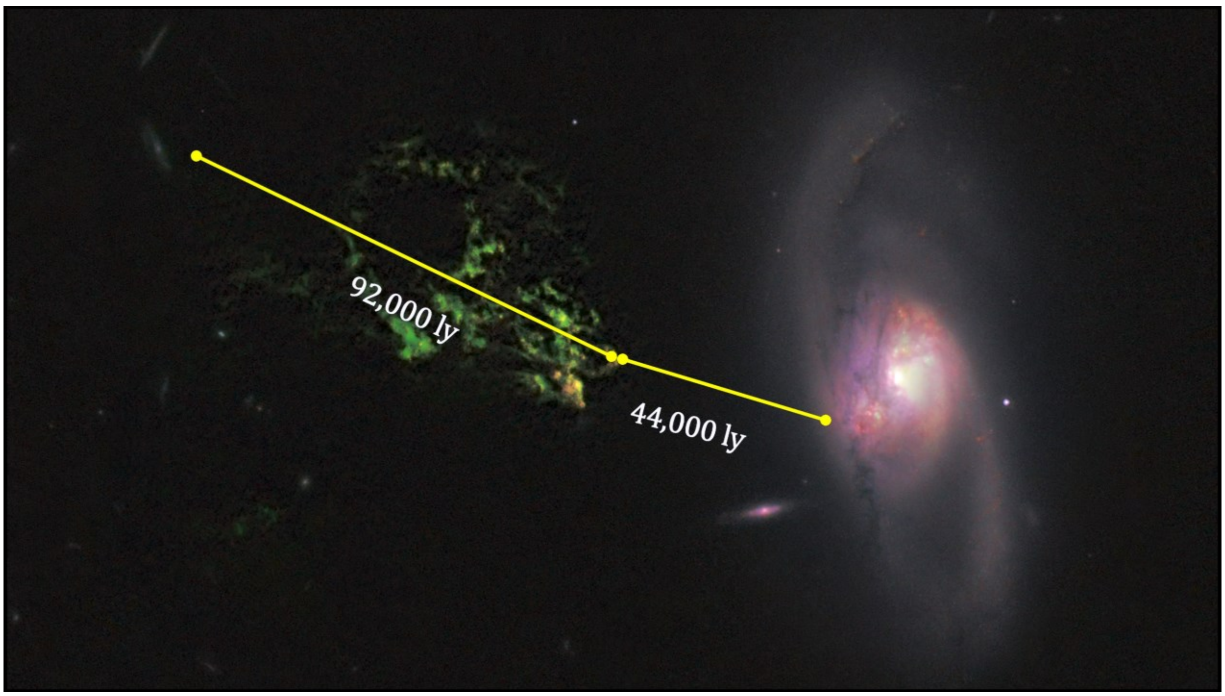


Current dark matter theory has it that galaxies form around dark matter. So, researchers were surprised when they discovered that this galaxy has hardly any dark matter at all. Measuring the motions of 10 giant globular clusters, astronomers found their velocities to be consistent with the estimated mass of the visible matter. There was no need to assume the presence of dark matter. Astronomers have competing theories about how this could happen. It goes to show you that we still have a lot to learn.

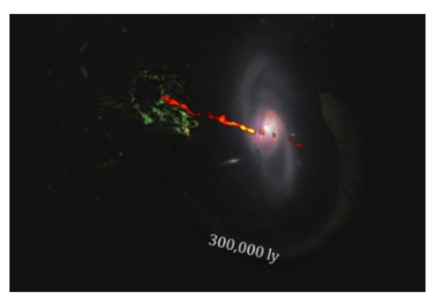


<u>Hanny's Voorwerp</u> – 64 mly

Hanny's Voorwerp is one of the strangest space objects ever seen. A mysterious, glowing green blob of gas is floating in space near a spiral galaxy (IC 2497). The object is so huge that it stretches from 44,000 light-years to 136,000 light-years from the galaxy's core.



It turns out that it's part of a 300,000 light-years long tidal tail that wraps around IC 2497. Our current understanding is that this part of the tail was illuminated by a high energy beam created by matter falling into the galaxy's central black hole. Their unmistakable emerald hue is caused by ionized oxygen, which glows green.



NGC 3982 – 70 mly

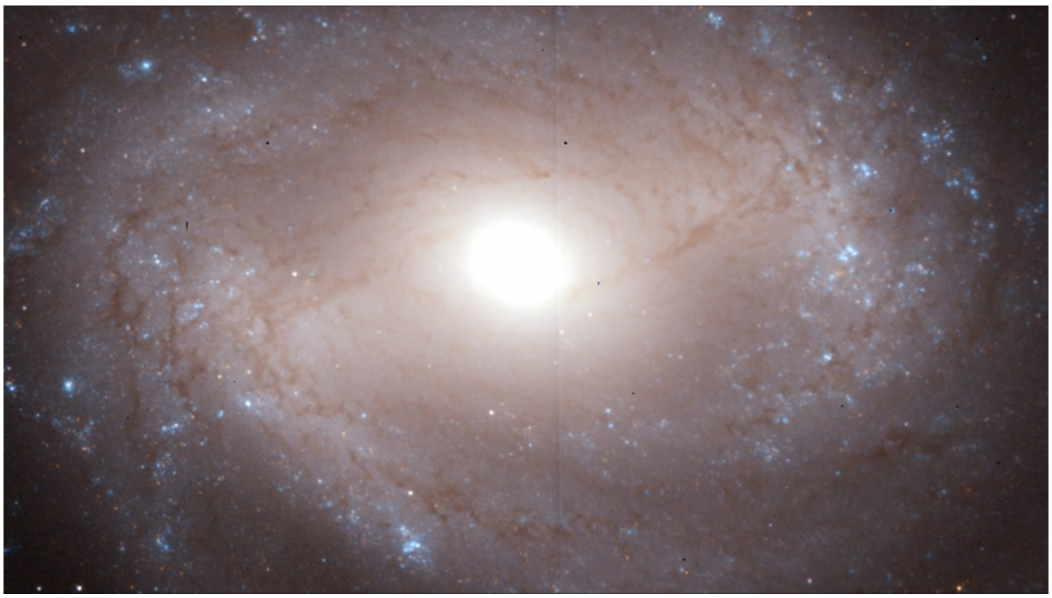
Though the universe is full of spiral galaxies, no two look exactly the same. NGC 3982 is striking for its rich tapestry of star birth, along with its winding arms. The arms are lined with pink star-forming regions of glowing hydrogen, newborn blue star clusters, and obscuring dust lanes that provide the raw material for future generations of stars.

NGC 5584 – 70 mly

NGC 5584 contains Cepheid variables and one recent Type 1a supernova. As you know, we use these two standard candles as reliable distance markers to measure the universe's expansion rate. NGC 5584 was one of the eight galaxies astronomers studied to measure this rate. In total, the project analyzed more than 600 Cepheid variables, including 250 in NGC 5584.

NGC 4639 – 75 mly **[Music:** Schubert - Andante con moto (from Symphony No. 8); from the album "Meditation: Classical Relaxation", 1991**]**

This Hubble image shows NGC 4639, a spiral galaxy located 78 million light-years away in the Virgo cluster of galaxies. The blue dots in the galaxy's outlying regions indicate the presence of young stars. Among them are older, bright Cepheids stars. After using Cepheids to calculate the distance to NGC 4639, the team compared the results to the peak brightness measurements of SN 1990N, a type 1a supernova located in the galaxy. Once again, Type 1a supernovae were found to be reliable standard candles.

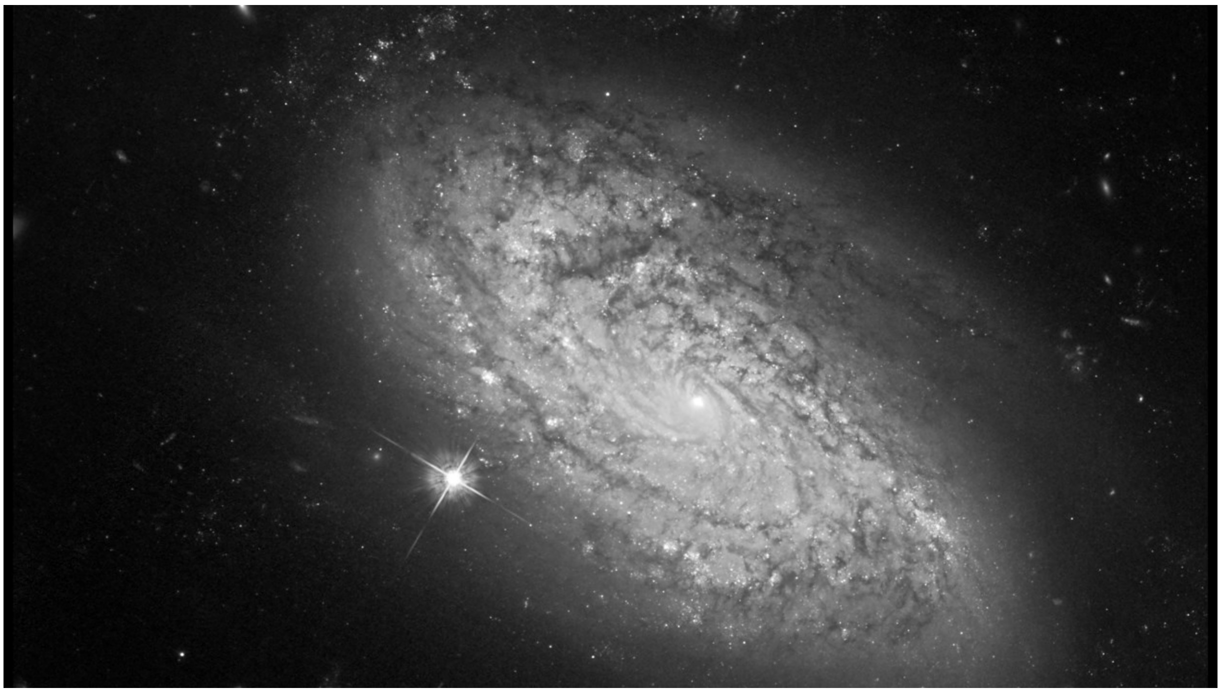


NGC 4319 – 80 mly

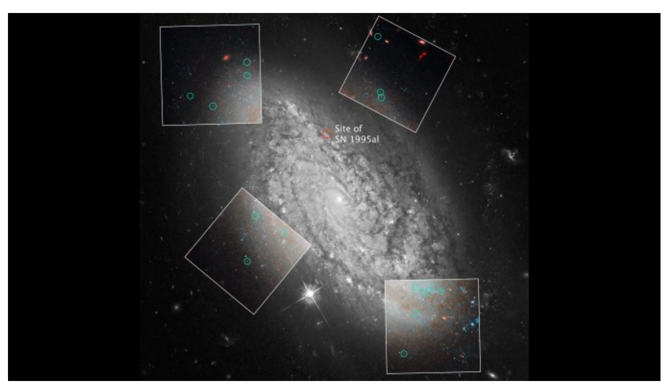
This Hubble image shows the inner region of NGC 4319. The unusually dark and misshapen dust lanes in the galaxy's inner region are evidence of a disturbance, probably caused by an earlier interaction with another galaxy.

NGC 3021 -90 mly

This galaxy was one of several hosts of recent type 1a supernovae observed by astronomers.



In the 1930s, Edwin Hubble made precise measurements of Cepheid variable stars in this galaxy, highlighted by green circles in the four inset boxes. These Cepheids are used to calibrate the supernova that was observed in the galaxy in 1995.



NGC 3370 – 90 mly

In 1994, NGC 3370 hosted a type 1a supernova designated SN 1994ae. This stellar outburst briefly outshone all of the tens of billions of other stars in its galaxy. Although supernovae are common, with one exploding every few seconds somewhere in the universe, this one was special. This supernova was one of the nearest and best observed supernovae since the advent of modern, digital detectors.

NGC 1309 – 100 mly

NGC 1309 is one of about 200 galaxies that make up the Eridanus galactic group. It was home to type 1a supernova SN 2002fk. Its light reached Earth in September 2002. It also contains a number of Cepheid variables resolved by the Hubble Space Telescope. And, once again, the type 1a was shown to be an excellent standard candle.

NGC 7049 – 100 mly

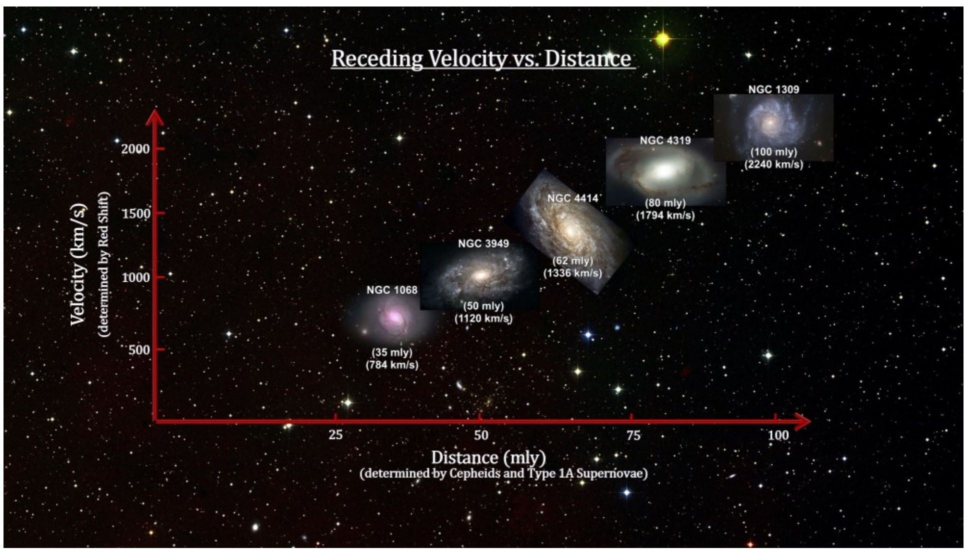
NGC 7049 is the brightest of a cluster of galaxies called Brightest Cluster Galaxies or BCG for short. Typical BCGs are some of the oldest and most massive galaxies. **[**The globular clusters in NGC 7049 are seen as the sprinkling of small faint points of light in the galaxy's halo.**]**

Hubble' Law

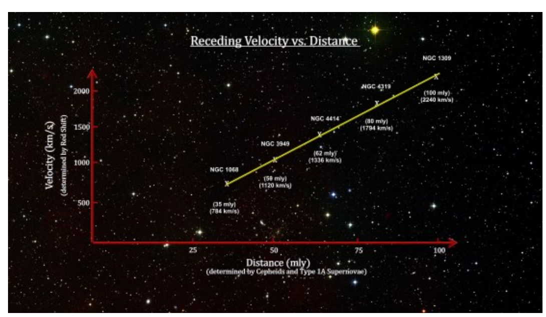
In 1923, after finding the V1 Cepheid variable in Andromeda, and determining that Andromeda was an entire galaxy over two million light years from our own, he turned his sights on other spiral and elliptical 'nebula' and found that they were galaxies as well. In his studies of these galaxies, he mapped their radial velocity as determined by the shift in spectral lines against their distance from us.

He found what we see here in the Virgo Supercluster.

- NGC 1068 is 35 mly away and receding at 784 km/s.
- NGC 3949 is 50 mly away and receding at 1120 km/s.
- NGC 4414, a galaxy studied by the Key Project on Extragalactic Distance Scales is 62 mly away and receding at 1336 km/s.
- NGC 4319, a galaxy with both Cepheid variables and Type 1a Supernova is 80 mly and receding at 1792 km/s.
- And NGC 1309, also a galaxy with both Cepheid variables and Type 1a Supernova is 100 mly away and receding at 2244 km/s.



He found that, except for a few near-by Local Group galaxies, all the spectra shifts were to the red. All the galaxies were moving away from us. And more than that, he found that the further away from us they are, the faster they are moving away from us. And even more than that, he found that the relationship between velocity and distance is linear – the graph is a straight line!



The equation is simple. The receding velocity of a galaxy is equal to the slope of the line (a constant) times the distance the galaxy is away from us. Today that constant is known as the Hubble Constant and the equation is known as Hubble's Law.

Hubble's Law

$v = H_0 d$

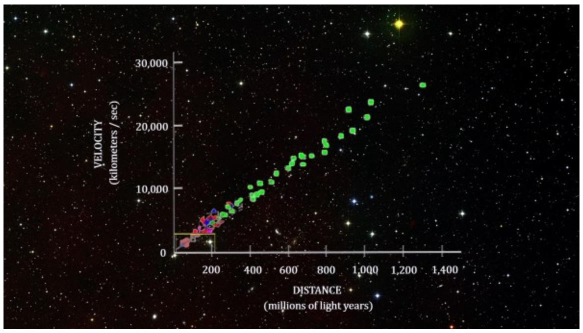
Where:

v = galaxy's velocity

d = distance to the galaxy

H_0 = The Hubble Constant

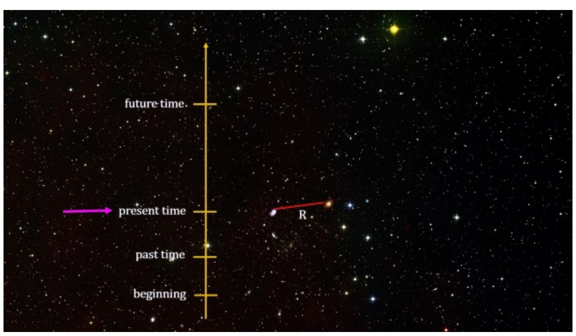
If we measure the redshift of a galaxy, we can determine its receding velocity, and knowing its receding velocity, this equation tells us how far away it is. This gives us a new rung on our cosmic distance ladder called 'Redshift'. The accuracy of this rung depends entirely on the value of the Hubble Constant. That's why it's one of the most studied numbers in astronomy and cosmology.

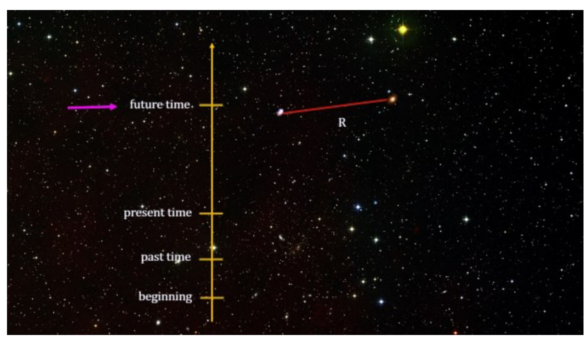


This constant has been refined over time, and the distances used to see how far it holds has increased by orders of magnitude with our modern ability to determine distances with space telescopes like Hubble analyzing Type 1a Supernova out to billions of light years. The box at the lower left shows the region that Hubble probed.

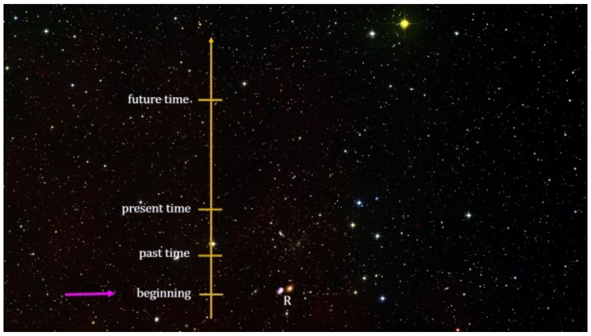
The current best value for the Hubble Constant using this approach is 22.4 km/s/mly plus or minus 3.2 (that's around 13 miles/sec per million-light-years) [70 km/s/MPc ± 10]. That is, the receding velocity of a galaxy goes up by 22.4 km/s for each additional million light years away from us it is.

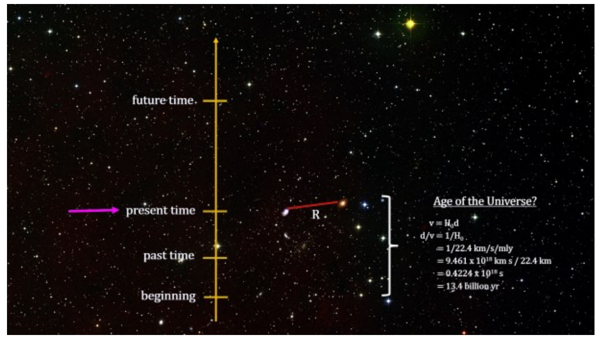
This slow and steady movement of galaxies away from us is called the Hubble Flow.





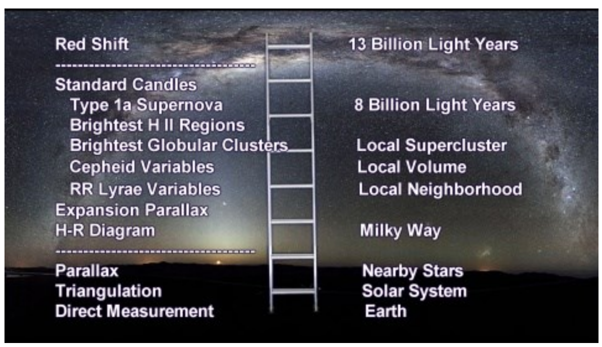
This Hubble Flow where galaxies are getting further away with time also implies that in the past, they were closer together. It follows that we can ask "How long would it take a galaxy to reach its current distance from us given its current velocity?" That's simply the distance divide by the velocity or one over the Hubble Constant – 13.4 billion years. That's the age of the Universe! We'll see later, in our chapter on the Cosmos, that the Hubble Constant turned out to not be constant over large enough times and distances. In modern cosmology it is called the Hubble Parameter and it gives us a slightly larger age for the Universe around 13.8 billion years.





<u>Distance Ladder</u>

Direct Measurements, Triangulation, and Parallax took us across Earth, the Solar System and nearby stars. We added expansion parallax for planetary nebula and a number of powerful standard candles that were verified against stars that could be measured via parallax. This took us all the way across the Milky Way and into our local Supercluster – the Virgo Supercluster.



Here, Cepheid variables confirmed the accuracy of type 1a supernova as an excellent standard candle. This is critical because, even with the Hubble Space Telescope, we can't see Cepheid stars much further than 100 million light years. But we can see type 1a supernova out to 8 billion light years. In addition, Cepheids and type 1a's have given us Red Shift as a way to tell distance. This rung is only limited by what is visible and we'll see in later segments, we can see out to around 13 billion light years.

Here we have just seen a few of the galaxies in the vast Virgo Supercluster. But Virgo is only one of millions of superclusters in the observable Universe. In the next segment, we'll take a look at our local group of superclusters and introduce a new way to measure supercluster boundaries with Laniakea being the one we are in.

Local Superclusters

***{Abstract** – In this segment of our "How far away is it" video book, we cover the superclusters closest to our supercluster, Virgo.*

First, we discuss the overall structure of the nearest 20 superclusters and illustrate the galactic structures of galaxy filaments, walls and voids including: the Sculuptor void; the Perseus-Pegasus filament; the Fornax, Centaurus, and Sculptor walls as well as the Great Wall or Coma wall. Then we take a look at several of these superclusters and some of the galaxies in each one we examine.

We start with the Hydra Supercluster with the Hydra Galaxy Cluster at its center. We examine NGC 2314, a rare double aligned pair of galaxies. We then move to the Centaurus Supercluster with the Centaurus Galaxy Cluster at its center. We then take a look at some of the galaxies in this supercluster including NGC 4603, NGC 4622, the unusual NGC 4650A, and NGC 4696. We then move on to the Perseus-Pisces Supercluster and the Perseus galaxy cluster within it and the remarkable galaxy NGC 1275 within it. Then we cover the Coma Supercluster with the Coma galaxy cluster at its center. We then take a look at the beautiful and wispy galaxy NGC 4921 along with NGC 4911. Then we review the distances to some of the other local superclusters including Hercules, Leo, Shapely, Horologium, and the 1 billion light years distant Corona-Borealis Supercluster.

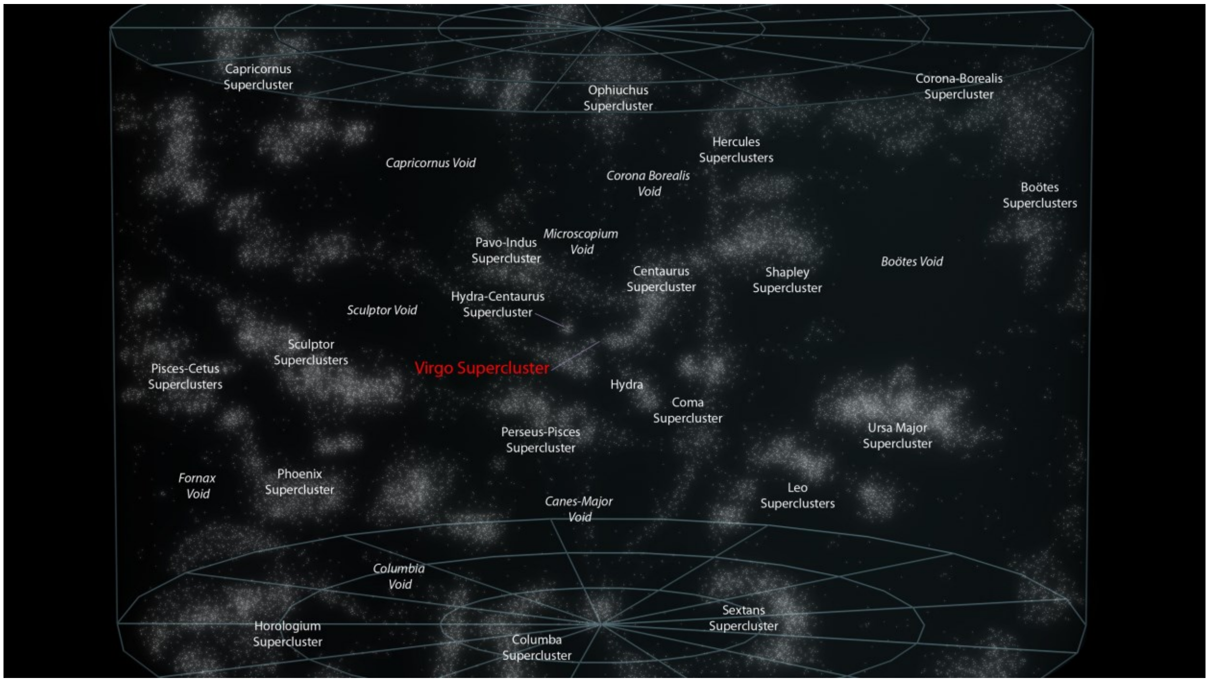
Next, we cover a new way to identify superclusters with a focus on our own called Laniakea. We then take a look at additional galaxies within a billion light years of us including: ESO 510 – G13; NGC 6782; ESO 243-49 HLX-1 with a supermassive back hole in its disk; Stephan's Quintet; interacting galaxies NGC 1409 and NGC 1410; interacting galaxies ARP 127 and NGC 5679; galaxy cluster Abell S0740; ESO 325-G004 with its unique gravitational lens arcs called Einstein's rings; and finish with the very interesting Hoag's Object.

*Finally, we cover the unusual peculiar motion superimposed on the normal Hubble flow that all the galaxies within a billion light years have. It appears that they are all moving towards a Great Attractor in the Norma or Shapley Supercluster. We end with a map of all the local superclusters where we highlight the ones we've seen and list the number of objects that exist out to this distance.***}**

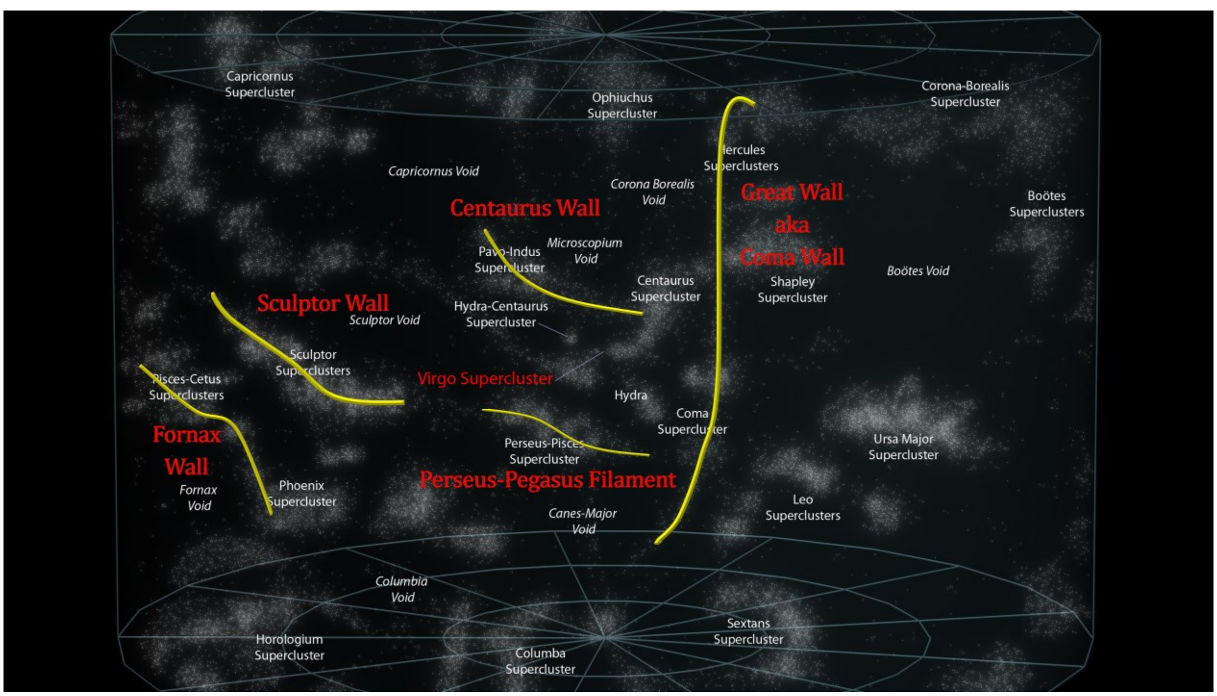
Introduction

> **[Music:** *@00:00 Ludwig van Beethoven – Piano Sonata No 14 in C sharp minor "Moonlight Sonata" –Dame Moura Lympany (piano) 1991- from the album "The most relaxing classical album in the world…ever!" 1997*

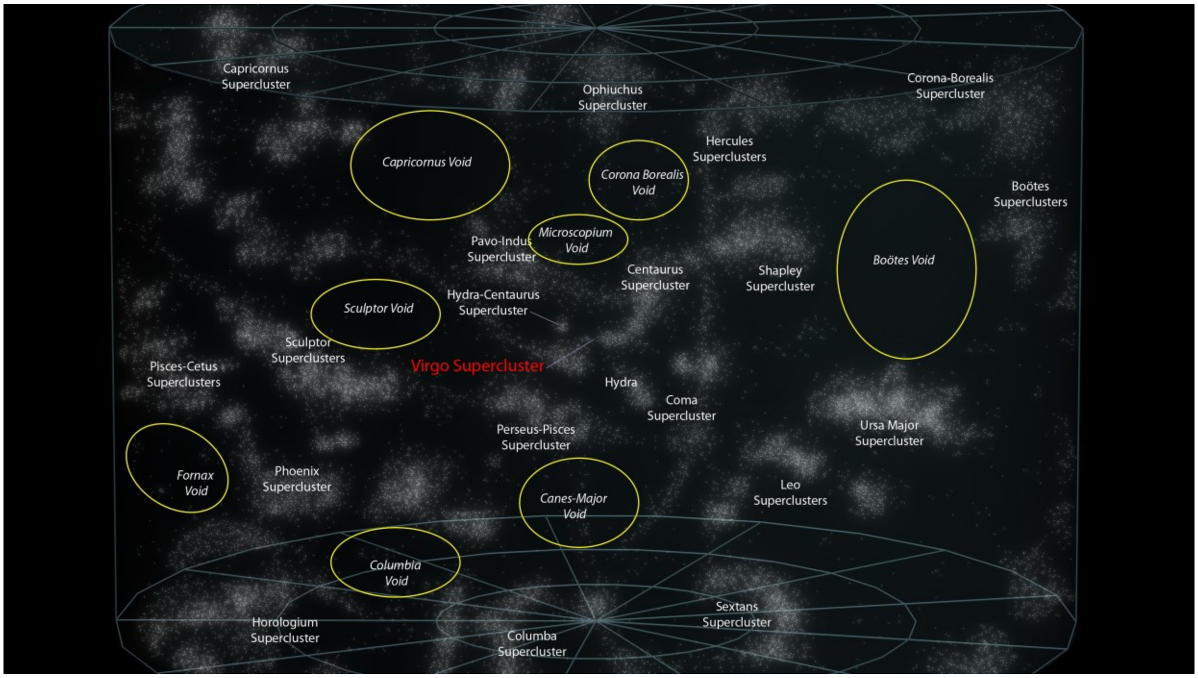
Here's a map of our local superclusters including the Virgo supercluster. As you can see, galaxies and clusters of galaxies are not uniformly distributed in the Universe. Instead they collect into vast clusters, filaments and walls of galaxies interspersed with large voids in which very few galaxies seem to exist.



A filament is constructed of galaxies and galaxy clusters. The Perseus-Pegasus Filament is an example. Walls are much wider and thicker than filaments. Here we see the Fornax, Centaurus, Sculptor and the Great Wall or Coma wall. The Great Wall is one of the longest known super-structures in the Universe. It is approximately 200 million light-years away and measures over 500 million light-years long, 300 million light-years wide and 16 million light-years thick.



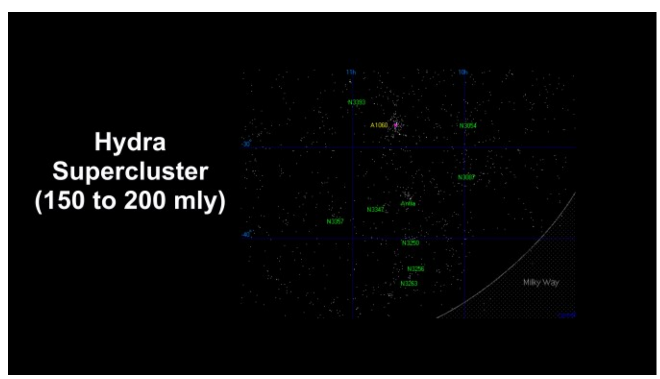
Voids are the vast empty spaces between filaments which contain very few, or no, galaxies at all. There are 25 major voids in our local superclusters. Only a few are marked here. The Sculuptor void is the largest in the nearby universe.



Let's take a look at some of these superclusters and some of the galaxies photographed by Hubble that are contained in these superclusters.

Hydra Supercluster

The Hydra Supercluster is close to the Virgo Supercluster and similar in size and shape to it. It's about 100 million light years long and contains the large Hydra galaxy cluster. This map plots every bright galaxy in the Supercluster. The galaxies in the supercluster range from 150 to 200 million light years away.



Hydra Galaxy Cluster

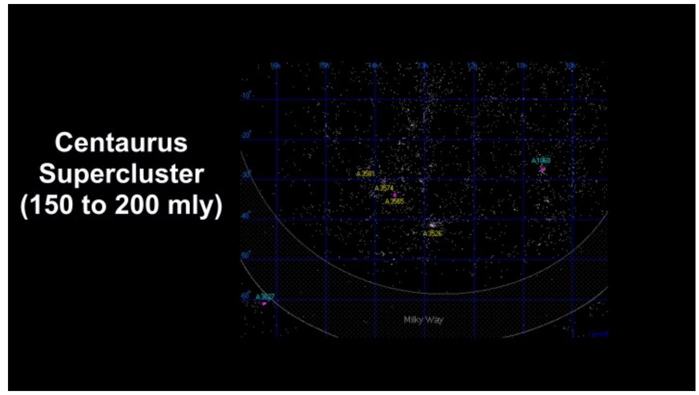
Here is a picture of the Hydra Cluster. Two stars within our own Milky Way galaxy can be seen in the foreground. There are three large galaxies near the cluster center, two yellow ellipticals [NGC 3311, NGC 3309] and one prominent blue spiral [NGC 3312]. These are the dominant galaxies, each about 150,000 light-years in diameter. And here's an interesting overlapping galaxy pair cataloged as NGC 3314. We'll take a closer look at this one.

<u>NGC 3314 A & B – 140 mly</u>

Through an extraordinary chance alignment, a face-on spiral galaxy lies precisely in front of another larger spiral. This line-up provides us with the rare chance to visualize dark material within the front galaxy, seen only because it is silhouetted against the object behind it. The bright blue stars forming a pinwheel shape near the center of the front galaxy have formed recently from interstellar gas and dust. A small, red patch near the center of the image is the bright nucleus of the background galaxy. [NGC 3314b**]**

Centaurus Supercluster

The Centaurus Supercluster is the closest neighbor of our Virgo Supercluster. It contains a number of large galaxy clusters including the Centaurus Cluster. The galaxies in the supercluster range from 150 to 200 million light years away. This map plots the brightest galaxies in this area of the sky. The supercluster structure is fairly obvious in the middle of the map.



Centaurus Galaxy Cluster

The Centaurus Cluster is a swarm of hundreds of galaxies 170 million light-years away. The cluster is filled with gas at temperatures of 10 million degrees or more, making it a luminous source for cosmic x-rays.

NGC 4603 – 108 mly

Here's a magnificent view of the spiral galaxy NGC 4603 in the Centaurus cluster. It is the most distant galaxy in which Cepheid variables have been found. Clusters of young bright blue stars highlight the galaxy's spiral arms. In contrast, red giant stars in the process of dying are also found.

Only the very brightest stars in NGC 4603 can be seen individually. Much of the diffuse glow comes from fainter stars that cannot be individually distinguished. **[**The reddish filaments are regions where clouds of dust obscure blue light from the stars behind them.**]**

NGC 4622 – 111 mly

Here is another galaxy in the Centaurus Cluster. The image shows NGC 4622 and its outer pair of winding arms full of new stars, shown in blue. Astronomers are puzzled by its clockwise rotation because of the direction the outer spiral arms are pointing. Most spiral galaxies have arms of gas and stars that trail behind as they turn. But this galaxy has two "leading" outer arms that point toward the direction of the galaxy's clockwise rotation.

NGC 4650A – 130 mly

Located about 130 million light-years away in the Centaurus cluster, NGC 4650A is one of only 100 known polar-ring galaxies. Their unusual disk-ring structure is not yet well understood. One possibility is that polar rings are the remnants of colossal collisions between two galaxies sometime in the distant past, probably at least a billion years ago.

NGC 4696 Black Hole – 150 mly

NGC 4696 is an elliptical galaxy in the Centaurus Cluster. In fact, it is the brightest galaxy in the cluster. This composite image was taken in a study of the galaxy's central black hole. It shows a vast cloud of hot gas (in red), surrounding high-energy bubbles 10,000 light years across (in blue). The green dots in the image show infrared radiation from star clusters on the outer edges of the galaxy.

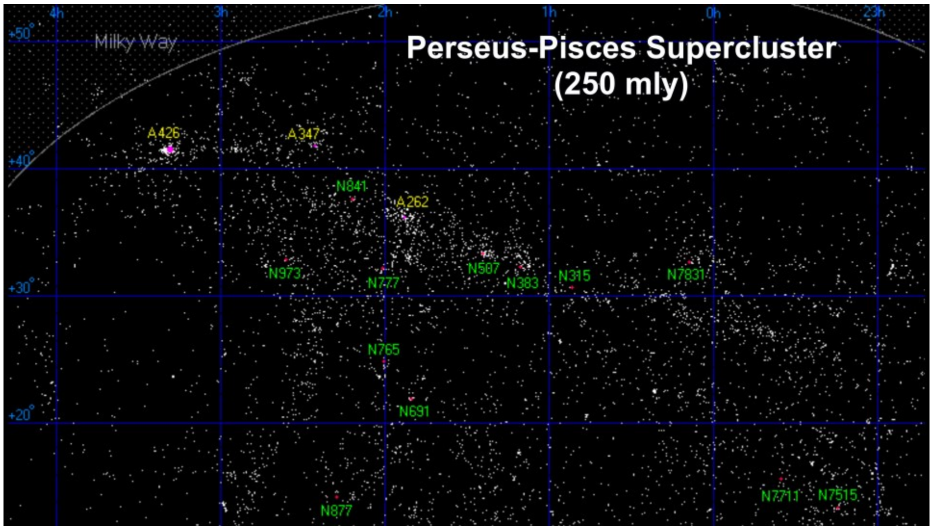
New observations from Hubble have revealed the intricate structure of the galaxy in greater detail than ever before. Astronomers have found that each of the dusty filaments has a width of about 200 light-years, and a density some 10 times greater than the surrounding gas. These filaments knit together and spiral inwards towards the centers supermassive black hole that's flooding the galaxy's inner regions with energy, heating the gas, and creating streams of heated material. It appears that these hot streams of gas bubble outwards, dragging the filamentary material with them as they go. The galaxy's magnetic field is also swept out with this bubbling motion, constraining and sculpting the material within the filaments.

[Additional info: Understanding more about filamentary galaxies such as NGC 4696 may help us to better understand why so many massive galaxies near to us in the Universe appear to be dead; rather than forming newborn stars from their vast reserves of gas and dust, they instead sit quietly, and are mostly populated with old and aging stars. This is the case with NGC 4696. It may be that the magnetic structure flowing throughout the galaxy stops the gas from creating new stars.**]**

[Music: *Antonín Leopold Dvořák – "String Serenade" moderato – London Chamber Orchestra, Christopher Warren-Green 1990 – from the album "The most relaxing classical album in the world…ever!" 1997*

__**Perseus-Pisces Supercluster**__

The Perseus-Pisces Supercluster is a long, dense wall of galaxies with a length of almost 300 million light-years that is around 250 million light-years away. It is one of the largest known structures in the universe. This plot of the brightest galaxies in the supercluster show how prominent it is. At the left end of the supercluster is the massive Perseus cluster – one of the most massive clusters of galaxies within 500 million light-years.



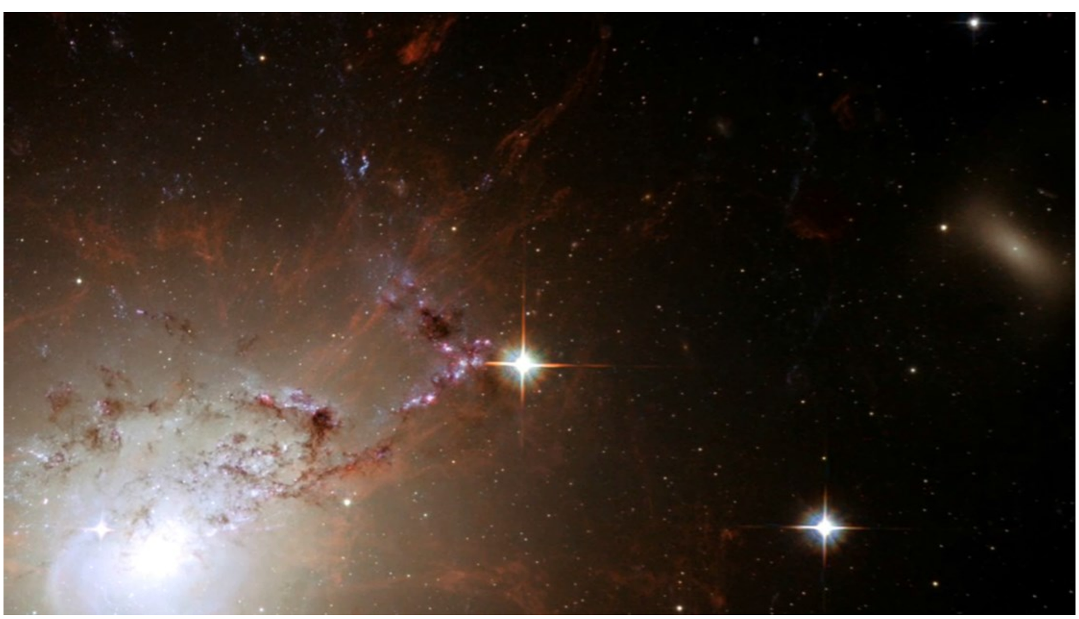
Perseus Cluster and NGC 1277 - 240 mly

Here we have the Perseus Galaxy Cluster containing thousands of galaxies immersed in a vast cloud of hot gas. It's moving away from us at over 5,000 km/s m (that's almost 2,000 miles/s).

Inside this galaxy cluster, Hubble discovered a very old and rare galaxy moving through the cluster at 3.2 million km per hour (that's 2 million miles per hour). It is though that NGC 1277 has remained essentially unchanged for the past 10 billion years. The evidence that this is the case lies in the ancient globular star clusters that swarm around it. Massive galaxies like this one tend to have both newer blue and older red globular clusters. Red ones are believed to have formed as their galaxies are formed. Blue ones are brought in later as the galaxy merges with others. However, NGC 1277 is almost entirely lacking in blue globular clusters. One explanation is that, because of its high velocity, it cannot merge with other galaxies to collect stars or pull in gas to fuel star formation.

<u>NGC 1275 – 230 mly</u>

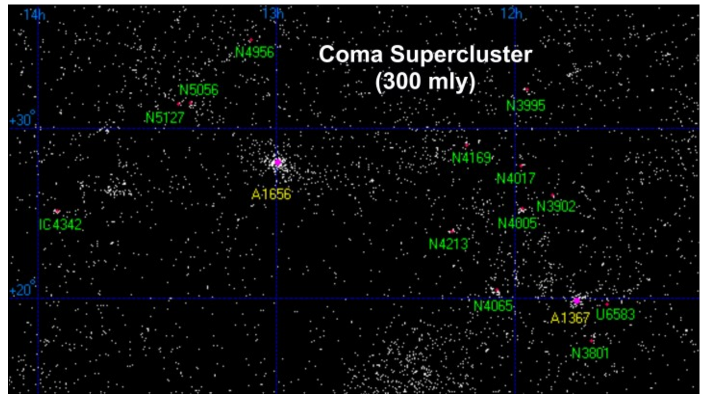
Here we are zooming into the giant elliptical galaxy NGC 1275 in the Perseus cluster. We see fine, thread-like filamentary structures in the gas surrounding the galaxy. The red filaments are composed of cool gas being suspended by a magnetic field, and are surrounded by the 100-million-degree hot gas in the center of the Perseus galaxy cluster.



The filaments are dramatic markers of the feedback process through which energy is transferred from the central massive black hole to the surrounding gas. The filaments originate when cool gas is transported from the center of the galaxy by radio bubbles that rise in the hot interstellar gas.

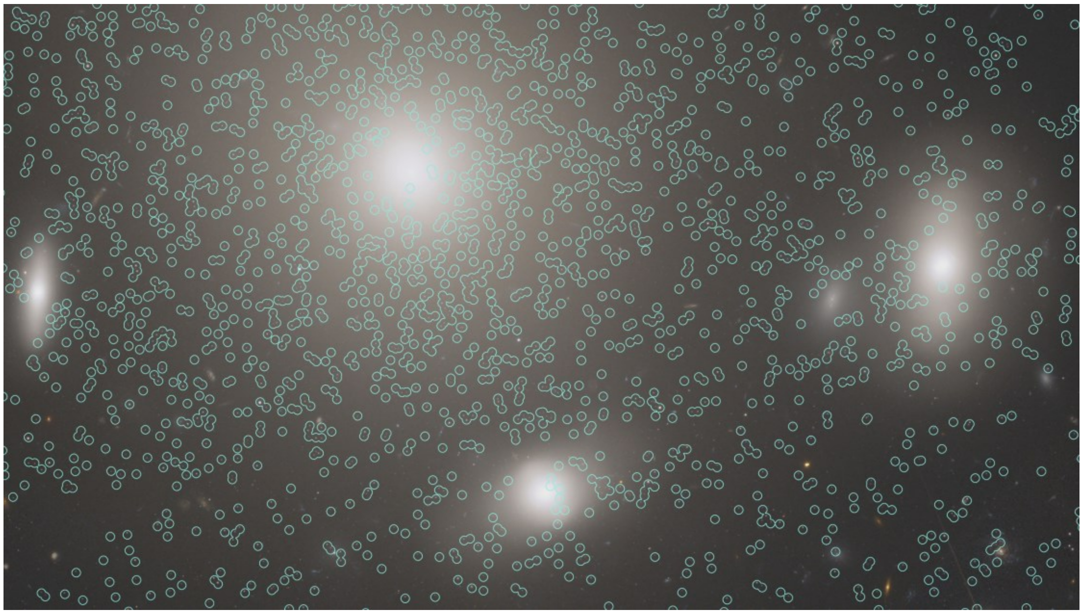
Coma Supercluster

The Coma Supercluster is a nearby supercluster of galaxies that includes the famous Coma Cluster (Abell 1656). The Supercluster is located 300 million light-years from Earth, it is roughly spherical, about 20 million light-years in diameter and contains more than 3,000 galaxies. Being one of the first superclusters to be discovered, Coma Supercluster helped astronomers understand the large-scale structure of the universe. This map plots the brightest galaxies in Coma Supercluster's region of the sky.



Here we are zooming into the immense Coma Cluster of over 1,000 galaxies, located 300 million light-years from Earth. The Coma cluster has received a huge amount of scientific research. This is partly because it lays a long way from the plane of our Galaxy and it is largely unobscured by any gas, dust or foreground stars.

Hubble was used to do a comprehensive survey of the Coma's globular star clusters. They found over 22,000 of them (circled in green). They found globular clusters scattered in space between the galaxies - ripped from their home galaxies by near-collisions with other galaxies. Astronomers will use the globular cluster field for mapping the distribution of matter and dark matter in the Coma galaxy cluster.



NGC 4921 – 320 mly

Here we are zooming into NGC 4921. It is one of the rare spirals in the Coma cluster, and a rather unusual one — it is an example of an "anemic spiral" where the normal vigorous star formation that creates a spiral galaxy's familiar bright arms is much less intense. As a result, there is just a delicate swirl of dust in a ring around the galaxy, accompanied by some bright young blue stars.

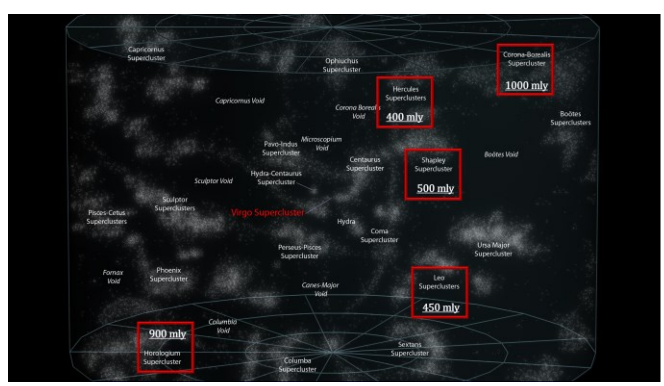
<u>NGC 4911 – 320 mly</u>

NGC 4911 contains rich lanes of dust and gas near its center. These are silhouetted against glowing newborn star clusters and iridescent pink clouds of hydrogen, the existence of which indicates ongoing star formation. 4911 and other spirals near the center of the cluster are being transformed by the gravitational tug of their neighbors. In the case of 4911, wispy arcs of the galaxy's outer spiral arms are being pulled and distorted by forces from a companion galaxy (NGC 4911A) to the upper right. The resultant stripped material will eventually be dispersed throughout the core of the Coma Cluster, where it will fuel the intergalactic populations of stars and star clusters.

Some Local Supercluster Distances

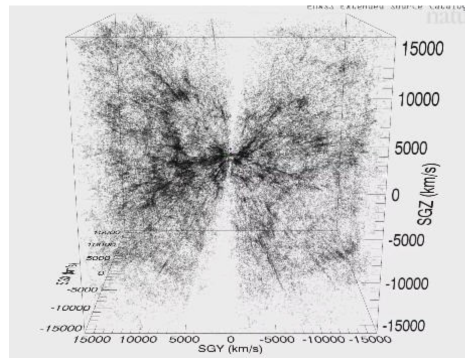
Here are the distances to a few additional superclusters in our local group:

Hercules is 400 million light years away.
Leo is 450 million light years away.
Shapley is 500 million light years away.
Horologium is 900 million light years.
Corona Borealis is 1 billion light years away

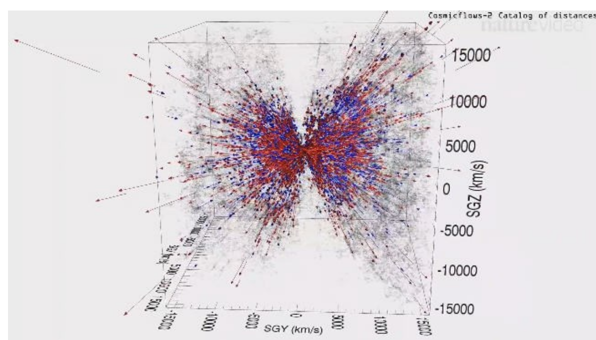


Laniakea: Our home supercluster

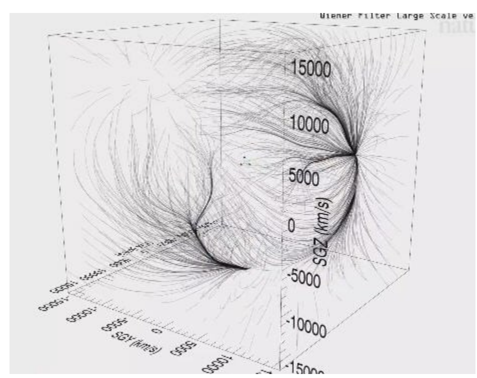
It has always been difficult for astronomers to determine where one supercluster ends and another begins. But now a team of astronomers have collected data on thousands of galaxies around us to understand their peculiar motion. the peculiar motion of an object is its motion less that part of its motion associated with the Hubble flow due to the expanding universe.



They used this data to identify which galaxies are moving towards us (shown in blue) and which galaxies are moving away from us (shown in red).

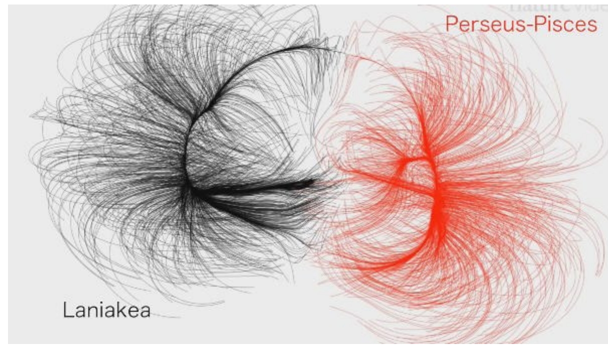


With this data, they were able to create a map of the paths galaxies are migrating along. These paths are called cosmic flows. Using this motion, they came up with a new way to map the distribution of matter in the universe.

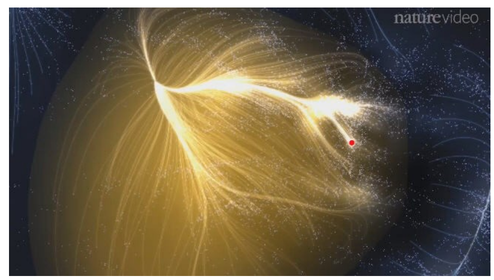


In our segment on the Virgo Supercluster, we counted the Virgo Galaxy cluster and a few hundred others as our local supercluster. But using this new technique we see that the Virgo Supercluster is part of a much larger structure that is 100 time larger and more massive. The astronomers who made this discovery have named this new supercluster "Laniakea" – Hawaiian for 'immeasurable heaven'.

For example, here is an illustration of Laniakea and Perseus-Pisces an adjacent supercluster. The boundary is where the supercluster objects are sharing apart like the North American Great Divide separates water flowing to the Atlantic Ocean from water flowing to the Pacific Ocean.



In this view, the red dot shows our Milky Way's location in Laniakea.



[Music: *@16:35 Edvard Grieg – "Peer Gynt – Morning" – Academy of St Martin in the Fields / Sir Neville Marriner 1991- from the album "The most relaxing classical album in the world…ever!" 1997***]**

Let's take a look at a few more galaxies found in our local superclusters.

<u>ESO 510-G13 150 mly</u>

This is an image of an unusual edge-on galaxy, revealing remarkable details of its warped dusty disk. The strong warping of the disk indicates that this galaxy has recently undergone a collision with a nearby galaxy and is in the process of swallowing it. In the outer regions, especially on the right-hand side of the image, we see that the twisted disk contains not only dark dust, but also bright clouds of blue stars. This shows that hot, young stars are being formed in the disk. Astronomers believe that the formation of new stars may be triggered by collisions between galaxies, as their interstellar clouds smash together and are compressed.

NGC 6984 – 180 mly

This spiral galaxy played host to a supernova explosion back in 2012, known as SN 2012im. Now, another star has exploded, forming supernova SN 2013ek — visible in this image as the prominent, star-like bright object just slightly above and to the right of the galaxy's center.

The observations that make up this new image were taken on 19 August 2013, and aimed to pinpoint the location of this new explosion more precisely. It is so close to where SN 2012im was spotted that the two events are thought to be linked; the chance of two completely independent supernovae so close together and of the same class exploding within one year of one another is a very unlikely event.

[Note: Neither of these were Type 1a like those covered in our video book. SN 2012im is known as a Type Ic supernova, while the more recent SN 2013ek is a Type Ib. Both of these types are caused by the core collapse of massive stars that have shed their outer layers of hydrogen. Type Ic supernovae are thought to have lost more of their outer envelope than Type Ib, including a layer of helium.**]**

NGC 6782 – 183 mly

The appearance of a galaxy can depend strongly on the color of the light with which it is viewed. This galaxy, when seen in visible light, exhibits tightly wound spiral arms that give it a pinwheel shape similar to that of many other spirals. However, when the galaxy is viewed in ultraviolet light, its shape is startlingly different.

Ultraviolet light has a shorter wavelength than ordinary visible light, and is emitted from stars that are much hotter than the Sun. At ultraviolet wavelengths, which are rendered as blue in this Hubble image, we see a spectacular, nearly circular bright ring surrounding its nucleus. The ring marks the presence of many recently formed hot stars.

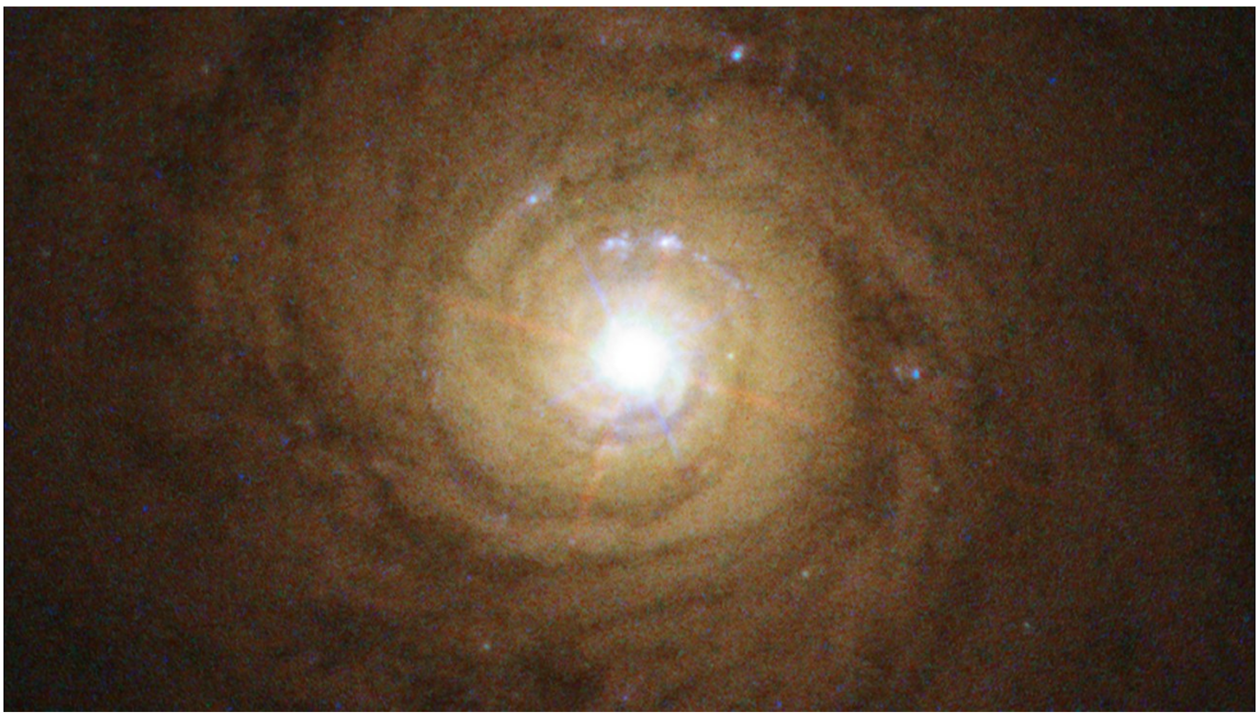
ESO 137-01 - 200 mly

This is ESO 137-001, a part of the Norma Galaxy Cluster near the Great Attractor. This image not only captures the galaxy and its backdrop in stunning detail, but also includes intense blue streaks streaming outwards from the galaxy, seen shining brightly in ultraviolet light. These streaks are actually hot young stars, encased in wispy streams of gas that are being torn away from the galaxy by its surroundings as it moves through the Norma cluster. This violent galactic star extraction is due to a process known as ram pressure stripping — a drag force felt by an object moving through a fluid. The fluid in question here is superheated gas that exists at the centers of galaxy clusters.

[Note: Studying ram pressure stripping helps us to understand the mechanisms that drive the evolution of galaxies. For example, it will leave this galaxy with very little of the cold gas that is essential for star formation. This will effectively end new star formation in the galaxy.**]**

NGC 5548 Black Hole - 244.6 mly

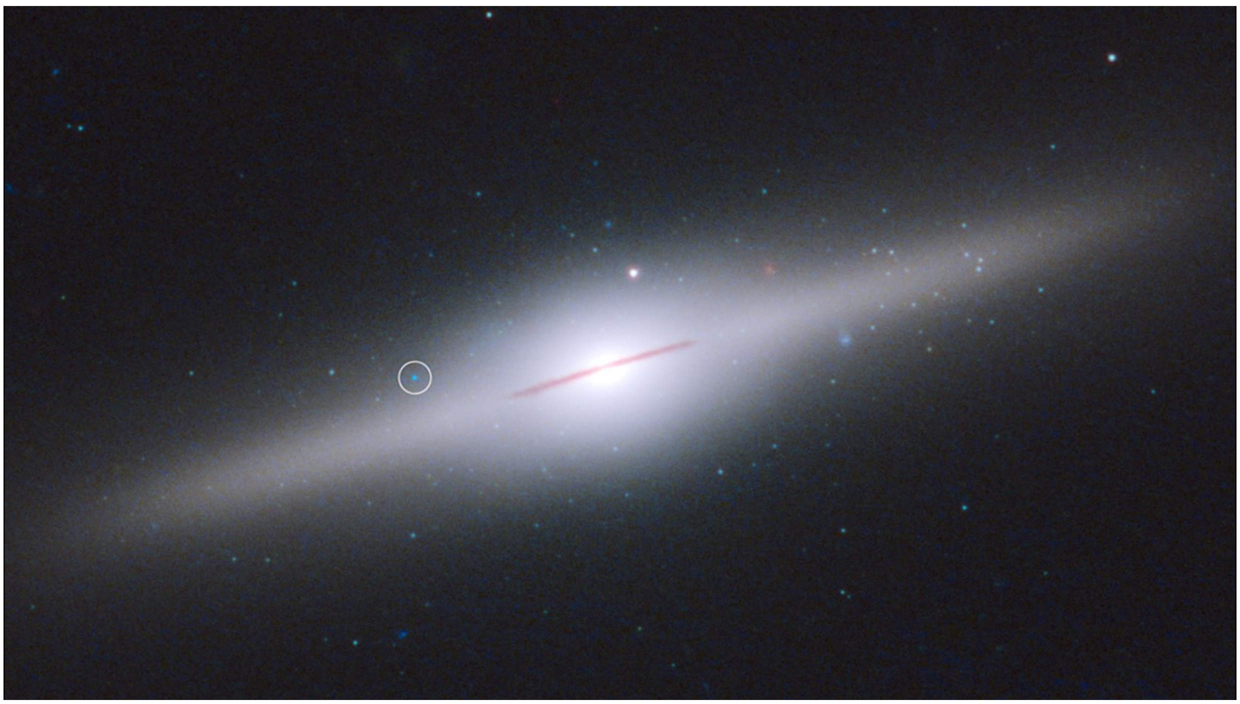
NGC 5548 is a well-studied Seyfert galaxy with a bright, active nucleus. This activity is caused by matter flowing onto a 65 million solar mass supermassive black hole at the core. As matter spirals down into a black hole it forms an accretion disc. The disc is heated so much that it emits X-rays, near to the black hole, and less energetic ultraviolet radiation further out. The ultraviolet radiation can create persistent winds strong enough to blow gas away from the black hole. NGC 5548's persistent wind, which has been known about for two decades, reaches velocities exceeding 3.5 million kilometers per hour (that's 2.1 million mi/hr). But a new wind has arisen which is much stronger and faster than the persistent wind. The new wind reaches speeds of up to 18 million kilometers per hour (that's 11 million mi/hr), but is much closer to the nucleus. This activity could provide insights into how supermassive black holes interact with their host galaxies.



[Music:** @21:45 Claude Debussy – "Clair De Lune" – Dane Moura Lympany, 1988 - from the album "The most relaxing classical album in the world…ever!" 1997]**

ESO 243-49 HLX-1 – 290 mly

This spectacular edge-on galaxy is believed to be home to an intermediate-mass black hole that may have been stripped off of a cannibalized dwarf galaxy. The estimated 20,000-solar-mass black hole lies above the galactic plane. This is an unlikely place for such a massive back hole to exist, unless it belonged to a small galaxy that was gravitationally torn apart by this one. The circle identifies a unique X-ray source that pinpoints the black hole.



Stephan's Quintet – 290 mly

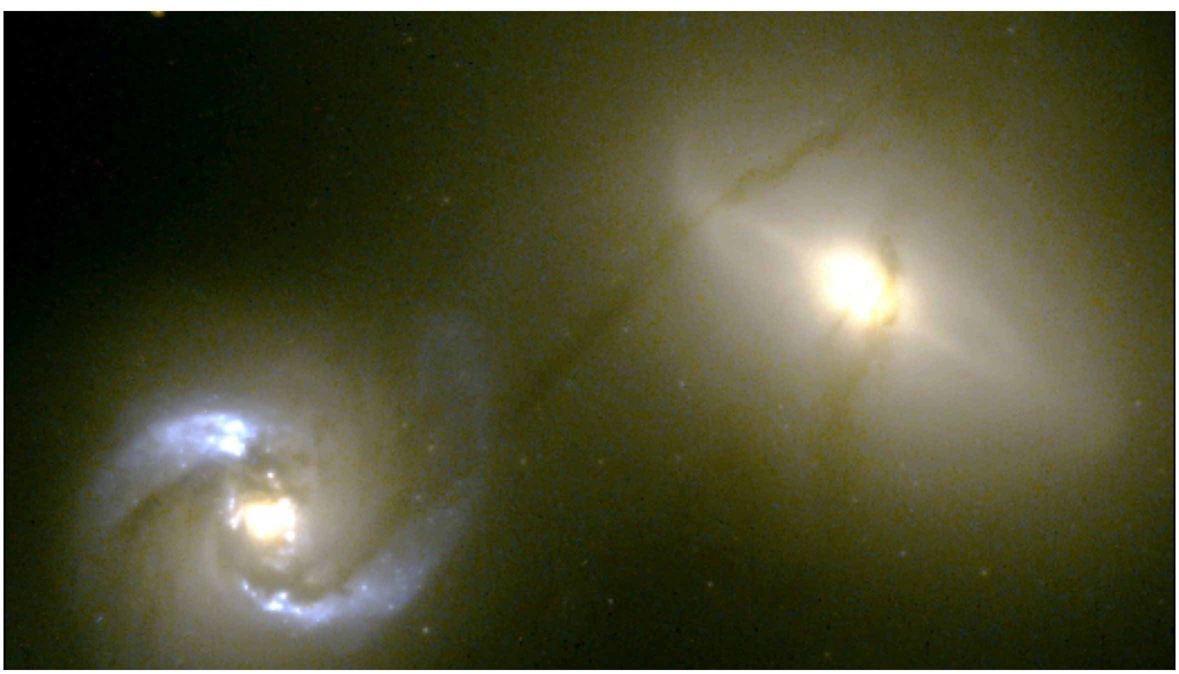
Here we are zooming into the Stephan's Quintet. As the name implies, it is a group of five galaxies. The name, however, is a bit of a misnomer. Studies have shown that group member NGC 7320 is actually a foreground galaxy. At 40 million light years, it is about seven times closer to Earth than the rest of the group.

Three of the galaxies have distorted shapes, elongated spiral arms, and long, gaseous tidal tails containing myriad star clusters, proof of their close encounters. These interactions have sparked a frenzy of star birth in the central pair of galaxies.

7319 is a barred spiral with distinct spiral arms that follow along 180 degrees back to the bar. Continuing clockwise, the next galaxy appears to have two cores, but it is actually two galaxies, 7318A and 7318B. NGC 7317 is a normal-looking elliptical galaxy that is less affected by the interactions. These farther members are markedly redder than the foreground galaxy, suggesting that older stars reside in their cores.

<u>NGC 1410, NGC 1409 – 300 mly</u>

This visible-light Hubble picture reveals an intergalactic "pipeline" of material flowing between two battered galaxies that bumped into each other about 100 million years ago. The pipeline (the dark string of matter) begins in 1410 (the galaxy on the left), crosses over 20,000 light-years of intergalactic space, and wraps around 1409 (the companion galaxy on the right).

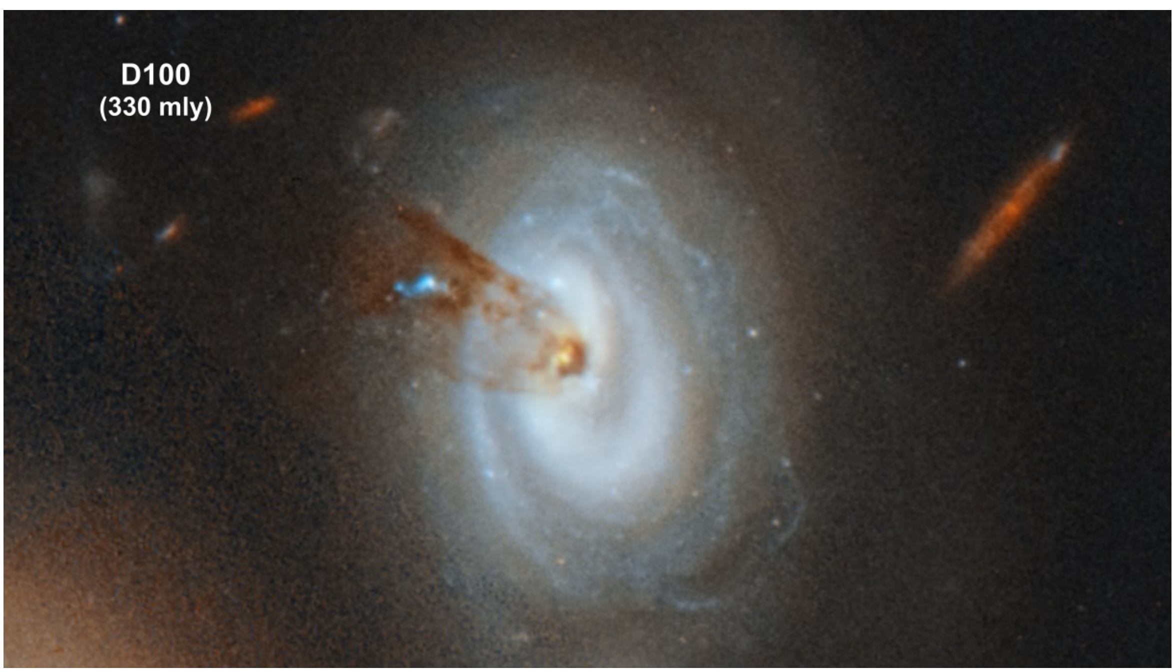


[Additional info: Scientists believe that the tussle between these compact galaxies somehow created the pipeline, but they're not certain why 1409 was the one to begin gravitationally siphoning material from its partner. And they don't know where the pipeline begins in 1410. More perplexing to astronomers is that NGC 1409 is seemingly unaware that it is gobbling up a steady flow of material. A stream of matter funneling into the galaxy should have fueled a spate of star birth. But astronomers don't see it. They speculate that perhaps the gas flowing into NGC 1409 is too hot to gravitationally collapse and form stars.**]**

D100 Loosing Gas – 330 mly

New images from NASA's Hubble Space Telescope show D100 a spiral galaxy being stripped of its gas as it plunges toward the cluster's center. A long, thin streamer of gas and dust stretches from the galaxy's core and on into space. The tail, a mixture of dust and hydrogen gas, extends nearly 200,000 light-years. But the structure is comparatively narrow, only 7,000 light-years wide. We saw this RAM Stripping earlier with ESO 137-01. Eventually, the galaxy will lose all of its gas. Without the material to create new stars, star formation in the galaxy will cease. It is estimated that the gas-stripping process in D100 began roughly 300 million years ago.

[The researchers' main goal was to study star formation along the tail. Hubble's sharp vision uncovered the blue glow of clumps of young stars. The brightest clump in the middle of the tail contains at least 200,000 stars, triggered by the ongoing gas loss from the galaxy. The Hubble data show that the gas-stripping process began on the outskirts of the galaxy and is moving in towards the center, which is typical in this type of mass loss. Based on the Hubble images, the gas has been cleared out all the way down to the central 6,400 light-years.**]**



Adding to this story is another galaxy in the image that foreshadows D100's fate. The object, named D99, began as a spiral galaxy similar in mass to D100. It underwent the same violent gas-loss process as D100 is now undergoing, and it can no longer form new stars.

Arp 274, NGC 5679 – 400 mly

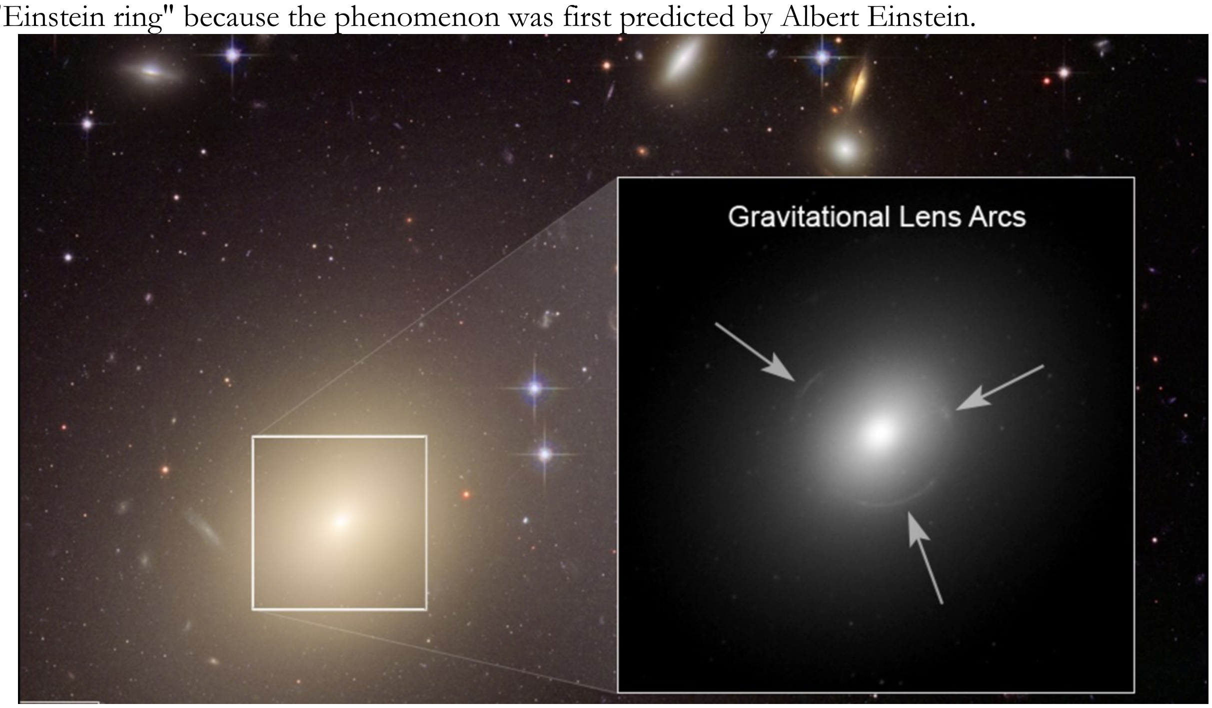
Here we are zooming into three galaxies that appear to be partially overlapping in the image, although they may be at somewhat different distances. The spiral shapes of two of these galaxies appear mostly intact. The third galaxy (on the far left) is more compact, but shows evidence of star formation.

[Additional info: Two of the three galaxies are forming new stars at a high rate. This is evident in the bright blue knots of star formation that are strung along the arms of the galaxy on the right and along the small galaxy on the left.**]**

Abell S0740 – 450 mly

This image shows the diverse collection of galaxies in the cluster Abell S0740. [Other fuzzy elliptical galaxies dot the image. Some have evidence of a disk or ring structure that gives them a bow-tie shape. Several spiral galaxies are also present.]

The giant elliptical ESO 325-G004 looms large at the cluster's center. In the course of analyzing this Hubble image, astronomers discovered that ESO325 is actually a "gravitational lens." This means that the focusing power of the enormous mass making up the galaxy caused the light from some background object, probably a distant "dwarf" galaxy, to be deflected and magnified. As a result, the more distant galaxy appears brighter, and distorted into the shape of an arc, or ring, known as an "Einstein ring" because the phenomenon was first predicted by Albert Einstein.



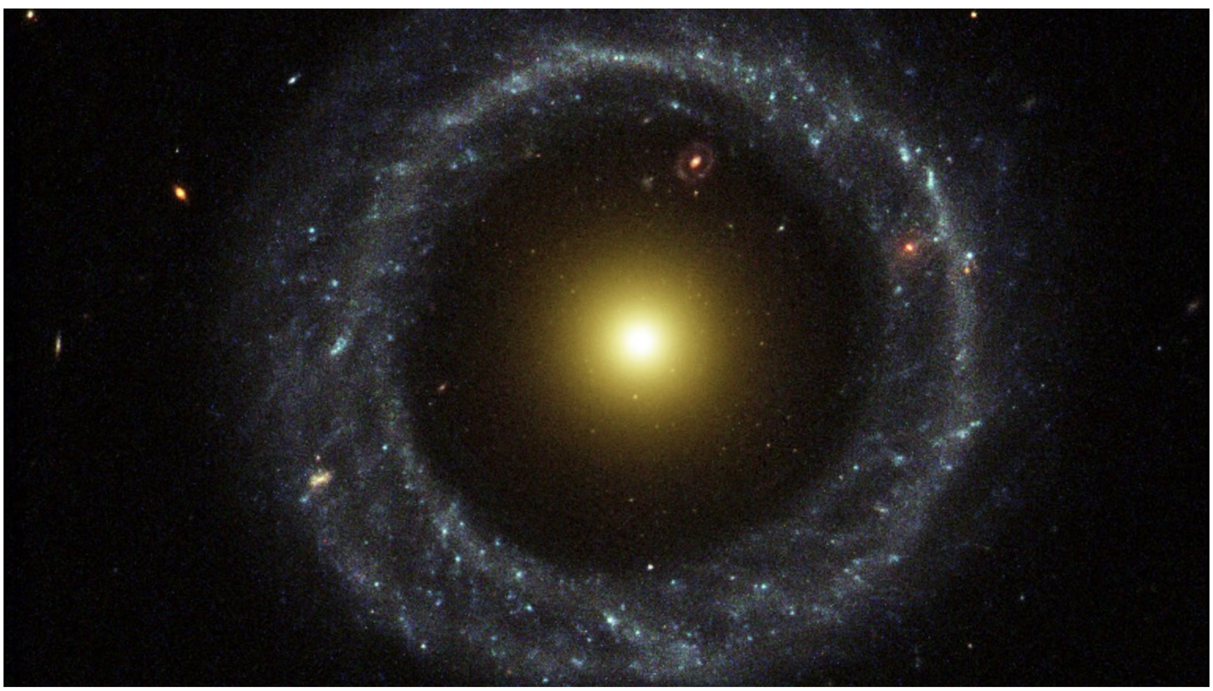
[Additional info: Although the universe is filled with galaxies, gravitational lensing is a rare occurrence because it requires an almost perfect alignment of a distant galaxy with an intervening one that has enough mass to gravitationally focus the light.

This particular system is unique because it is the closest known example of strong gravitational lensing. The galaxy is close enough that the dynamics of its stars can be studied in detail using spectrographs. The spectrographs reveal how fast the stars in the galaxy are moving, and this allows astronomers to estimate how much mass must be present in the center of the galaxy. This estimate can in turn be compared to the amount of mass needed to produce the observed gravitational lensing effect.

In this way, astronomers can build up a detailed, self-consistent picture of the matter distribution and dynamics of this unique nearby lensing system.**]**

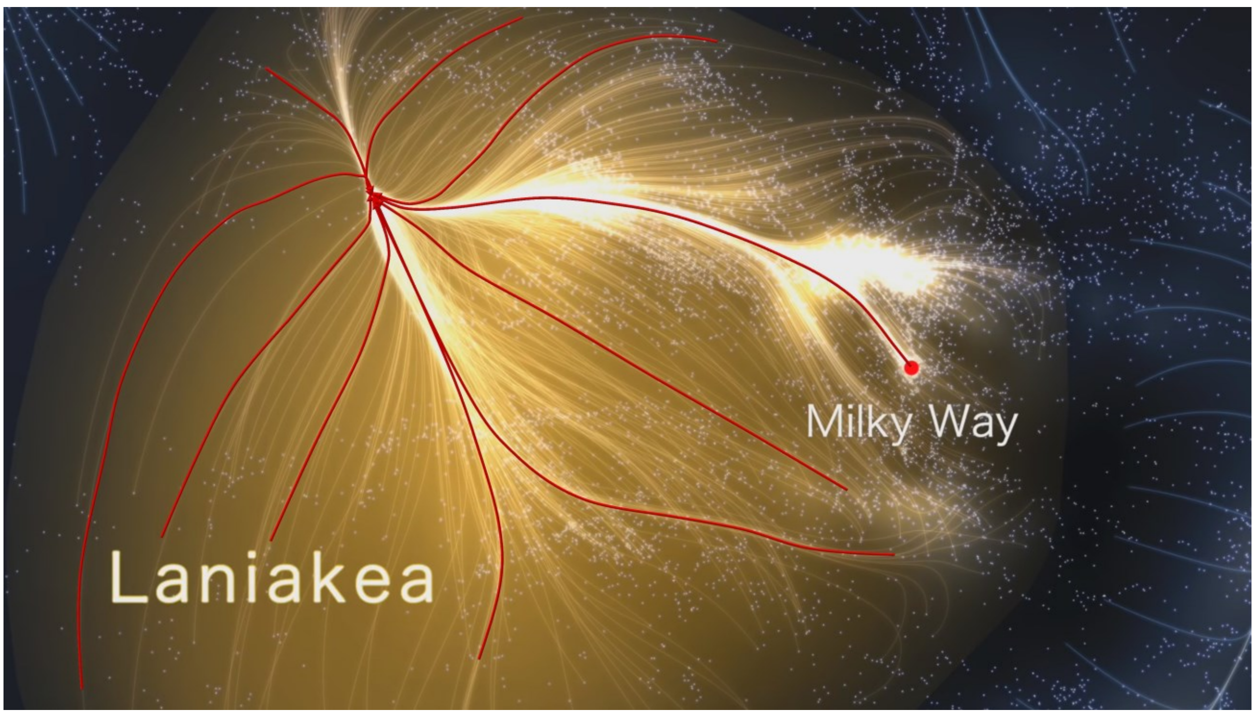
Hoag's Object – 600 mly

A nearly perfect ring of hot blue stars pinwheels about the yellow nucleus of an unusual galaxy known as Hoag's Object. A blue ring, which is dominated by clusters of young, massive stars, contrasts sharply with the yellow nucleus of mostly older stars. What appears to be a "gap" separating the two stellar populations may actually contain some star clusters that are just too faint to see. Curiously, an object that bears an uncanny resemblance to Hoag's Object can be seen in the gap at the one o'clock position. The object is probably a background ring galaxy.



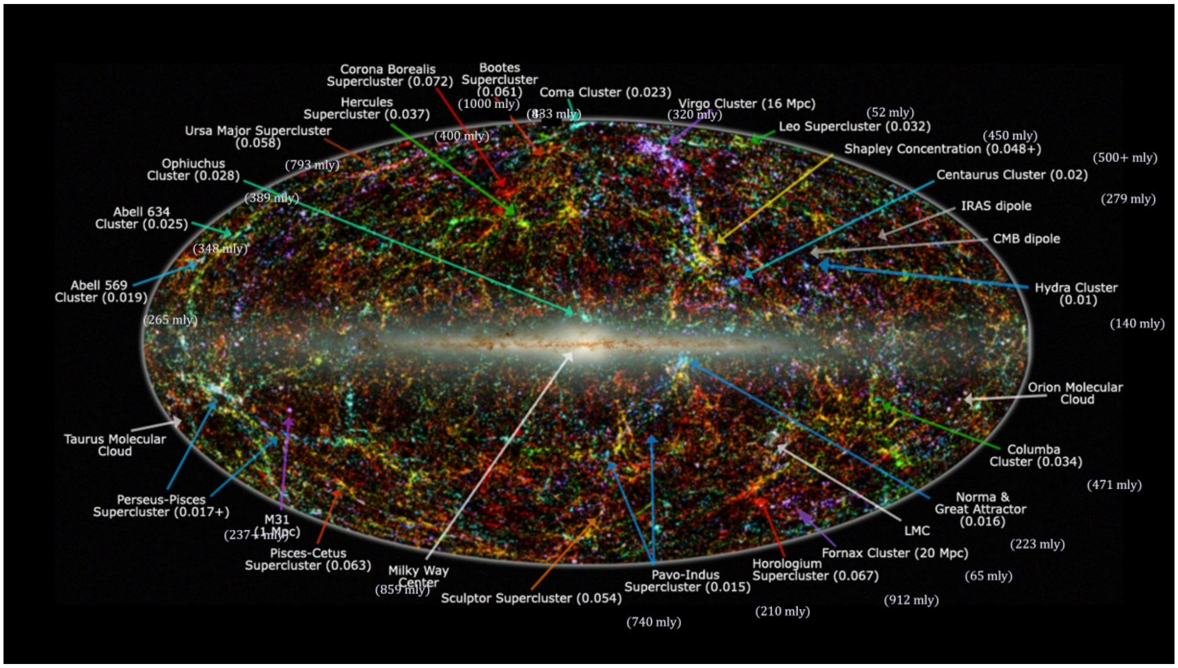
The Great Attractor

There's one more thing about the galaxies in our local Superclusters – They all have an unusual peculiar motion. Normally, galaxies are expected to have a motion consistent with the Hubble flow. That is, given the Hubble law, and the distance to a galaxy, its velocity is set. But in our local area – within 1 billion light years – there is an additional flow superimposed on the Hubble flow. It appears that our galaxy and a large number of the galaxy clusters in our area are flowing towards what is called 'the great attractor'. Our velocity is estimated to be around 700 km/s towards this point. That's 435 miles/s. Recent observations indicate that the point is the place all the galaxies in the Laniakea supercluster are moving. The mass at this theorized location is estimated to be thousands of times more than the mass of the entire Milky Way.

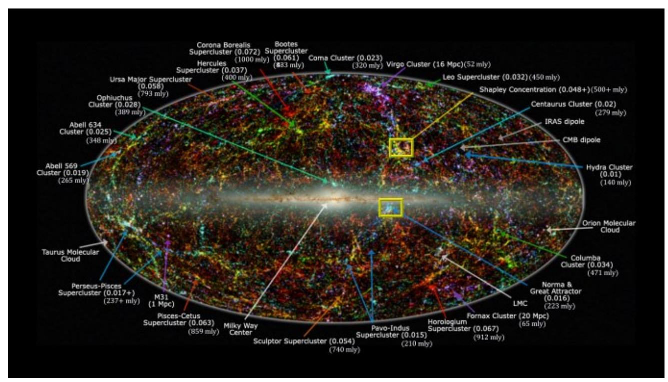


Here's a panoramic view of the entire sky as seen in near-infrared. It shows the distribution of galaxies beyond the Milky Way (at the center). **[**The image is derived from the 2MASS Extended Source Catalog (XSC)—more than 1.5 million galaxies, and the Point Source Catalog (PSC)--nearly 0.5 billion Milky Way stars.**]** The galaxies are color coded by redshift (numbers in parentheses) obtained from various sky surveys. **[**the UGC, CfA, Tully NBGC, LCRS, 2dF, 6dFGS, and SDSS surveys (and from various observations compiled by the NASA Extragalactic Database), or photo-metrically deduced from the K band (2.2 μm).**]** Blue/purple are the nearest sources eithing

140 million light years (z < 0.01); green are at moderate distances our to 600 mly (0.01 < z < 0.04) and red are the most distant sources out to a billion light years (0.04 < z < 0.1).



Initially, it looked like the great attractor was located close to the Norma Cluster. But Norma is so close to our galactic plane or 'area of avoidance' that we cannot see into it very well. More recently, updates to motion vectors indicate that the flow is not so much to the Norma Cluster, but to the much more massive Shapley Galaxy cluster behind it.

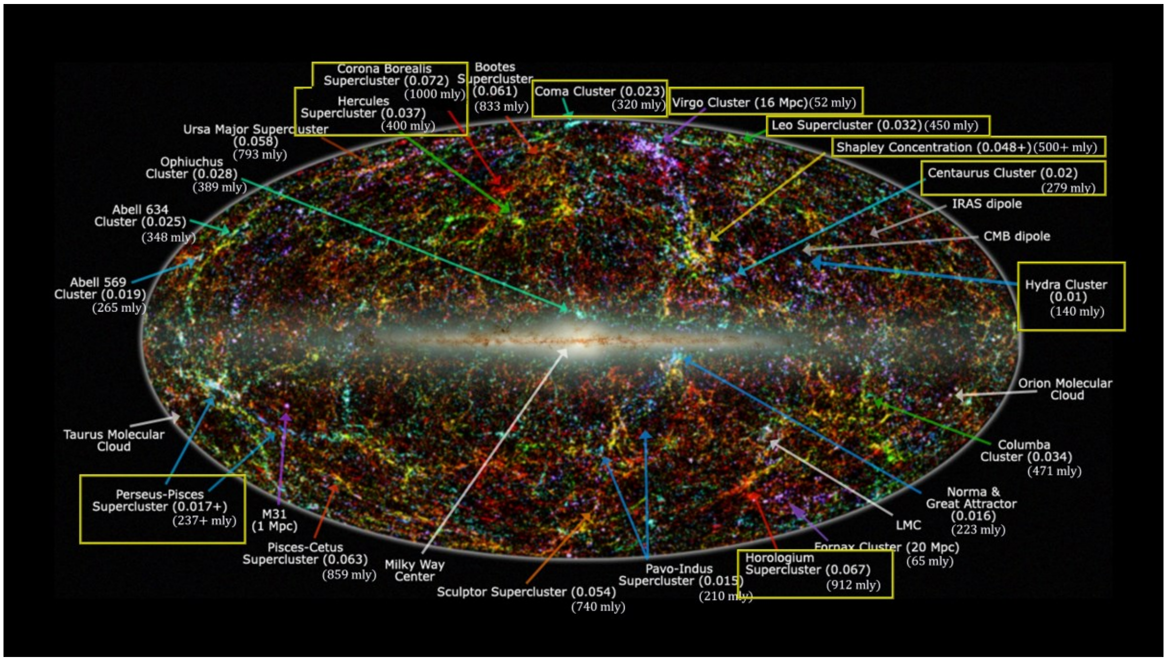


As you can imagine, understanding this peculiar flow is an area of active research.

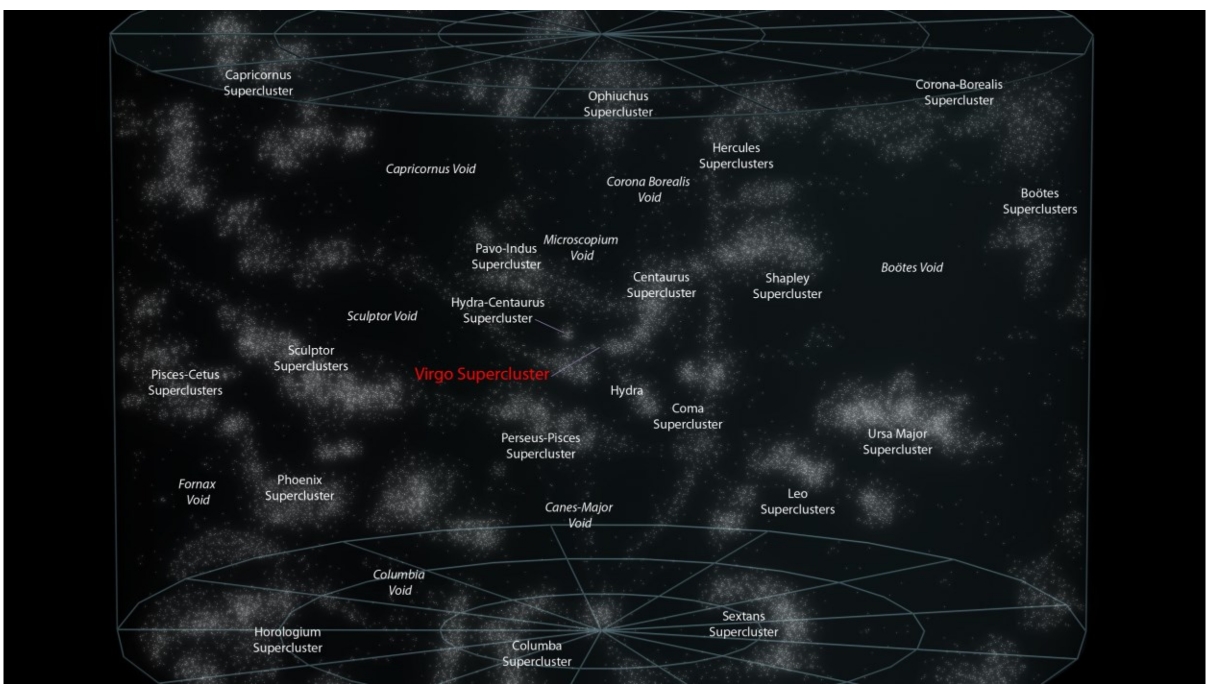
<u>The Local Superclusters Big Picture</u>

Here I have marked the galaxy clusters and local superclusters we covered in this segment. Within this 1 Billion light year radius from us, there are:

- 100 superclusters
- 240 thousand galaxy groups
- 3 million large galaxies
- 60 million dwarf galaxies
- 250,000 trillion stars



At this range, the Milky Way is too small to be seen, and our entire local volume is little more than a dot. But the entire map only represents about 7 percent of the entire visible Universe.



In this segment, we've seen several interacting galaxies. So, before we conclude the video book covering the cosmos as a whole, we'll take a closer look in our next segment at what it means for galaxies to collide.

Colliding Galaxies

*{**Abstract** – In this segment of our "How far away is it" video book, we cover interacting or colliding galaxies.*

We describe what it means for galaxies to collide given the great distances between stars within each galaxy. We then take a look at some of the interacting galaxies photographed by the Hubble Telescope. These include: The Antennae Galaxies, The Mice, NGC 2207 with IC 2163; Apr 256; ESO 576-69; APR 142; NGC 6240; the Tadpole Galaxy; UCG 1810 with UCG 1813; The Mice; the spectacular APR 147; NGC 454; South America Galaxy; and ZW II 28.

We spend some time on peculiar galaxy NGC 7603 with its multiple red-shift objects that challenge well accepted theories on Dark Matter and Cosmology.

Next, we discuss how we go about seeing a process that takes a billion years by observing interactions at various stages along the process as understood by computer simulations. Here we show a few that illustrate the phases of an interaction: the initial approach with NGC 6786 and LEDA 62867; first contact with VV 304A and VV 304B; penetration with Mayall's Object; out the other side with ESO 77-14; wrap around with VV 705; and merge with The Owl.

We end with another simulation. This time it's the collision between Andromeda and the Milky Way.}

Introduction

> **[Music:** @00:00 *Vangelis – "Heaven and Hell" "3rd Movement" – Vangelis' "3rd Movement" on his 1975 album "Heaven and Hell" was chosen by Carl Sagan as the theme for his wonderful 'Cosmos' series.***]**

Welcome to our segment on interacting galaxies. Here's our old friend Andromeda. As we noted in earlier segments, Andromeda is heading towards the Milky Way. Andromeda will collide with the Milky Way, and start a one-billion-year long collision process.

If you recall, from our discussion about how far away stars are in the galaxy; for example, our nearest star, Proxima Centauri, is 4 light years away. Those large distances between stars mean that it's a million to one shot that any star will actually collide when the galaxies passed through each other. But the form and shape will change dramatically and change forever for the interacting galaxies themselves. The key factors are the shapes and relative masses of the colliding galaxies, the collision velocity, and the angle of collision – a glancing blow vs. a head on collision, they'll have different outcomes.

I'd like to show you a few of the over 100 interacting galaxies photographed by the Hubble Space telescope.

Interacting Galaxies NGC 4490 and NGC 4485 – 24 mly

Here we see NGC 4490 and NGC 4485. Together they form the system Arp 269. Over millions of years, their mutual gravitational attraction has dragged the two galaxies into each other. In this image, the two galaxies have moved through each other and are speeding apart again. [But the galaxies are likely to collide once more (within a few billion years).]

NGC 4490 was once a barred spiral galaxy, like the Milky Way. But now the outlying regions have been stretched out, resulting in its nickname - the Cocoon Galaxy.

Interacting Galaxies NGC 1510 and NGC 1512 – 38 mly

Here we're zooming into the tiny galaxy NGC 1510 and its colossal neighbor NGC 1512. The large galaxy to the left in this image, is classified as a barred spiral. The tiny NGC 1510 to the right, on the other hand, is a dwarf galaxy. Despite their very different sizes, each galaxy affects the other through gravity, causing slow changes in their appearances.

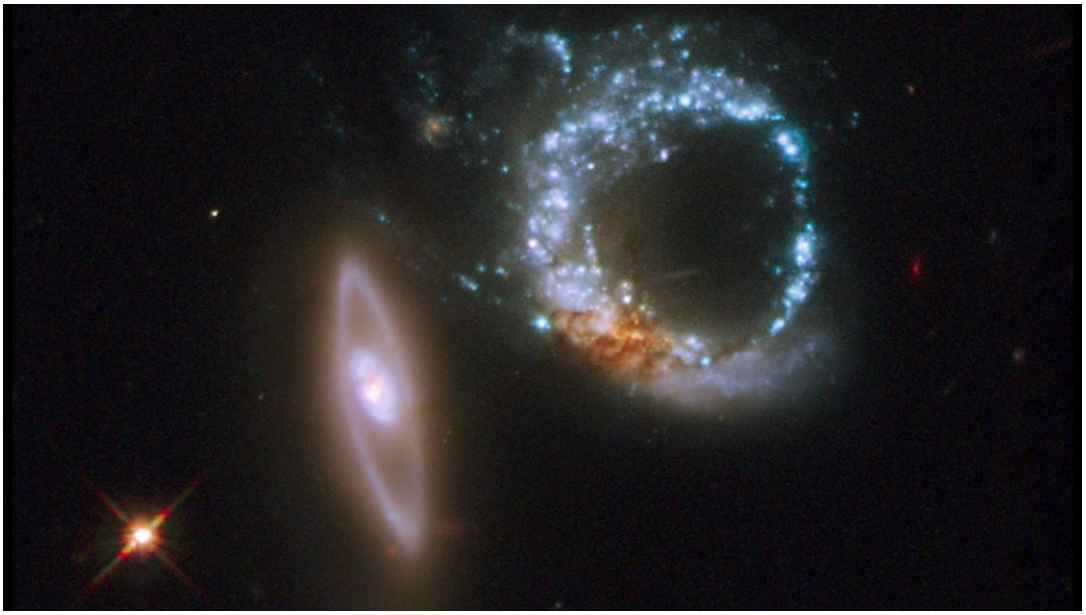
[The bar in NGC 1512 acts as a cosmic funnel, channeling the raw materials required for star formation from the outer ring into the heart of the galaxy. This pipeline of gas and dust in NGC 1512 fuels intense star birth in the bright, blue, shimmering inner disc known as a circumnuclear starburst ring, which spans 2400 light-years.]

Interacting Galaxies NGC 4298 and NGC 4302 – 55 mly

Here's an image of two galaxies: one is seen almost face-on and the other is seen edge-on. They were observed by Hubble in 2017 to celebrate its 27th year in orbit. In the face-on galaxy, we can see spiral arms and the blue patches of ongoing star formation and young stars. In the edge-on galaxy, we can see huge swathes of dust responsible for the mottled brown patterns. We also see a burst of blue to the left side of the galaxy indicating a region of extremely vigorous star formation. Their galaxy centers are 35,000 light years apart. At their closest points, the galaxies are separated from each other by only around 7,000 light-years. Given this very close arrangement, astronomers are intrigued by the galaxies' apparent lack of any significant gravitational interaction. [The only indication of an interaction is a faint bridge of neutral hydrogen gas -- not visible in this image – that appears to stretch between them.] The long tidal tails and deformations in their structure that are typical of galaxies lying so close to each other are missing completely.

Arp 147 – 440 mly

Here we have another ring galaxy. This one more clearly demonstrates how the ring came from a direct collision. The relatively undisturbed one on the left most probably punched through the one on the right producing a burst of star formation appearing as the bright blue ring. Note the dusty reddish knot at the lower left of the blue ring probably marks the location of the original nucleus of the galaxy that was hit.

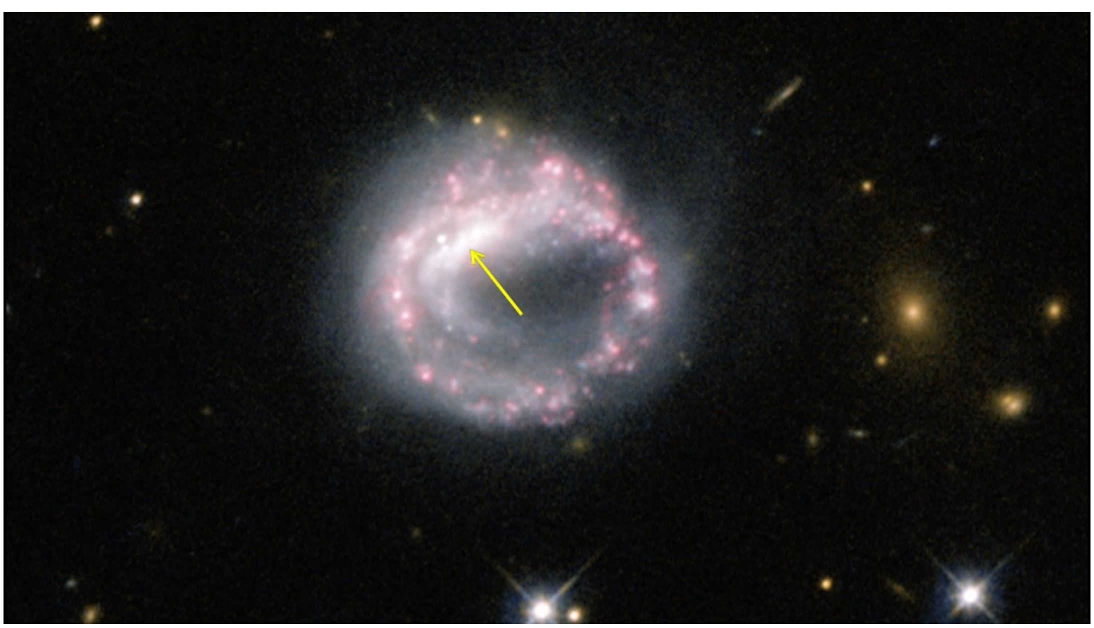


Cartwheel Galaxy – 500 mly

Lying about 500 million light-years away, the cartwheel shape of this galaxy is the result of a violent galactic collision. As with the other ring galaxies, the striking ring-like feature is a direct result of a smaller intruder galaxy — possibly one of two objects to the left of the ring — that careened through the core of the host galaxy. Presumably the Cartwheel Galaxy was a normal spiral galaxy like our Milky Way before the collision. This spiral structure is beginning to re-emerge, as seen in the faint arms or spokes between the outer ring and bulls-eye shaped nucleus. The ring contains at least several billion new stars that would not normally have been created in such a short time span and is so large (150,000 light-years across) that our entire Milky Way Galaxy would fit inside.

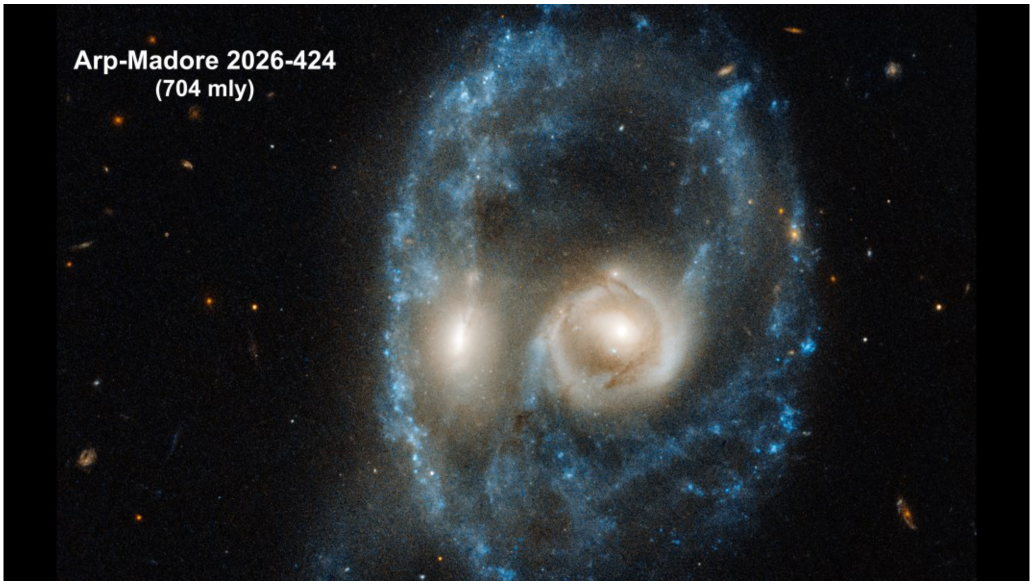
Zw II 28 – 319 mly

The sparkling pink and purple loop in Zw II 28 is not a typical ring galaxy due to the fact that it doesn't seem to have the usual visible central companion. For many years it was thought to be a lone circle on the sky, but observations using Hubble have shown that there may be a possible companion lurking just inside the ring, where the loop appears to double back on itself.



Arp-Madore 2026-426 – 704 mly

Here we are zooming into one more rare Ring galaxy 704 mly away. Only a few hundred Ring galaxies reside in our local supercluster. The fact that the two central bulges are the same size tells us that the colliding galaxies where themselves the same size.



Antennae Galaxies, NGC 4038 and 4039 – 62 mly

Named the Antennae Galaxies, these two spiral galaxies, drawn together by gravity, started to interact a few hundred million years ago. They are the nearest and youngest examples of a pair of colliding galaxies. This Hubble image has uncovered over 1,000 bright; young star clusters bursting to life in a brief, intense, brilliant "fireworks show". By the way, they are called the Antennae because the pair of long tails of luminous matter formed by the encounter resembles an insect's antennae.

[Music: @07:56 *Vangelis – "Conquest of Paradise" – Vangelis released this song in 1992. It was the theme for the movie "1492 Conquest of Paradise"***]**

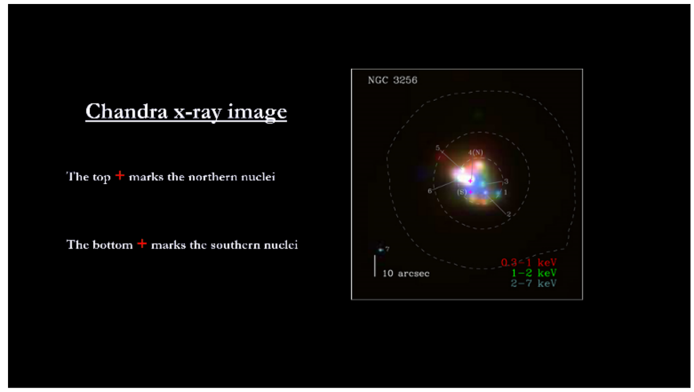
NGC 2207 and IC 2163 – 80 mly

Here's a spectacular sight. Strong tidal forces from the lager have distorted the shape of the smaller, flinging out stars and gas into long streamers stretching out a hundred thousand light-years toward the right-hand edge of the image.

NGC 3256 – 100 mly

Here we are zooming to NGC 3256. It is approximately the same size as our Milky Way and bears the marks of its past galactic collision in the extended luminous tails that sprawl out around the galaxy. These are thought to have formed around 500 million years ago during the initial encounter between the two galaxies, which today form just one. These tails are studded with young blue stars. It is believed that their birth was triggered by the collision. The brightness in the center of the galaxy makes it a starburst galaxy, host to vast amounts of infant stars born into groups and clusters.

As well as being lit up by over 1000 bright star clusters, the central region is home to crisscrossing threads of dark dust and a large disc of molecular gas spinning around two distinct nuclei — the relics of the two original galaxies. It takes an x-ray telescope to spot the second nuclei. In a few hundred million years, their nuclei will merge.



NGC 922 – 150 mly

Bright pink nebulae almost completely encircle this spiral galaxy. The ring structure and the galaxy's distorted spiral shape result from a smaller galaxy scoring a cosmic bull's-eye, hitting the center of NGC 922 some 330 million years ago. The small interloper can still be seen shooting away from the scene of the crash. As the small galaxy passed through the middle of NGC 922, it set up ripples that disrupted the clouds of gas, and triggered the formation of new stars whose radiation then lit up the remaining gas. The bright pink color of the resulting nebulae is a characteristic sign of this process.

In theory, if two galaxies are aligned just right, with the small one passing through the center of the larger one, the ring of nebulae should form a perfect circle, but more often the two galaxies are slightly off kilter, leading to a circle that, like this one, is noticeably brighter on one side than the other. The chances of seeing one of these galaxies nearby is therefore quite low. Despite the immense number of galaxies in the Universe, this is one of only a handful known in our cosmic neighborhood.

ESO 576-69 - 254 mly

This image from the NASA/ESA Hubble Space Telescope captures an ongoing cosmic collision between a spiral galaxy and a lenticular galaxy. The collision looks almost as if it is popping out of the screen in 3D, with parts of the spiral arms clearly embracing the lenticular galaxy's bulge. The bright spot in the middle of the plume above the galaxies is what makes this image unique. This spot is believed to be the nucleus of the former spiral galaxy, which was ejected from the system during the collision and is now being shredded by tidal forces to produce the visible stellar stream.

Arp 142 – 326 mly

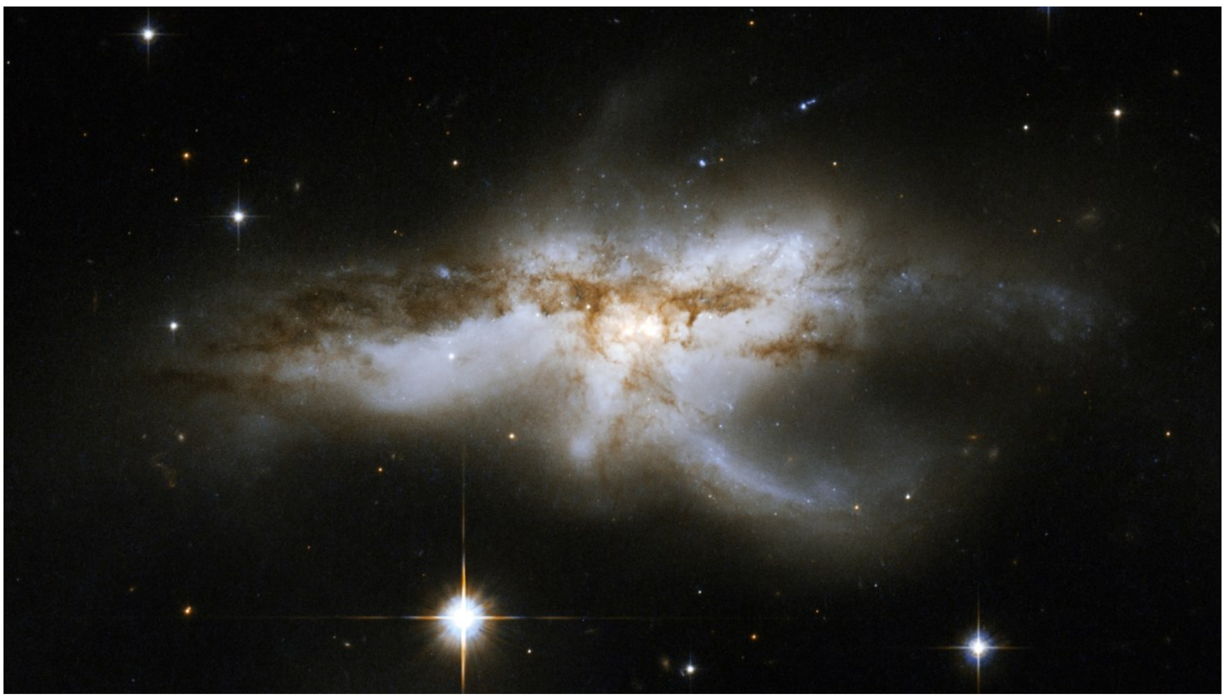
These two galaxies resemble a penguin safeguarding its egg. This Hubble image of the interacting pair shows the blue, twisted form of galaxy NGC 2936 (the penguin), and its partner NGC 2937 (the egg). The remnants of 2936's spiral structure can still be seen. The former galactic bulge now forms the "eye" of the penguin, around which it is still possible to see where the galaxy's pinwheeling arms once were. These disrupted arms now shape the cosmic bird's "body" as bright streaks of blue and red across the image.

Arp 256 – 350 mly
Here we see a pair of barred spiral galaxies that have just begun a merger. Though their nuclei are still separated by a large distance, the shapes of the galaxies are significantly distorted. For example, the galaxy on the left contains very pronounced tidal tails — long, extended ribbons of gas, dust and stars. The bright blue areas are stellar nurseries. These vigorous bursts are triggered by the massive gravitational interactions, which stir up interstellar gas and dust out of which stars are created. The galaxies in this system will continue their merger for millions of years, before finally becoming a single galaxy.

Markarian 266 - 350 mly
Here we are zooming into Markarian 266 (aka NGC 5256). The odd structure of this galaxy is due to the fact that it is not one galaxy, but two — in the process of a galactic collision. It is composed of two disc galaxies whose nuclei are currently just 13,000 light-years apart. Their constituent gas, dust, and stars are swirling together igniting newborn stars in bright star formation regions across the galaxy. In addition, each merging galaxy contains an active galactic nucleus, where gas and other debris are fed into supermassive black holes.

[NGC 6240, VV 617 – 400 mly

This is a peculiar, butterfly or lobster shaped galaxy consisting of smaller merging galaxies. With two giant black holes 3,000 light-years apart, which will drift toward one another and eventually merge together into a larger black hole. The merging process, which began about 30 million years ago, triggered dramatic star formation and sparked numerous supernova explosions. The merger will be complete in some tens to hundreds of millions of years.


]

Tadpole Galaxy, UGC 10214 – 420 mly

Here we have the "Tadpole" galaxy. Its distorted shape was caused by a small interloper, a very blue, compact galaxy visible in the upper left corner of the more massive Tadpole galaxy. Seen shining through the Tadpole's disk, the tiny intruder is likely a hit-and-run galaxy that is now leaving the scene of the accident. Strong gravitational forces from the interaction created the long tail of debris, consisting of stars and gas that stretch out more than 280,000 light-years. The other interesting thing here is that most of the stars in the background are all galaxies. There are 6,000 galaxies behind the Tadpole moving very deep into space.

[Additional info: Numerous young blue stars and star clusters, spawned by the galaxy collision, are seen in the spiral arms, as well as in the long "tidal" tail of stars. Each of these clusters represents the formation of up to about a million stars. Their color is blue because they contain very massive stars, which are 10 times hotter and 1 million times brighter than our Sun.

Two prominent clumps of young bright blue stars in the long tail are separated by a "gap" — a section that is fainter than the rest of the tail. These clumps of stars will likely become dwarf galaxies that orbit in the Tadpole's halo.**]**

Arp 273, UGC 1810 – 340 mly

Here is an especially photogenic group of interacting galaxies. The larger of the spiral galaxies has a dark disk that is tidally distorted into a rose-like shape by the gravitational tidal pull of the companion galaxy below it. A series of uncommon spiral patterns in the large galaxy is a tell-tale sign of interaction. The larger, outer arm appears partially as a ring, a feature seen when interacting galaxies actually pass through one another. This suggests that the smaller companion actually dived deep, but off-center, from the large galaxy.

[Additional info: The larger galaxy has a mass that is about five times that of the smaller galaxy. In unequal pairs such as this, the relatively rapid passage of a companion galaxy produces the lopsided or asymmetric structure in the main spiral. The image shows a tenuous tidal bridge of material between the two galaxies that are separated by tens of thousands of light-years from each other.**]**

The Mice, NGC 4676 – 300 mly

These colliding galaxies have been nicknamed "The Mice" because of the long tails of stars and gas emanating from each galaxy. The pair will eventually merge into a single giant galaxy. Computer simulations show that we are seeing two nearly identical spiral galaxies approximately 100 million years after their closest encounter. This is an example of what might happen to the Milky Way several billion years from now when it collides with Andromeda.

[Additional info: The long, straight arm is actually curved, but appears straight because we see it edge-on. The simulations also show that the pair will eventually merge, forming a large, nearly spherical galaxy (known as an elliptical galaxy). The stars, gas, and luminous clumps of stars in the tidal tails will either fall back into the merged galaxies or orbit in the halo of the newly formed elliptical galaxy.**]**

NGC 454 – 164 mly

NGC 454 is galaxy pair with a large red elliptical galaxy and an irregular gas-rich blue galaxy. The system is in the early stages of an interaction that has severely distorted both components. Although the dust lanes that stretch all the way to the center of the elliptical galaxy suggest that gas has penetrated that far, no signs of star formation are visible.

[The three bright blue knots of very young stars to the right of the two main components are probably part of the irregular blue galaxy.**]**

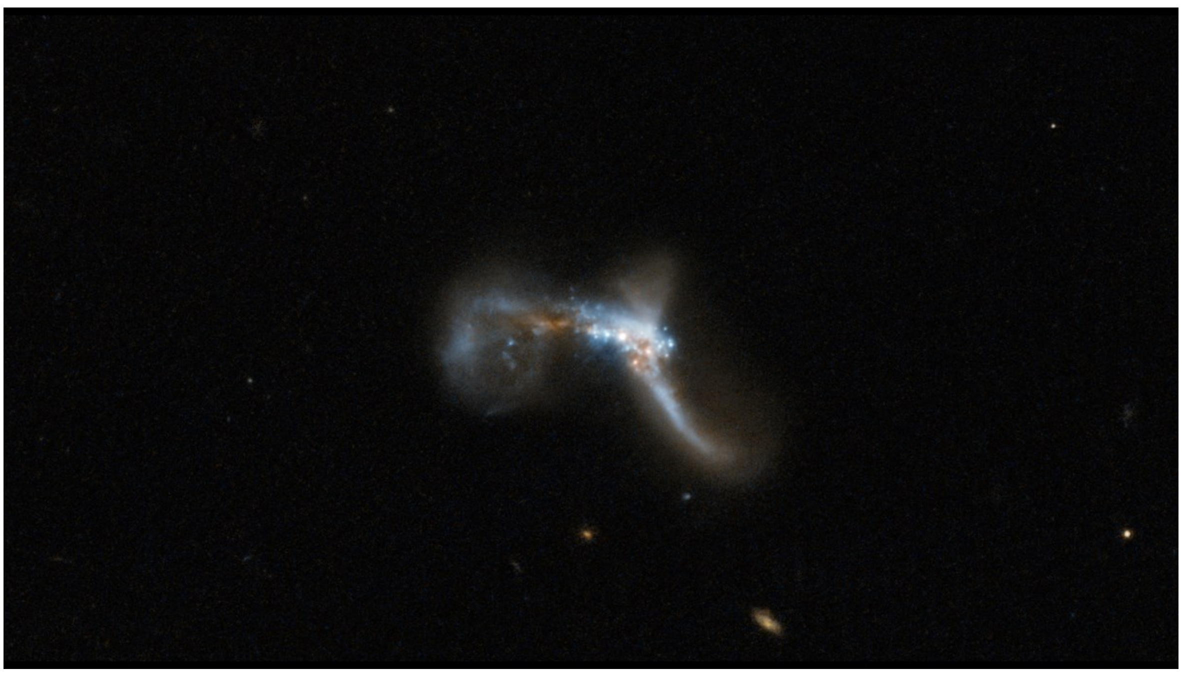
Arp 81 – 300 mly

Arp 81 is a strongly interacting pair of galaxies, seen about 100 million years after their closest approach. It consists of NGC 6621 (to the right) and NGC 6622 (to the left). 6621 is a very disturbed spiral galaxy. The encounter has pulled a long tail out of it that has now wrapped behind its body. The collision has also triggered extensive star formation between the two galaxies. Scientists believe that Arp 81 has a richer collection of young massive star clusters than the notable Antennae galaxies we covered earlier.

[Music: @17:28 *Beethoven - Piano Concerto No. 3, Largo – Anton Dikov, from the album "Meditation: Classical relaxation" 2010***]**

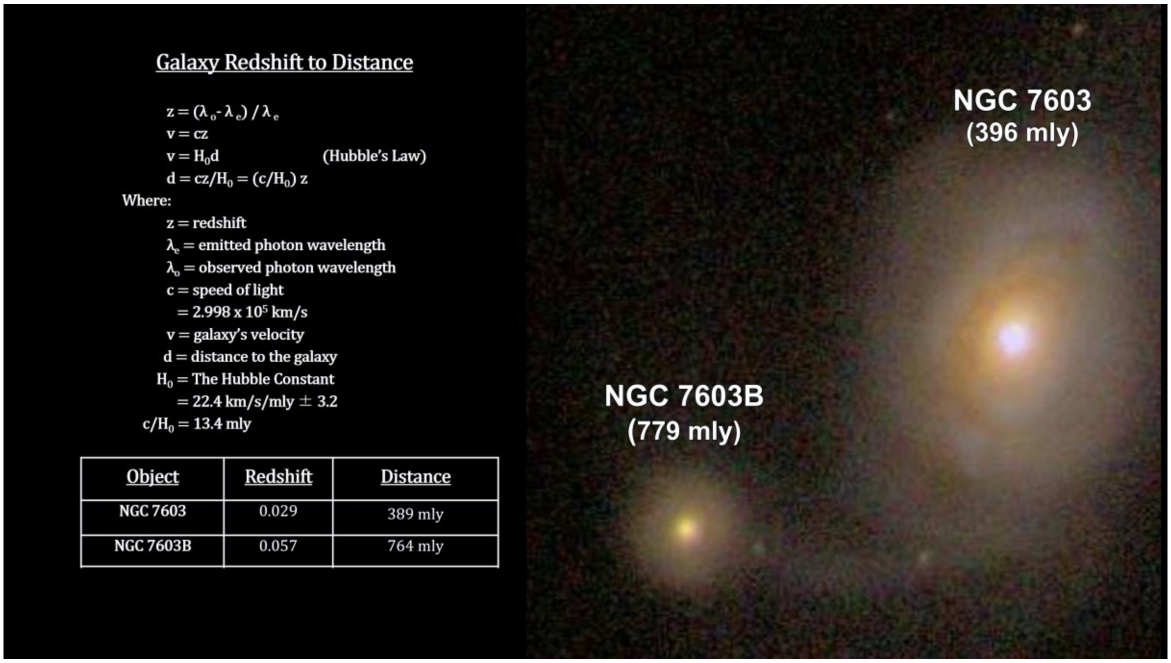
IRAS 22491-1808 - 1,079 mly

The contorted object captured by Hubble in this picture is known as the South America Galaxy. It is an ultraluminous infrared galaxy that emits a huge amount of light at infrared wavelengths. The reason for this intense infrared emission lies in an episode of strong star formation activity, which was set off by a collision between two galaxies. In the central region, which is very complex and disturbed, scientists have been able to distinguish two nuclei, remains of the two different galaxies that are currently colliding to form this new one. Other traces of the galactic collision are the three very noticeable tails in the image — two linear and one circular.



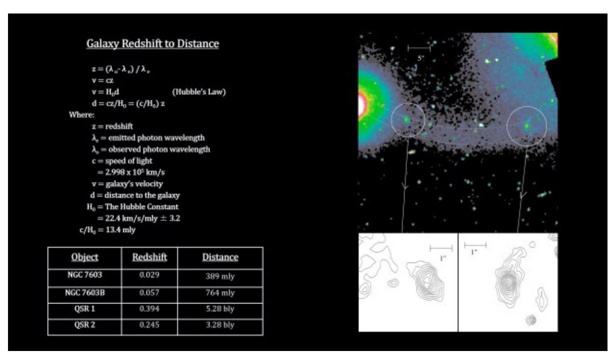
Peculiar galaxy NGC 7603

Here we have what astronomers call a peculiar galaxy. NGC 7603 and 7603B are identified as interacting according to the Sloan Digital Sky Survey. But they have a very interesting problem. As you recall from discussions on Hubble's law in our segment on the Virgo Supercluster, an object's redshift gives us its distance. But in this case, the redshift for 7603 is a good deal smaller than the redshift for 7603B. If redshift is only cased by the expansion of the universe, these two galaxies are to far apart to be interacting as they appear to be. Looking at it the other way around, if they are actually interacting, then there must be more than one explanation for redshift.



On top of that, two quasi-stellar objects (aka Quasars) have been found in the filament connecting the two main galaxies. [They are officially categorized as HII galaxies with very vigorous star formation. The rest of the filament and 7603B lack star formation. HII Galaxies are compact dwarf galaxies with the same optical spectra of Giant HII regions like the ones we covered in our chapter on the Milky Way. The thing is that the QSRs' redshifts are dramatically larger than either large galaxy.] That puts them billions of light years further away than the galaxy system they appear to be a part of. These numbers have held up under significant spectroscopic analysis. The standard explanation is that they are actually not a part of the NGC 7603 system and their apparent position is a coincidence. But the odds that this is true are extremely small. Plus, there are other interacting galaxy observations with similar redshift problems. Some astronomers are calling for a new physics to explain the situation. This would put the expansion of the Universe and the corresponding Big Bang theory in jeopardy. Time will tell.

[Some astronomers suggest that electrons and other atomic constituents can be created with initially smaller mass. Then smaller atomic transition emissions and absorptions would result in new galaxy light shifted to the red. As the galaxy ages, its atomic parameters asymptotically approach that of older matter. Such a theory would upend all of modern cosmology and particle physics.]



The Collision Process

Of course, we cannot watch a collision of galaxies unfold. It takes billions of years. But we do see colliding galaxies in various stages of a collision process across the cosmos. The ones we saw are only a few of the hundreds photographed by the Hubble telescope. Computer models show how galaxies of similar sizes might be transformed during a collision. The next six interacting galaxies represent various phases in the billion-year collision process.

NGC 6786, LEDA 62867

This Hubble image displays a beautiful pair of interacting spiral galaxies with swirling arms. The smaller of the two seems to be safe for now, but will probably be swallowed by the larger spiral galaxy eventually. **[**There is already some disturbance visible in both components.**]**

VV 340

Here is a pair of very gas-rich spiral galaxies in their early stages of interaction.

Arp 148 Mayall's object

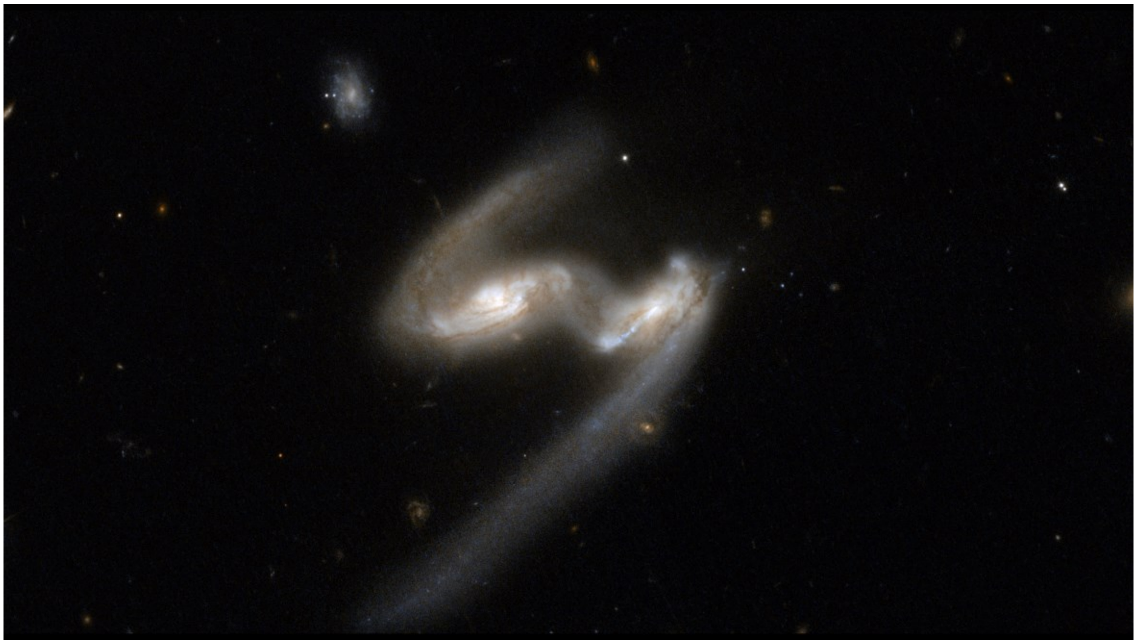
Here we see the staggering aftermath of an encounter between two galaxies, resulting in a ring-shaped galaxy and a long-tailed companion. The collision between the two parent galaxies produced a shockwave effect that first drew the matter into the center and then caused it to propagate back outwards in a ring. The elongated companion perpendicular to the ring suggests that Arp 148 is a unique snapshot of an ongoing collision.

ESO 77-14

This Hubble image is a stunning snapshot of a celestial dance performed by a pair of similar sized galaxies. Two clear signatures of the gravitational tug of war between the galaxies are:

1. The bridge of material that connects them
2. And the disruption of their main bodies.

The dust lanes between the two galaxy centers show the extent of the distortion to the originally flat disks that have been pulled into three-dimensional shapes.



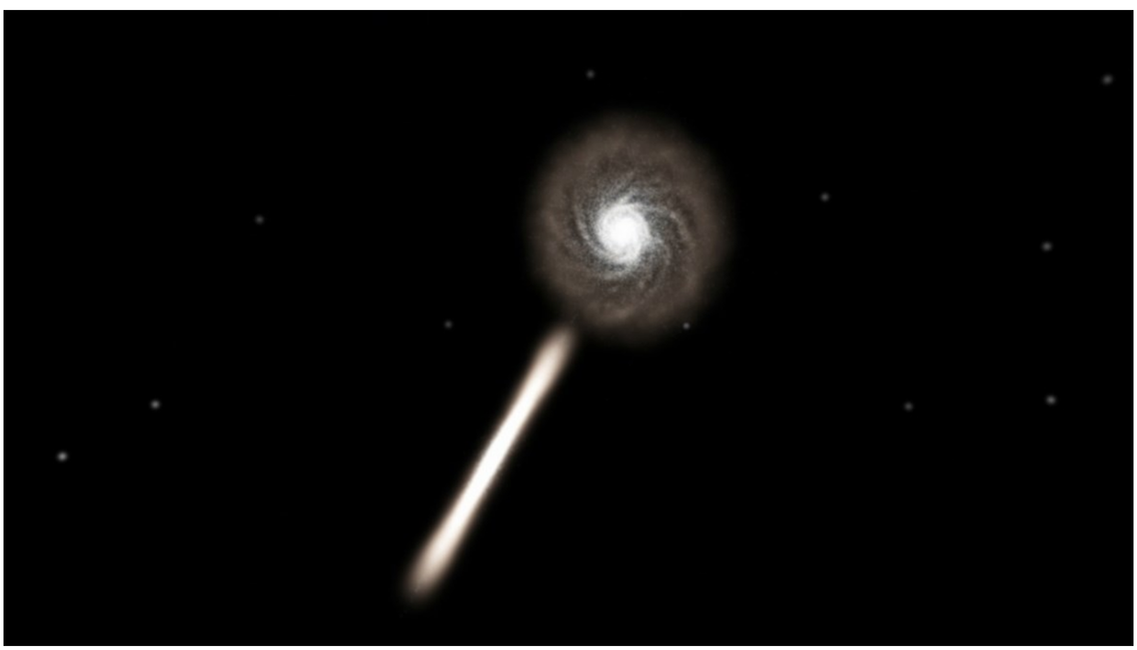
VV 705

Here we have two galaxies that seem to be embracing each other. Two long, highly curved arms of gas and stars emerge from a central region that has two cores. The two cores are 16,000 light-years apart. The pair is thought to be midway through a merger.

ESO 148-2 the Owl

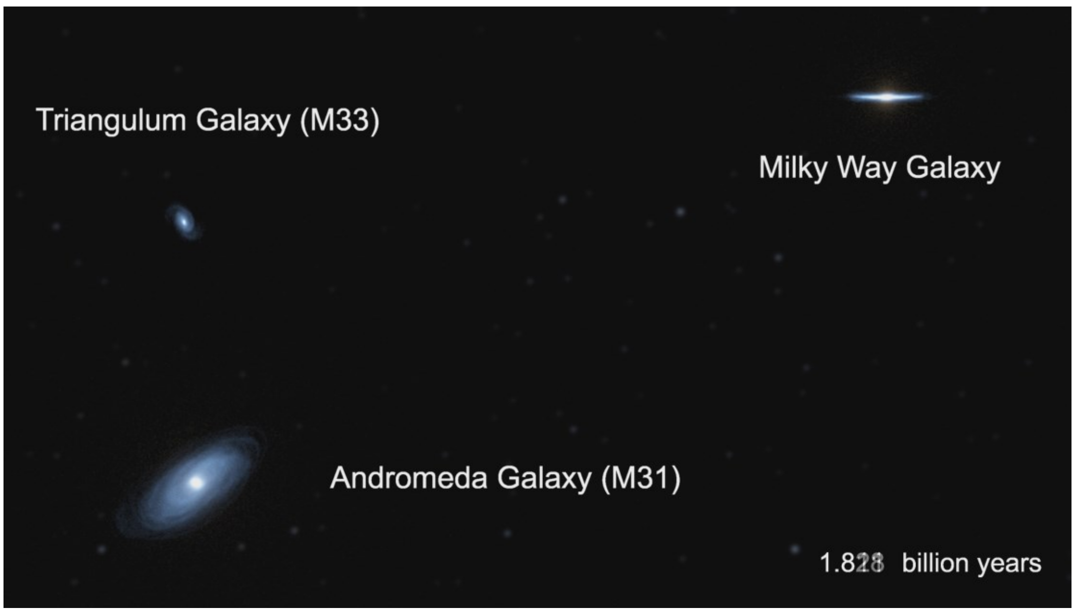
This is a beautiful object that resembles an owl in flight. It consists of a pair of former disk galaxies undergoing a collision. The cores of the two individual galaxies - seen at the center of the image - are embedded in hot dust and contain a large number of stars. Two huge wings sweep out from the center and curve in opposite directions. These are tidal tails of stars and gas that have been pulled from the easily distorted disks of the original galaxies.

Here's a computer simulation. You'll recognize the last six objects we discussed at key points along the way.



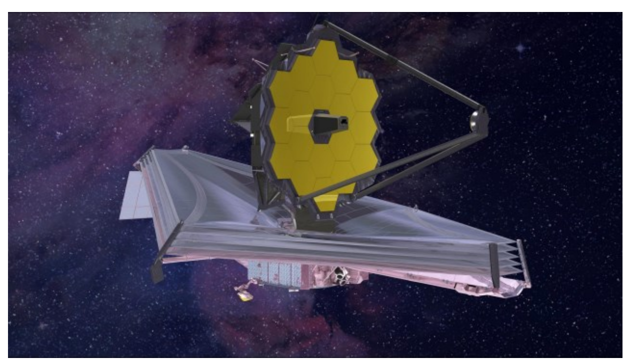
Milky Way - Andromeda Collision

The three largest galaxies in our Local Group are our Milky Way, Andromeda and Triangulum. This Hubble Space Telescope visualization of a computer simulation depicts their joint evolution over the next several billion years and ends with the massive collision between the Milky Way and Andromeda. Hubble observations indicate that the two galaxies, orbiting the Local group's center of gravity, will impact each other in a head-on collision around 4 to 4.5 billion years from now. On the first pass, the thin disk shapes of these spiral galaxies will be strongly distorted by the encounter. Subsequent passes will turn the two spiral galaxies into one giant elliptical galaxy. Their cores will merge along with their central supermassive black holes. The Triangulum galaxy will continue to orbit the merged pair through the end of this computer simulation, although other computer models show it joining the collision.



Colliding Galaxies Conclusion

In the How Far Away Is It video book, we have covered distances for the Earth, our solar system, the Milky Way, and galaxies from our Local Group, out to our Local Superclusters. In our final segment, we'll put it all together as we consider the Cosmos as a whole and look forward to the launch of the James Web Space Telescope.



The Cosmos

*{**Abstract** – In this final segment of our "How far away is it" video book, we cover the structure of the visible Universe as we currently know it.*

We start with some galaxy and galaxy clusters beyond our local superclusters, including: Abell 2029 with its supermassive galaxy IC 1101; Quasar Markarian; a massive cluster gravitationally lensing a more distant cluster; El Gordo; some distant supernovae remnants; gravitational lensing in giant galaxy clusters like Abell 1689, Abell 68, and more. We then cover dark matter discovery in the Coma cluster and evidence for it in the Bullet cluster. We see a gravitationally lensed supernova;

Next, we cover slowly expanding space and the impact that has on measuring distances using GN-z11, currently beyond the visible horizon, as an example. We also cover how recent redshift measurements from distant Type 1a Supernovas have provided evidence that the expansion is accelerating. We explain how this leads to the concept of 'Dark Energy' by examining the concept of a cosmic scale factor and how it changes over time. With this we introduce 'cosmological redshift' as a measure of the expansion.

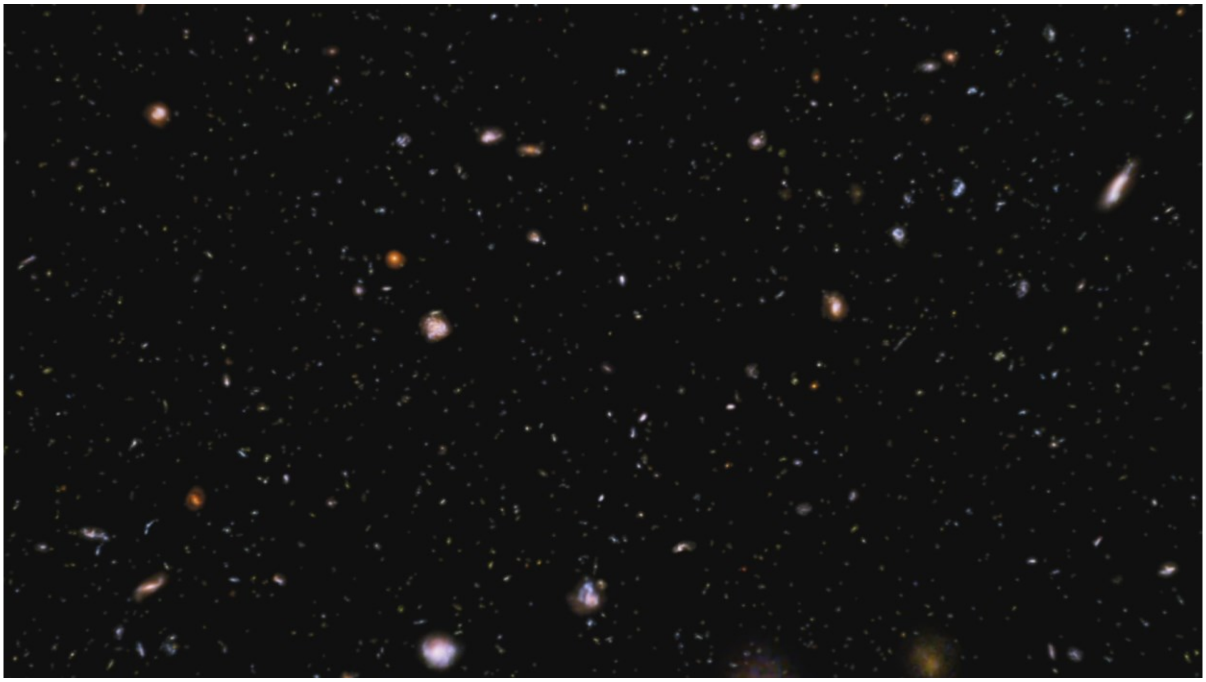
We then cover the creation of the Cosmic Background Microwave (CMB) radiation and what that tells us about the formation of galaxy walls around great voids. We then cover some of the recent galaxy surveys that are helping us understand the fabric of the visible Universe. These include the 2dF Galaxy Redshift Survey of 52,000 galaxies out to 3 billion light years, and the Sloan Digital Sky Survey that mapped one million galaxies. We show the 3D supercomputer video that shows the fabric of the Universe is like a web of galaxies with massive voids. We show some of the galaxy surveys that show this web-like structure.

We conclude with a review of the cosmic distance ladder and our last adjustment based on cosmological redshift. And we end with Edwin Hubble's own words on the limits of our knowledge.}

> *[**Music:** @00:00 Mendelssohn – "Violin Concerto in E Minor Op.64 Andante"; 101 Strings; from the album The Most Relaxing Classical Music, 1997]*

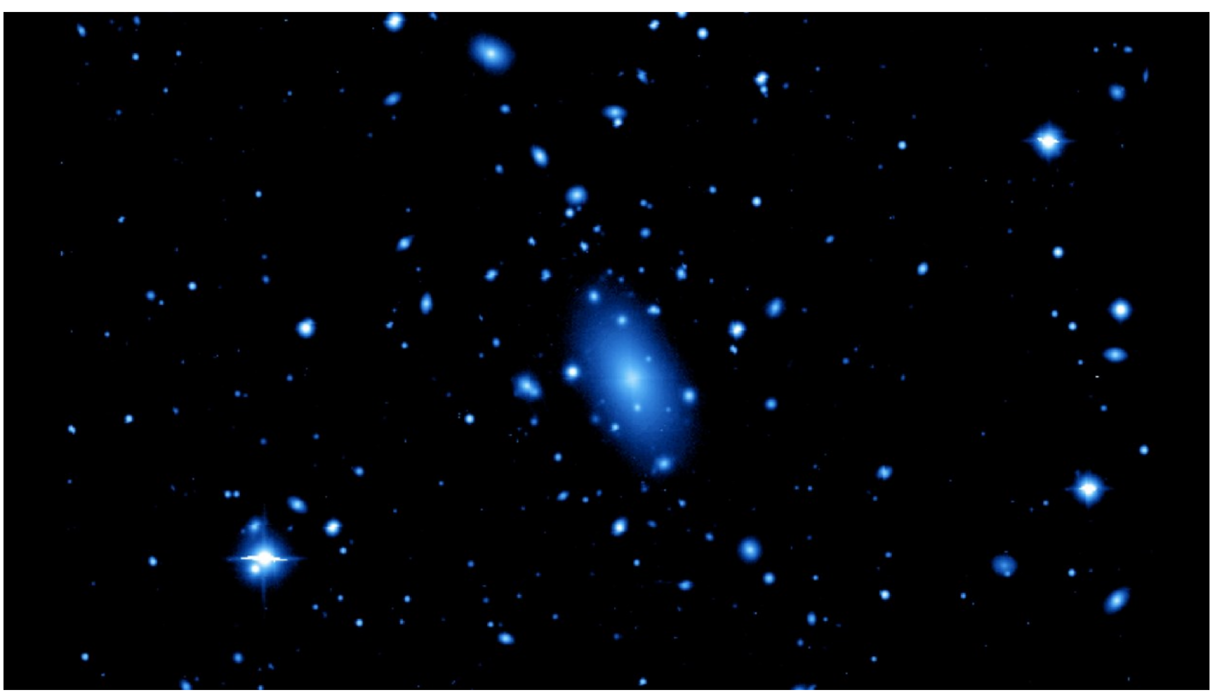
Beyond the Local Superclusters

In this final segment, we'll go beyond the 7% covered by Local Superclusters, and examine the Universe as a whole. At the end, we'll quickly review all the territory we've covered since we began our journey exploring the dimensions of the Earth. So, let's start with a look at some of the objects photographed by Hubble that lay beyond our Local Supercluster.

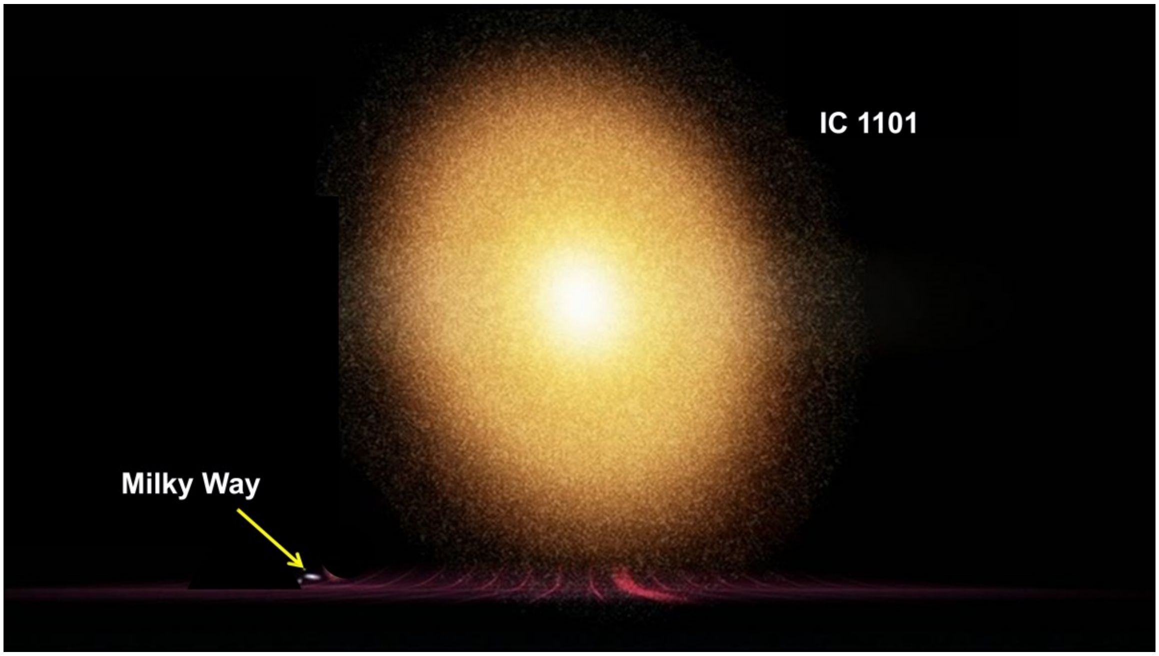


Abell 2029 with IC 1101 – 1,000 mly

This optical image shows the massive galaxy cluster Abell 2029. This galaxy cluster has a Redshift that indicates that it is one billion light-years away.

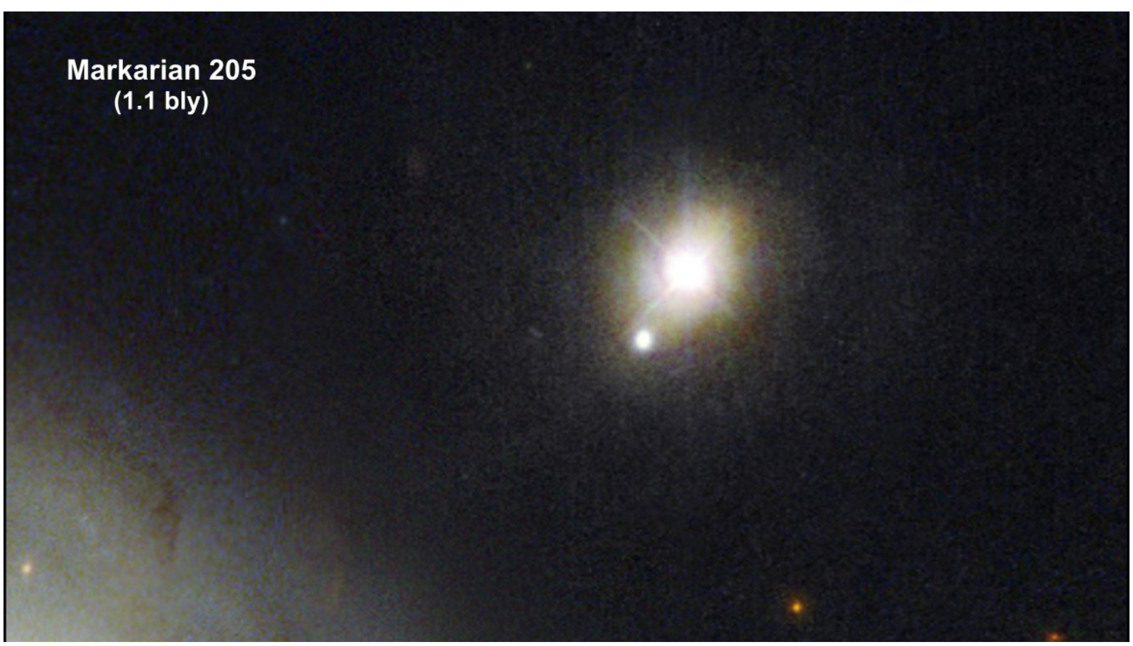


The large elliptical galaxy visible in the center of the image is IC 1101. It is the largest galaxy ever seen. It is 6 million light-years across – 60 times larger than our Milky Way, and it contains around 100 trillion stars!



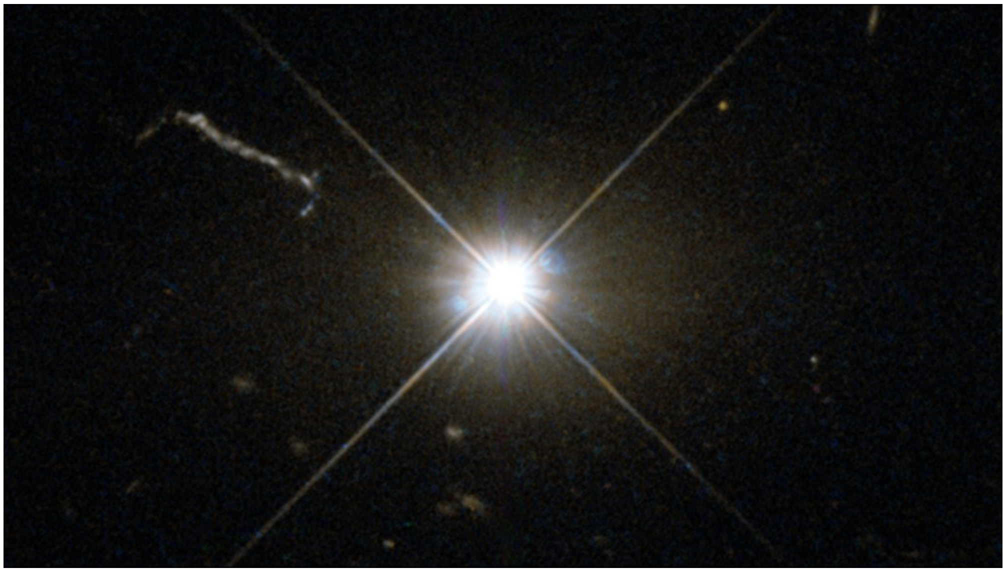
Markarian 205 – 1,100 mly

You might recognize NGC 4319. It is a galaxy in the Virgo Supercluster. Of interest now is the small light in the upper right. It's the quasar called Markarian 205. It's 1.1 billion light years away. Markarian 205 is a relatively nearby quasar. Many quasars reside much farther away. **[Additional info:** Markarian 205 has a companion, a compact galaxy just below it. The objects appear to be interacting. The compact galaxy may be responsible for the structure in Markarian 205's halo.**]**



Quasar 3C 273 – 2.5 bly

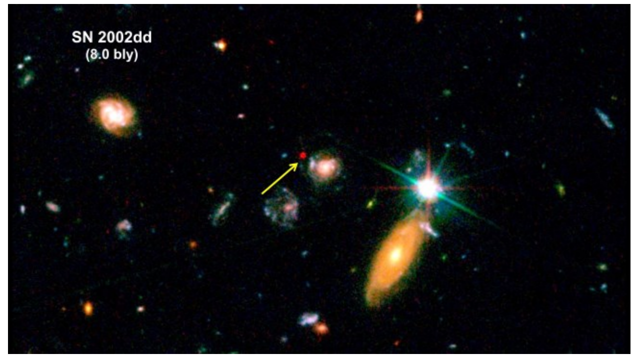
Quasars are the intensely powerful centers of distant, active galaxies, powered by a huge disc of particles surrounding a supermassive black hole. As material from this disc falls inwards, some quasars — including this one, have been observed to fire off super-fast jets into the surrounding space. In this picture, one of these jets appears as a cloudy streak, measuring some 200,000 light-years in length. Despite its great distance, 3C 273 is still one of the closest quasars to our home. It was the first quasar ever to be identified, and was discovered in the early 1960s. Quasars are capable of emitting hundreds or even thousands of times the entire energy output of our galaxy, making them some of the most luminous and energetic objects in the entire Universe. Of these very bright objects, 3C 273 is the brightest in our skies.



El Gordo – 7 bly
This is a combined ESO Very Large Telescope and Chandra image of the newly discovered galaxy cluster called El Gordo. It consists of two separate galaxy subclusters colliding are seeing what this cluster looked like when the Universe was only half its current age.

SN2002dd – 8,000 mly

Hubble is a 'supernova machine' for probing the early universe. Here's a type 1a it found that's approximately 8 billion light-years from Earth.

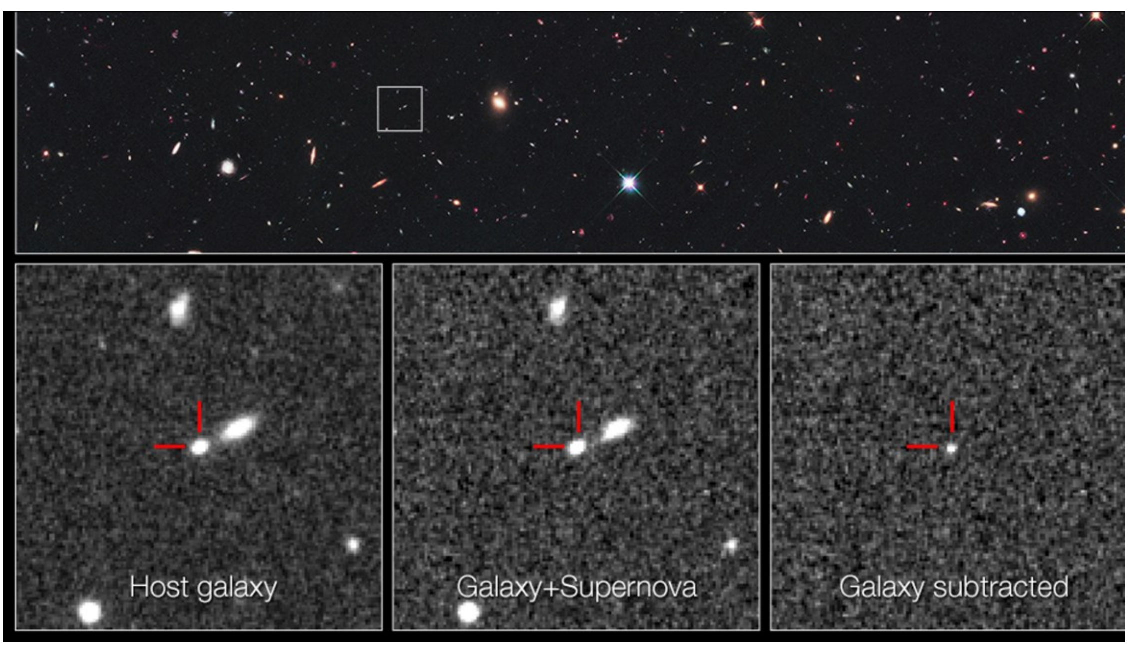


SN UDS10Wil – 10 bly

If you recall, type 1a supernova represent one of our most important standard candles because they are so bright, we can see them from very far away.

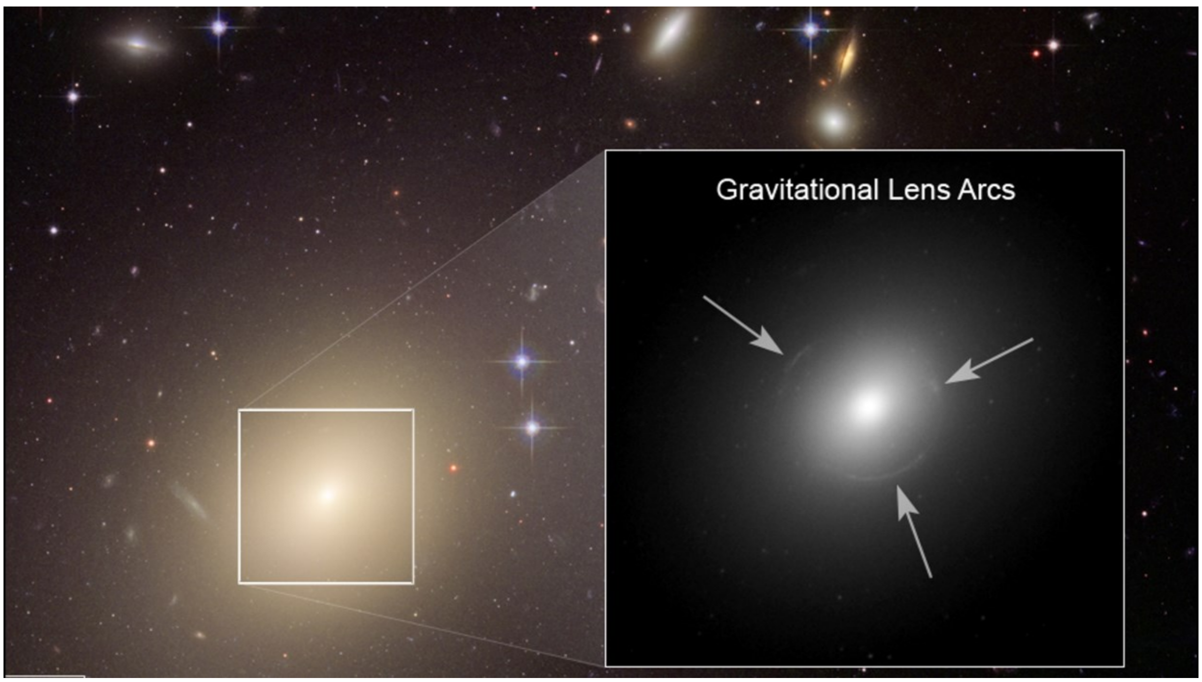
In 2013, Hubble broke the record in the quest to find the furthest type 1a with the discovery of SN UDS10Wil, a supernova that exploded more than 10 billion years ago at a time the Universe was in its early formative years and stars were being born at a rapid rate.

The image at the far left shows the host galaxy without the supernova. The middle image, taken a year later, reveals the galaxy with the supernova. The supernova cannot be seen because it is too close to the center of its host galaxy. To detect the supernova, astronomers subtracted the left image from the middle image to see the light from the supernova alone, shown in the image at far right.

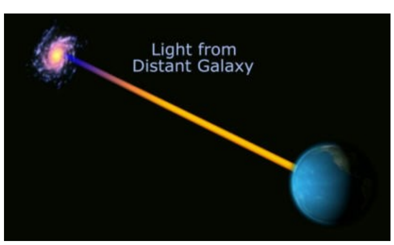


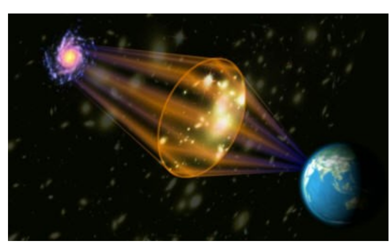
Gravitational Lensing

You'll remember the Einstein Ring we saw around ESO 325-G004 in our segment on Local Superclusters. The ring was the image of a more distant galaxy. The arc shape was created by the bending of the background galaxy's light by the gravity of the massive foreground galaxy. The process is called Gravitational Lensing because the mass between us and the background galaxy behaves just like an optical lens.



This same light bending leads to the warping of light from distant galaxies as the light encounters super-massive galaxies on their path to us. This is called gravitational lensing. Here's a clip that shows how this lensing works on a grand scale. A distant galaxy would be seen here on Earth directly if there were no intervening massive cluster to bend its light. But with such a cluster, the light from the distant galaxy gets bent into rings and arches that continue on to Earth.





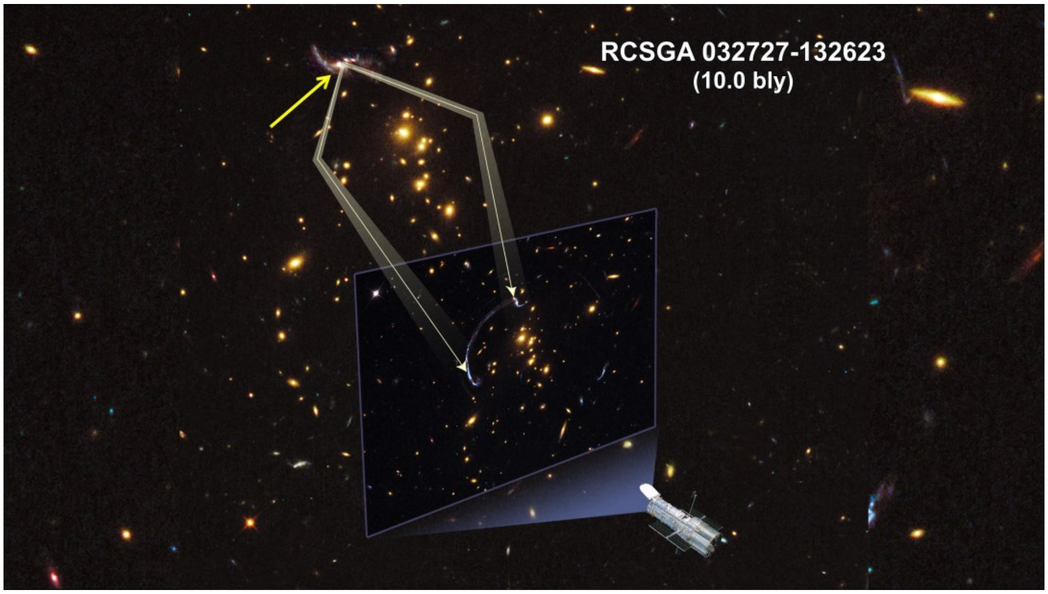
This is Abell 1689 [2.2 billion light years away]. It's one of the most massive galaxy clusters known. It's gravity acts like a 2-million-light-year-wide "lens" in space.

Abell 68 – 2.1 bly

Here again we see how the gravitational field surrounding this massive cluster of galaxies acts as a natural lens in space to brighten and magnify the light coming from very distant background galaxies. This galaxy is visible twice, because its light followed two separate paths around Abell 68 before reaching us.

RCS2 032727-132623 - 10,000 mly   RCSGA 032727-132609 – 5,000 mly

This is a close-up look at the brightest distant "magnified" galaxy in the universe known to date. It is one of the most striking examples of gravitational lensing. In this image the light from a distant galaxy, nearly 10 billion light-years away, has been warped into a nearly 90-degree arc of light in the galaxy cluster. The galaxy cluster that is bending the light lies 5 billion light-years away.

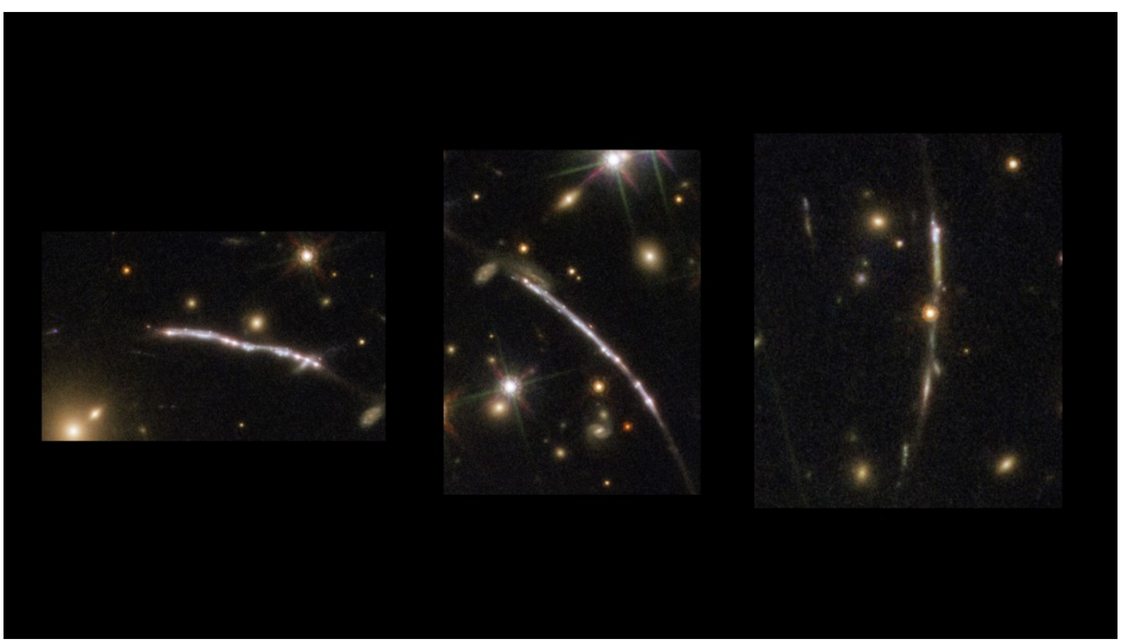


And here's MACS J0416.1–2403, 5.47 billion light years away. These foreground galaxy clusters are magnifying the light from the faint galaxies that lie far behind the clusters themselves. These faint lensed galaxies are around 12 billion lightyears away. It's the gravitational lensing that allows us to see that far back in time. Without the magnification, these galaxies would be invisible for us.

PSZ1 G311.65-18.48 Sunburst Arc galaxy – 11 bly

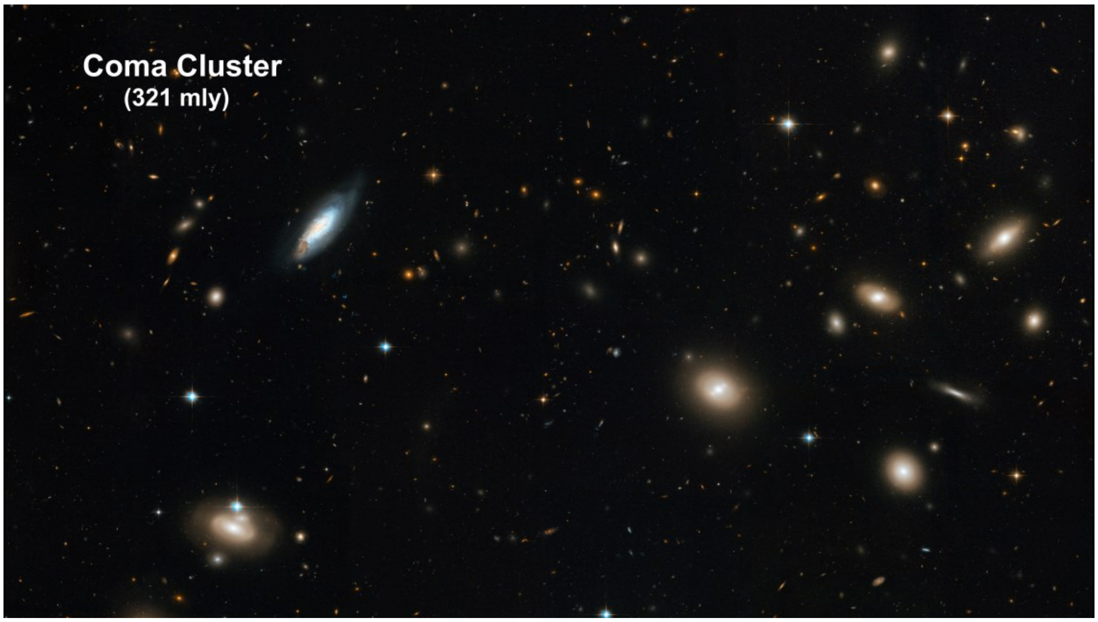
This Hubble image shows a massive galaxy cluster, about 4.6 billion light years away. Along its borders, four bright arcs are visible; these are copies of the same distant galaxy, nicknamed the Sunburst Arc. It's almost 11 billion light-years away. It's light is being lensed into multiple images by strong gravitational lensing. The Sunburst Arc is among the brightest lensed galaxies known and its image is visible at least 12 times within the four arcs.

Here's a closer look at three of them. The lens makes various images from 10 and 30 times brighter. This allows Hubble to view structures as small as 520 light-years across — a rare detailed observation for an object that far away.

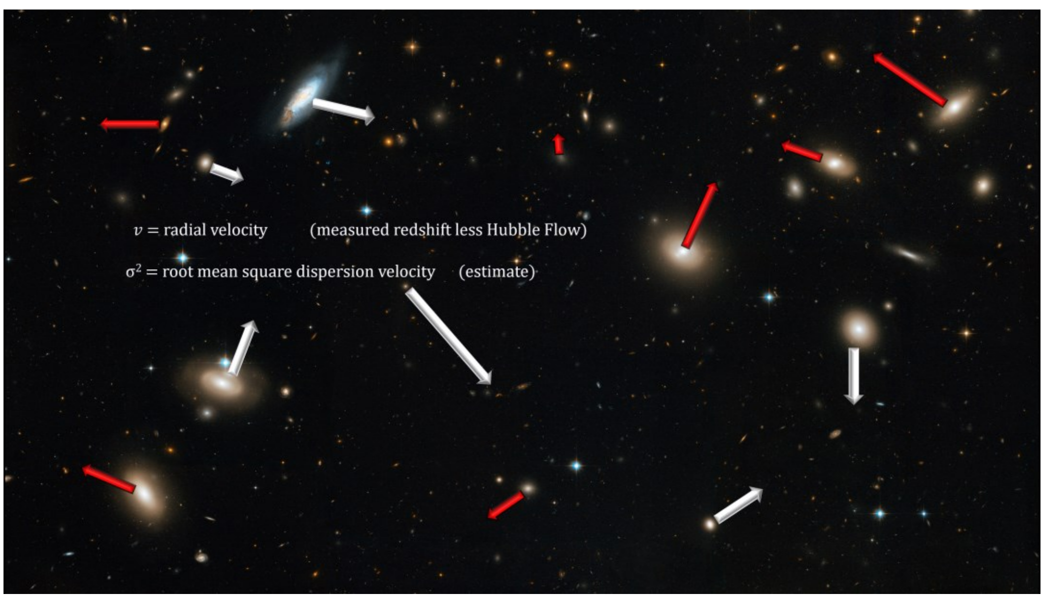


Dark Matter Discovery

Until the early part of the 20th century it went without saying that the matter we see is most of the matter there is. That would be protons and neutrons with accelerating electrons creating the light we "see". But that came into question in the early 1930s when Fritz Zwicky, a Swiss astronomer out of Caltech, studied the Coma galaxy cluster 321 mly away with a thousand galaxies spanning 25 mly in diameter. He looked at it in a number of ways – two of which are very revealing. In one he used galaxy motion to calculate mass and in the other he used galaxy luminosity.



His processes are not precise, but they do provide ballpark figures for the mass of the cluster. For motion, he had the cluster galaxy's radial velocities from the Doppler shifts in the light we see. He then generalized them into their three-dimensional velocity dispersion statistical equivalent.



This galaxy motion gives us the kinetic energy of the cluster. Zwicky used the well understood virial theorem that has the kinetic energy of a system equal to ½ its gravitational potential energy. This allows us to solve for the mass of the cluster. This is the mass as measured by its gravitational effects.

Gravitational Based Mass

$$E_K = -\left(\frac{1}{2}\right) E_P$$
$$E_K = \left(\frac{1}{2}\right) M\langle v^2\rangle$$
$$E_P = \left(\frac{1}{2}\right) GM^2/R$$
$$M = 6\sigma^2 R/G$$

Where

v = radial velocity (measured redshift less Hubble Flow)
$\langle v^2\rangle$ = root mean square velocity
σ^2 = root mean square dispersion velocity (estimate)
$\langle v^2\rangle = 3\sigma^2$ (for galaxy clusters)
E_K = kinetic energy
E_P = potential energy
M = mass of the cluster
R = radius of the cluster
G = gravitational constant = $6.67 \times 10^{-11}\ m^3kg^{-1}s^{-2}$
$M_\odot$ = Mass of the Sun = 1.99 x 1030 kg

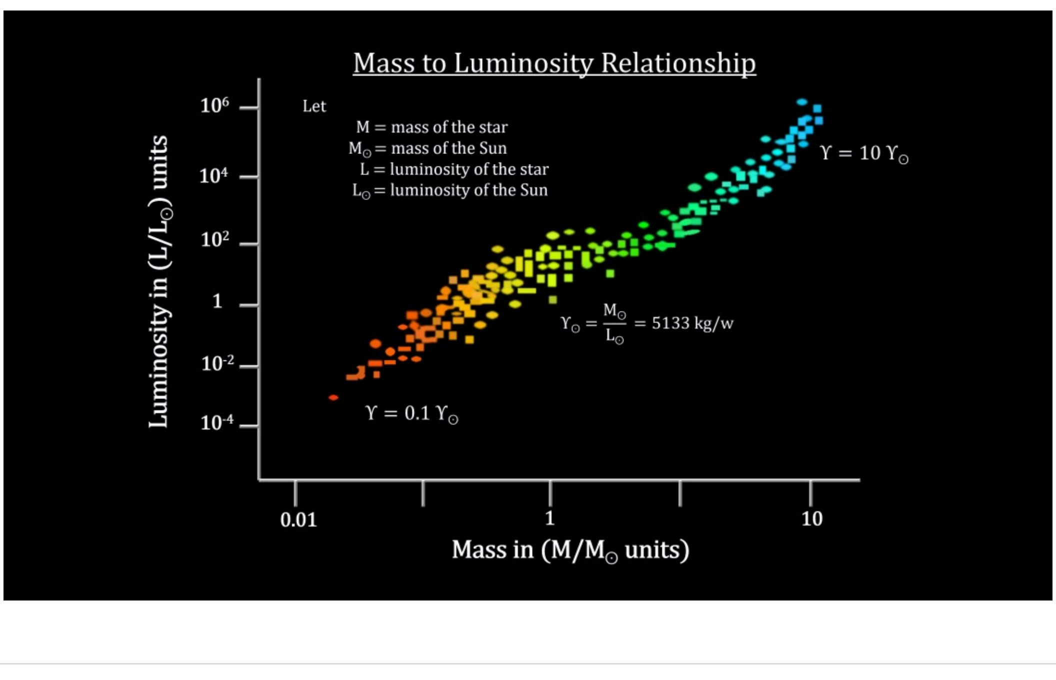
And for the Coma Cluster $M_\odot$

$\sigma^2 = 10^{12} m^2s^{-2}$
$R = 9.78 \times 10^6$ ly

We get

$M = 4.18 \times 10^{15}\ M_\odot$

The second way he calculated the cluster's mass was to use the cluster's luminosity. You may recall from our discussion of the Hertzsprung-Russel diagram in our "How Far Away is it" segment on "Distant Stars" that there is a relationship between a star's mass and its luminosity. We can use that relationship to estimate the mass of groups of stars by measuring their luminosity.



We use the mass to light ratio of the sun as the base for comparisons.

Luminosity Based Mass

Let

L_G = measured luminosity of analyzed galaxy

= $1.2 \times 10^{10}\ L_\odot$

$L_\odot$ = luminosity of the Sun

L = luminosity of the Coma cluster

M_G = mass of analyzed galaxy

$M_\odot$ = mass of the Sun

M = mass of the Coma cluster

N = number of galaxies in cluster

= 1000

Assume

$M/L = \Upsilon = 3M_\odot/L_\odot$

Then

$L = 1000\ L_G = 1.0 \times 10^{13}\ L_\odot$

$M/(1.2 \times 10^{13}\ L_\odot) = 3M_\odot/L_\odot$

$M = 3.6 \times 10^{13}\ M_\odot$

Zwicky measured the luminosity of the average galaxy in the Coma Cluster. Using a mass to light ratio of 3, he calculated its mass.

When he multiplied the average times the 1,000 galaxies in the cluster, he came out with a number that was over a 100 time less than the mass calculated via the virial theorem based on gravity. In other words, the motion of the galaxies in the cluster indicated a mass that was over 100 times the mass from luminous matter.

Mass Ratio

$$\frac{M_{gravitational}}{M_{luminosity}} = \frac{(4.18 \times 10^{15}\ M_\odot)}{(3.6 \times 10^{13}\ M_\odot)}$$

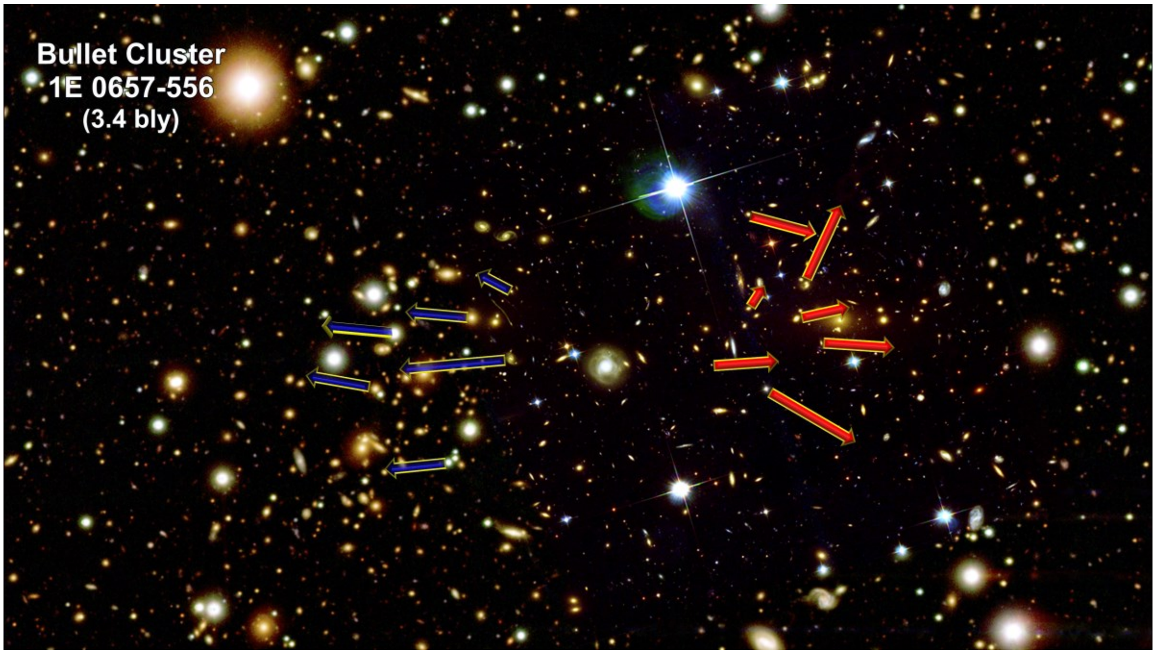
$$= 116$$

Zwicky concluded that either the laws of gravity as we know them (Newton's and Einstein's) did not work for volumes as large as the Coma Cluster, or the luminous matter is only a very small part of the total matter in the cluster. He called the rest of the matter – 'dark matter', and suggested that gravitational lensing would help quantify this dark matter. In the 1930s, nobody believed him.

[Music:** @11:55 Mozart - Piano Concerto No.21 in C 'Elvira Madigan' K.467 - Andante; from the album The Most Relaxing Classical Music, 1997**]

Bullet cluster - 3.4 bly

With this new understanding about the possibility and impact of dark matter, astronomers turned their attention-to galaxy clusters like the one studied by Zwicky in 1936. Our case in point is the galaxy cluster is known as the "bullet cluster." The virial motion of its galaxies indicates that a collision has occurred. Two massive clusters have passed through each other millions of years ago and the member galaxies are now flying apart.



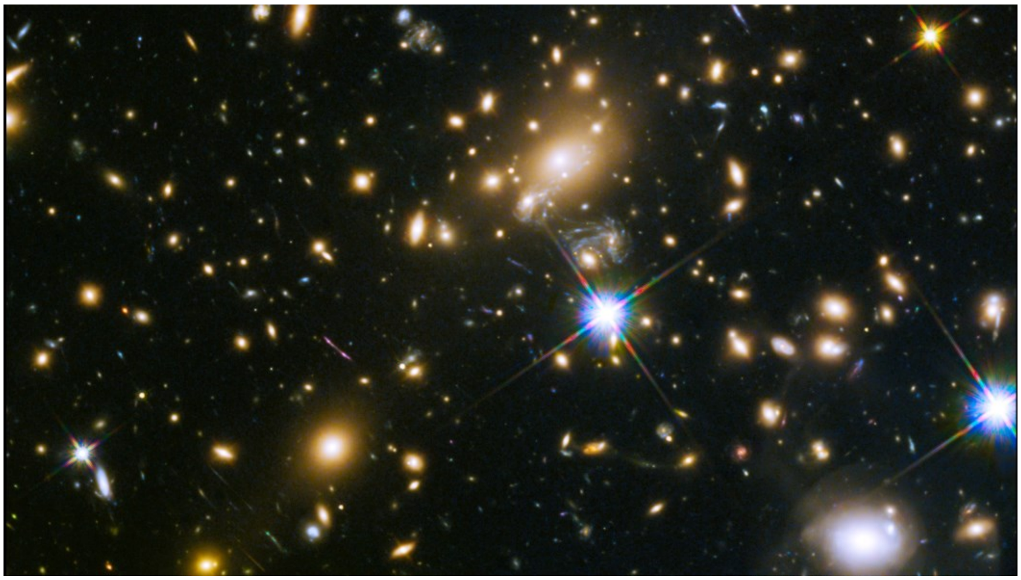
If we zoom in a bit closer, we can see the telltale arcs of more distant galaxies lensed by the gravity of the bullet cluster. Counting the lensed objects and the estimated amount of light bending involved for each one, a map of the areas containing most of the mass of the cluster can be superimposed on the visible image. We have used blue to indicate the locations where the vast majority of the matter must be located in order to get the observed lensing.

Here we have the cluster's hot x-ray emitting gas detected by the Chandra X-ray observatory. The two pink clumps contain most of the "normal," matter – sometimes referred to as baryonic matter or matter made up of protons and neutrons. The bullet-shaped clump on the right is the hot gas from one cluster, which passed through the hot gas from the other larger cluster during the collision.

When we superimpose the dark, baryonic and visible components of the cluster's mass we get the full picture. The galaxies and the dark matter have traveled a great deal further than the gas. This indicates that the galaxies and dark matter in the two colliding clusters did not interfere with each other. In other words, they passed through each other without slowing down. On the other hand, during the collision, the gas clouds were slowed by a drag force, similar to air resistance. This combination had the effect of separating the gas from the dark matter. This separation is considered to be direct evidence that dark matter exists. Measurement indicate that galaxy clusters on average have 85% dark matter, 14% intergalactic gas, and only 1% stars.

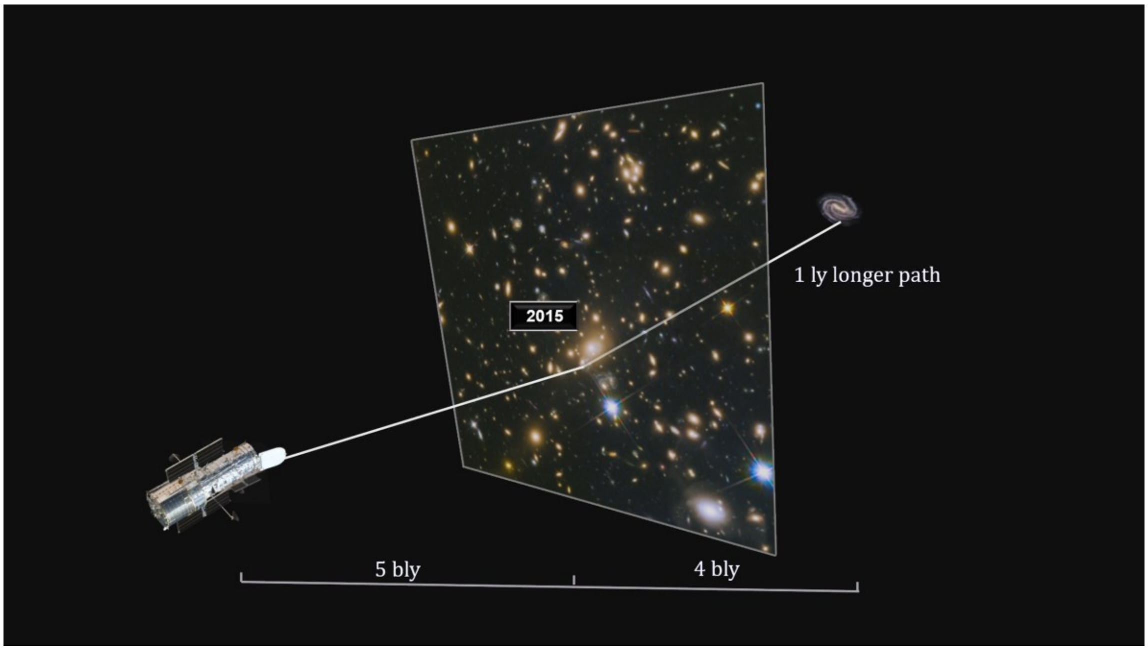
Dark Matter Gravitational lensing

In 2014, a team of astronomers found a supernova in this galaxy cluster [MACS J1149+2223] over 5 billion light years away.



The supernova actually happened in a galaxy 4 billion light years behind this cluster – making it 9 billion light years away. The huge mass of the foreground galaxy and the cluster bent the light from the distant supernova - creating four separate images of the same explosion. The images are arranged around an elliptical galaxy in a formation known as an Einstein cross – because he was the one who predicted these phenomena.

Following this discovery, astronomers modeled several possible gas and dark matter distributions in the galaxy cluster. Each model predicted that another image of this supernova will appear in the cluster, but they had different time estimates ranging from 2015 through 2025. In December 2015 it appeared. For the first time in history, the time and location of a supernova was accurately predicted. We actually saw the supernova happen. Instead of detecting a flash in the sky and turning telescopes to its location, we had the telescopes already focused on the correct area and recorded the event from beginning to end. This was powerful evidence for dark matter.

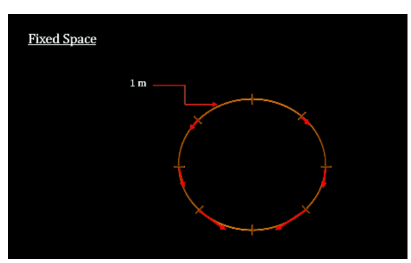


Expanding Space

In the 1920s, Edwin Hubble discovered that, except for a few nearby galaxies, all galaxies were moving away from us, and the further away they are, the faster they are moving. Along with the assumptions that there are no preferred places and directions in space, this means that all galaxies (not bound together by gravity) are moving away from each other.

The flow of all galaxies away from each other, with faster velocities the further away from each other they are, cannot happen in a fixed volume because, in a fixed volume, some reference frames would have to have distant objects heading towards them for others to have them moving away. It can only be explained if the space that these galaxies exist in is itself expanding. Here's a one-dimensional example to illustrate why this is the case.

Consider an 8-meter circle with marks one meter apart. If we are the top mark, and all the other marks are moving away from us, then from other points of view, marks are getting closer. The system is not homogenous.



But if the apparent motion is due to the amount of space expanding, we get a different picture. Here the marks hold their position on the line, but the line grows. Let's say each meter on the line expands to 2 meters over the course of a minute. We see that the distance between adjacent marks goes up one meter and their apparent velocity as seen by each other is 1 meter per minute. But more distant marks have increased their distance and velocity by more than that. And the further away any two marks are, the more their distance and velocity have increased. And most importantly, this will be the same no matter which mark is used for the reference frame.

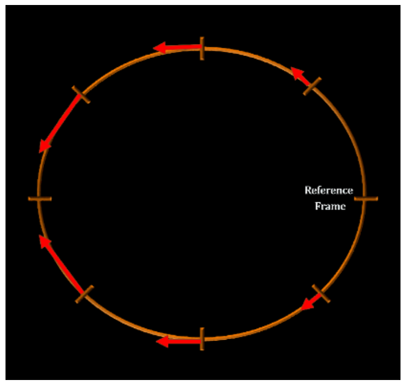
Expanding Space

If expansion = 1 m/min , then

$$K = V/R = (1m/min)/1m = 1/m = 1/60s = 1.67 \times 10^{-2} s^{-1}$$

Where

V = velocity of a mark
R = distance to the mark
K = constant of proportionality



Velocity Formula

$$V = K R$$

V = mark velocity
R = mark distance
$K = 1.67 \times 10^{-2} s^{-1}$

In order to illustrate the point, this example used an expansion rate that is 74 thousand trillion times greater than the actual expansion rate as determined by the Hubble constant.

$$\frac{K = 1.67 \times 10^{-2} s^{-1}}{H = 2.27 \times 10^{-18} s^{-1}} = 0.74 \times 10^{20}$$

]

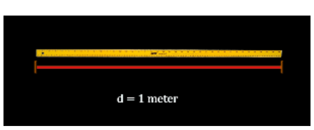
The real expansion is very slow. If we take a look at what the expansion does to one meter, we see that it would take a million years to expands by just 7 millionths of a meter. That's way too slow to ever notice or even measure in a lab in a lifetime. And it is why it's so easy to overcome it with local gravity out to the Andromeda galaxy.

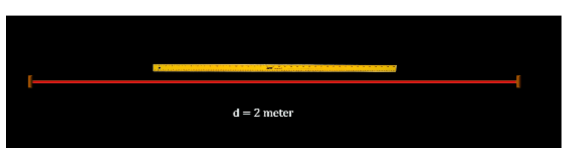
$$V = HR$$
$$V = 2.2 \times 10^{-18} m/s$$
$$\delta d = Vt = 6.94 \times 10^{-6} m$$

Where

V = expansion velocity
R = 1 meter
$H = 2.2 \times 10^{-18} s^{-1}$
δd = meter expansion
t = 1 million years $= 3.145 \times 10^{12}$ s

It should be noted that this expansion of space itself does not pull apart objects that exist in that space. A meter stick does not expand. That's because the size of the meter stick is determined by the forces that hold it together, and these forces are not changing.

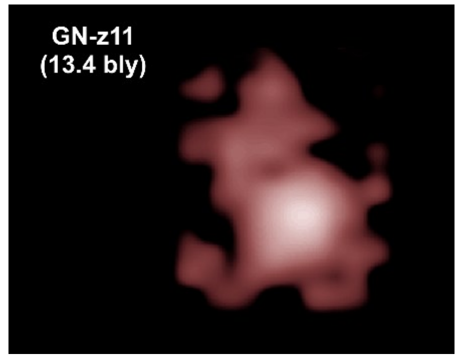




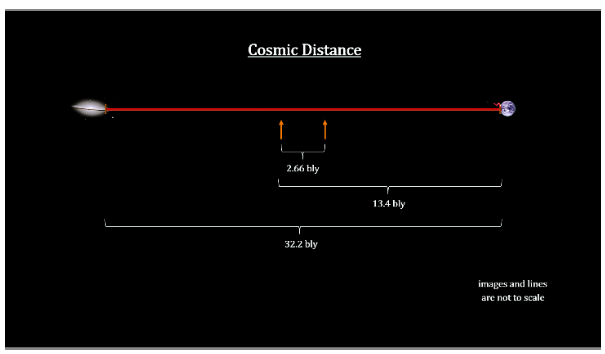
Cosmic Distance

Expanding space has significant implications for measuring distance.

Here we are zooming into GN-z11, the most distant object ever found. The galaxy's redshift combined with Hubble's law gives us the distance the light traveled – 13.4 billion light-years. And we know the speed of light so the time traveled was 13.4 billion years. We normally say that the galaxy is therefore 13.4 billion light years away.



But, during its long travel time, space expanded considerably. In fact, GN-z11 was less than 2.7 billion light years away from us when the light started its journey. And the galaxy is now over 30 billion light years away. In order to calculate these distances, we need to know how the Universe expanded during the light's journey.

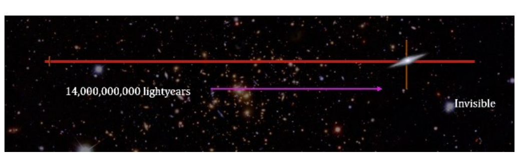


Visible Horizon

Note that, if a galaxy is far enough away, its apparent velocity will be faster than the speed of light – and its light would never reach us. It would be beyond the physical visible horizon for the Universe. It's not that it is moving through space that fast, it's just that more space is being created per second between us and them than light can travers in one second. Plugging in the numbers, we find that all galaxies beyond 14 billion light years could never be seen here. GN-z11 is now 32 billion lightyears away, so the light that is leaving GN-z11 now, can never reach us.

Let

V_c = speed of light = 3×10^8 m/s
$H = 2.27 \times 10^{-18} s^{-1}$
R_h = visible horizon



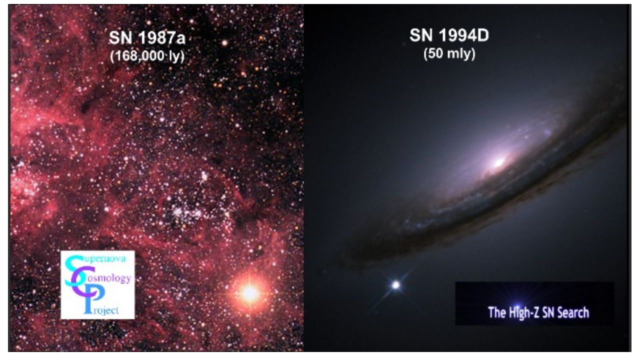
Then

$V_c = H\,R_h$
$R_h = V_c / H$
$= (3\times10^8 ms^{-1}) / 2.27 \times 10^{-18} s^{-1}$
$= 1.32 \times 10^{26}$ m $= 14\times10^9$ ly

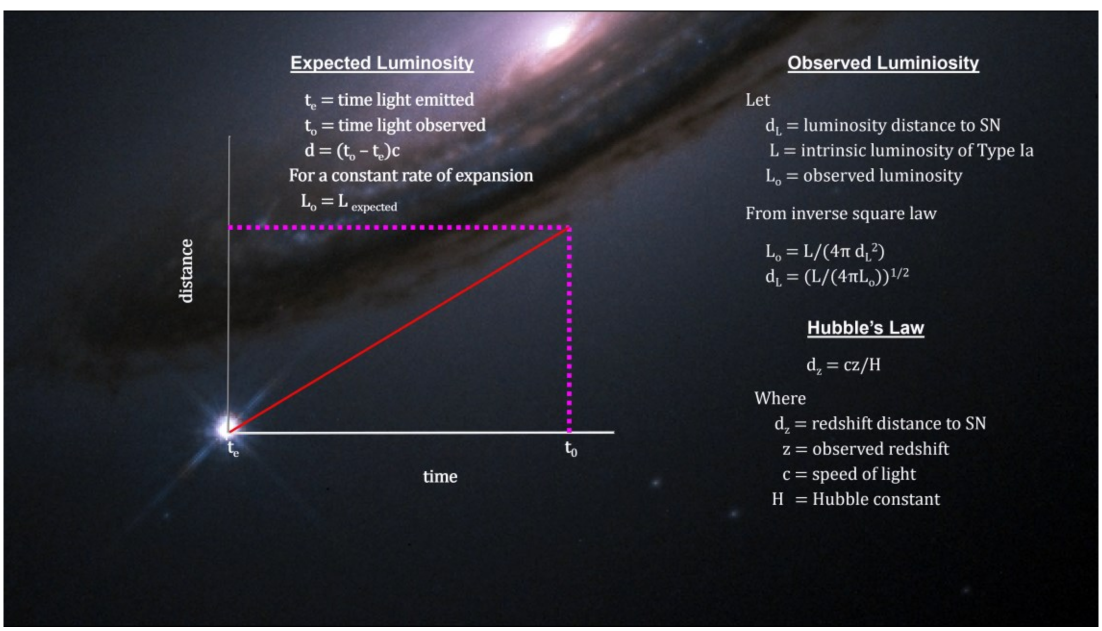
*[**Music:** @21:34 Rachmaninov - Piano Concerto No 2 in C minor; from the album The Most Relaxing Classical Music, 1993]*

Accelerating Expansion

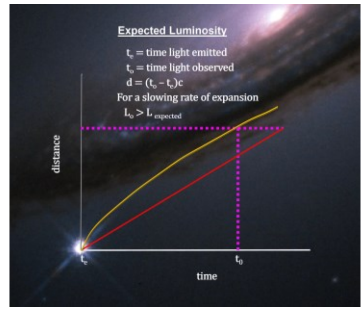
After Hubble discovered that the Universe was expending, it was assumed that it started off with a tremendous expansion rate and because of the gravitational attraction of all the matter in the Universe, the expansion would be slowing down. Two major efforts were started in the late 1990s to prove that the Universe's expansion was decelerating. Both groups used distant Type 1a Supernova as their standard candles. One examined SN 1987A and the other examined SN 1994D.



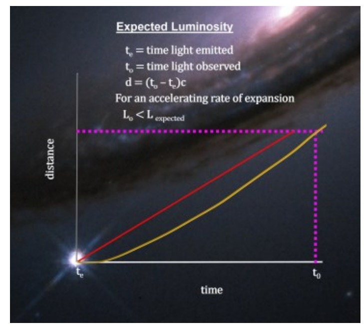
Supernovae provide a luminosity reading that enables us to determine their distance via the inverse square law. This distance is called the luminosity distance. Type 1a Supernova also provide a redshift reading that gives us the distance via Hubble's Law [$d_z = cz/H$]. Luminosity and redshift combined can tell us if the expansion is constant, decelerating or accelerating. Here's how it works. First, we measure the luminosity of a distant type 1a SN like SN 1994D and measure its redshift. Second, we calculate the luminosity distance via the inverse square law, and the redshift distance via Hubble's Law. Then we map the distance between us and the SN over time. If the expansion rate is constant, the luminosity distance and the redshift distance will be the same.



But if the expansion is slowing down, the expansion rate in the past would have been greater than what we see now. Which means, it would have taken a shorter time to expand from its size at light emission time to its present distance compared to a non-accelerating universe. This would result in a shorter light-travel time, shorter distance traveled and a brighter observed supernova compared to a non-accelerating universe.



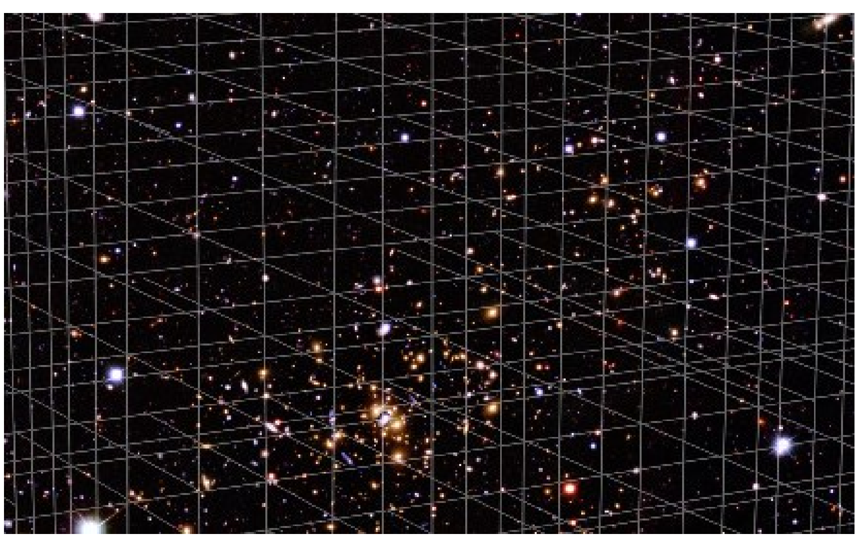
By the same token, if the expansion is speeding up, the expansion rate in the past would have been smaller than what we see now. Which means, it would have taken a longer time to expand from its size at light emission time to its present distance compared to a non-accelerating universe. This would result in a longer light-travel time, larger distance traveled and a dimmer observed supernova compared to a non-accelerating universe. This is what both studies found.



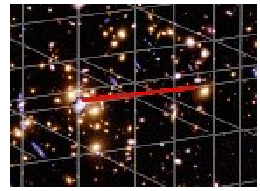
The universe is expanding and the expansion is accelerating! [This also means that the Hubble Constant is not constant. It is changing over time. We call it the Hubble parameter with H_0 used to identify the value at the current time.]

The Cosmic Scale Factor

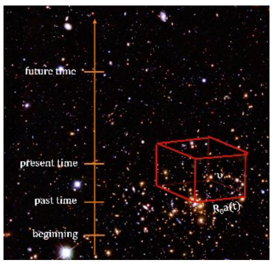
In order to more precisely analyze our expanding Universe, modern cosmology places a grid over our three-dimensional space.

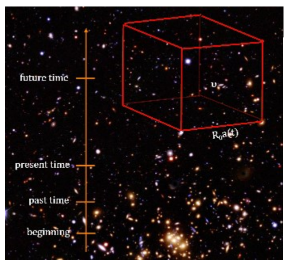


We treat the distance between two galaxies (R) as a constant. Then, we set the grid's scale factor 'a' equal to one at the present time, and vary it, to account for changes in distances over time instead of changing R.



Now consider a cube inclosing a volume of space containing some number of galaxies. With our scale factor approach, the amount of matter inside the volume remains the same as the volume increases or decreases. But the matter density goes down when the scale factor increases, and it goes up when the scale factor decreases. We see that matter density depends on the scale factor.

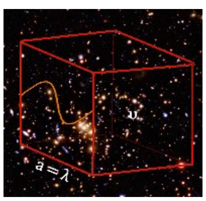




Let
- D = distance
- V = velocity
- A = acceleration
- R_0 = current distance
- a(t) = scale factor
- υ = mass in unit volume
- ρ = mass density

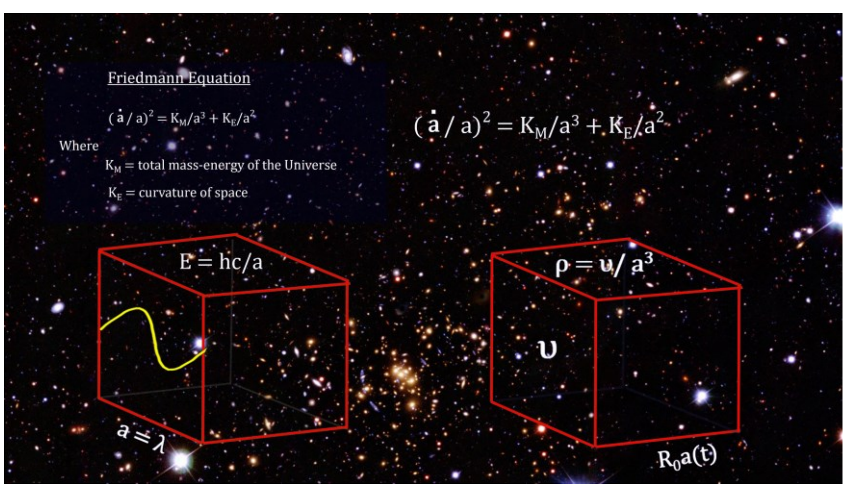
Then
- $D = R_0\, a(t)$
- $V = R_0\, \dot{a}$
- $A = R_0\, \ddot{a}$
- $\rho = \upsilon / a^3$

Unlike matter that moves through space, photons are attached to the space they propagate through. So, an expanding space will impact photons in a way that does not affect matter.



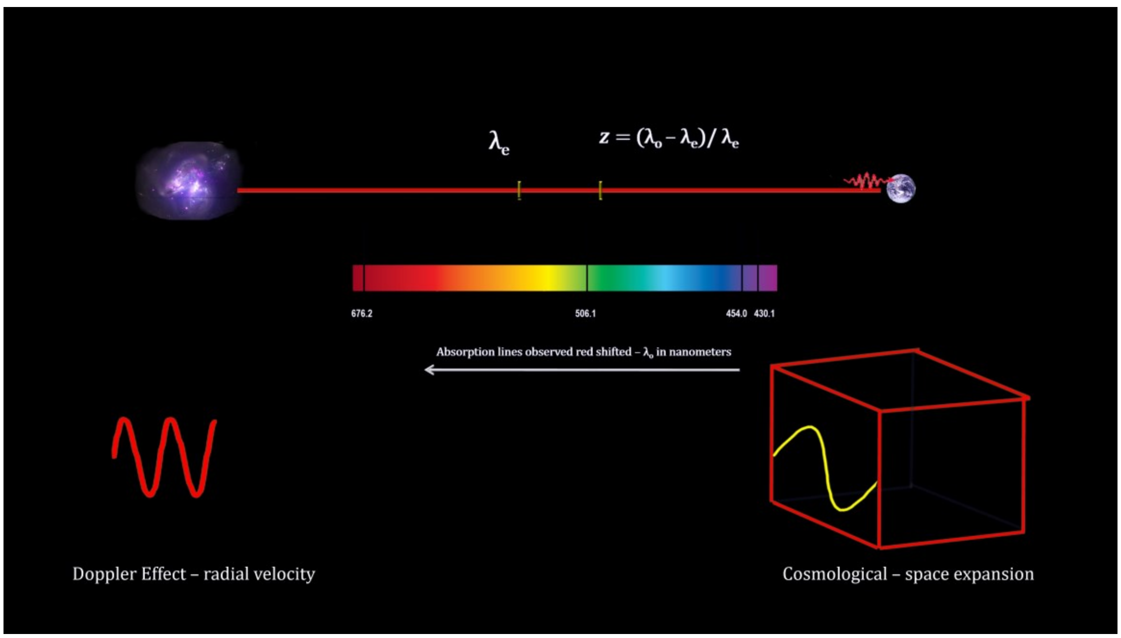
Here's a cubic volume of space with a photon inside. The photon's wavelength (λ) is equal to the length of the cube (a). Its energy is equal to Planck's constant time the speed of light divided by the wavelength (E = hc/λ).

As the wavelength increases with an increase in the scale factor, the energy decreases - unlike matter where it remained constant. We see that the energy density also depends on the scale factor. In fact, we find that the scale factor 'a' is the only variable. In other words, the history of the Universe comes down to the history of the scale factor. And the history of the scale factor depends completely the contents of the Universe and how that content effects the space it exists in.



Cosmological Redshift

When we observe light from distant galaxies, we are seeing the light from the stars in those galaxies. And that light has absorption lines. The same lines measured in a lab give us the wavelength of the light at the time it was emitted. A stretching of the wavelength creates a shift in the spectral lines to the red. For our nearby galaxies, light travels for a relatively short period of time, so the stretching due to space expansion is small. Our use of the doppler effect that shifts spectral lines as the basis for determining radial velocities provides excellent measurements. But as the distance increases to hundreds of millions and billions of light years, space expansion becomes the dominant factor. In either case, we continue to measure redshift z as the difference between the wavelength emitted and the wavelength observed divided by the wavelength emitted. In this hypothetical example, we have an object with a redshift equal to 6.



Once a model for the change in the cosmic scale factor over time is specified, redshift gives us a great deal of information. For now, we'll assume a flat, matter dominated universe.

Matter Dominated flat model

$$\mathbf{H_0} = 2.2 \times 10^{-18} s^{-1}$$
$$\Omega_r = 0$$
$$\Omega_m = 1$$
$$a(t) = \left({}^{t}/_{t_0}\right)^{2/3}$$

First, redshift gives us an object's receding velocity. With our model, we have the object moving away at 6 times the speed of light. Redshift also gives us the actual cosmic scale factor at the time the light was emitted. When the light we see from this object started, the Universe was a little over a tenth of its current size.

Z Scale Factor & Time

$$V_r = zc = 6c$$
$$a(t_e) = 1/(z+1) = 0.14$$

It gives us the age of the universe at the time the light was emitted, and the amount of time the light was traveling. We're seeing it as it looked almost 8 billion years ago when our Universe was only 2 billion years old.

$$t_0 = 2/3H_0 \quad = 9.6 \text{ billion years}$$
$$t_e = t_0 a(t_e)^{2/3} \quad = 1.9 \text{ billion years}$$
$$\text{Light travel time} = t_0 - t_e = 7.7 \text{ billion years}$$

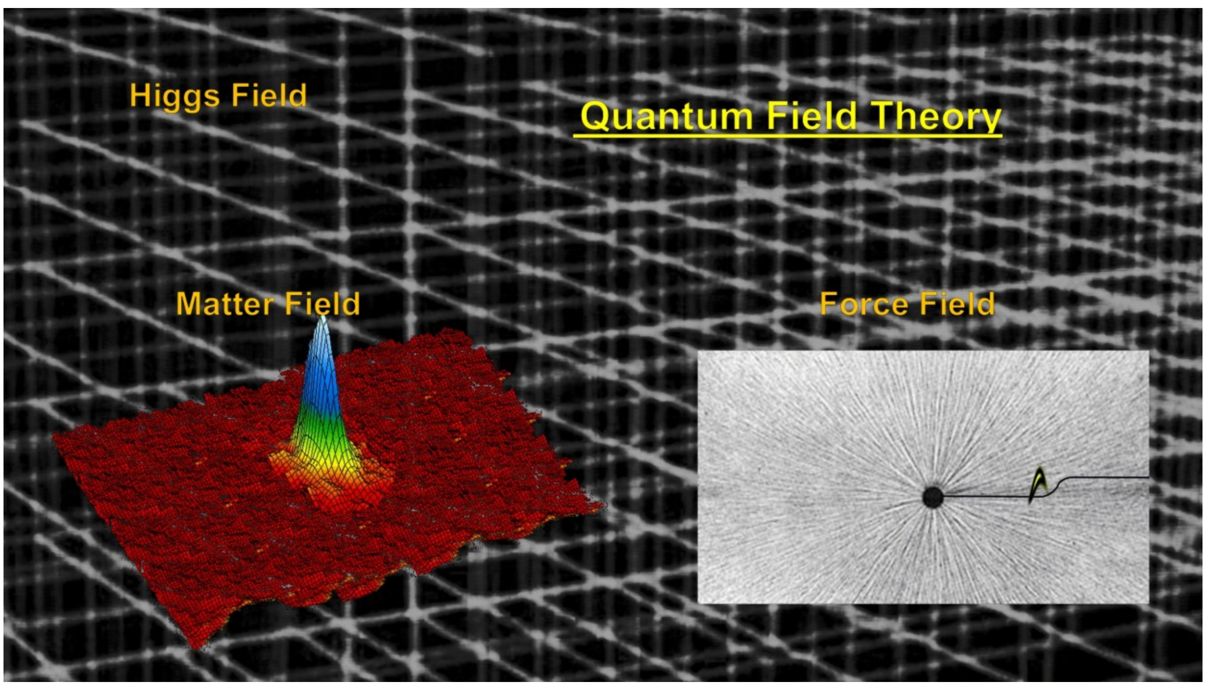
Redshift gives us the distance to the object at the current time. And it gives us the distance to the object at the time the light was emitted. You can see why astronomers rely so heavily on redshift measurements.

$$d_p(t_0) = c\int_{t_e}^{t_0} \frac{dt}{a(t)^{2/3}} = c\int_{t_e}^{t_0} \frac{dt}{\left({}^{t}/_{t_0}\right)^{2/3}} = \frac{2c}{H_0}\left[1 - \frac{1}{(1+z)^{1/2}}\right] = 18 \text{ bly}$$

$$d_p(t_e) = \frac{d_p(t_0)}{(1+z)} = 2.6 \text{ bly}$$

Dark Energy

We now ask, what could be accelerating the expansion of the Universe. In the How Small Is It video book chapter on the Higgs Boson, we covered how so-called empty space is actually filled with matter and energy fields.



We model the waves in these fields as quantum harmonic oscillators. And, given the Heisenberg Uncertainty Principle, the Zero Point Energy for any wave in the field must be greater than zero.

Harmonic Oscillator Energy Levels

$E_n = (n + \hbar\omega/2)$

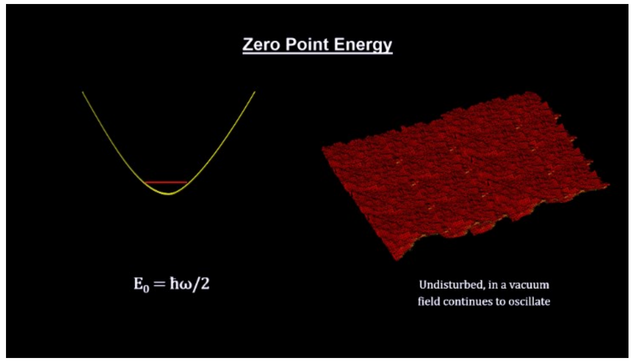
Where

E = energy

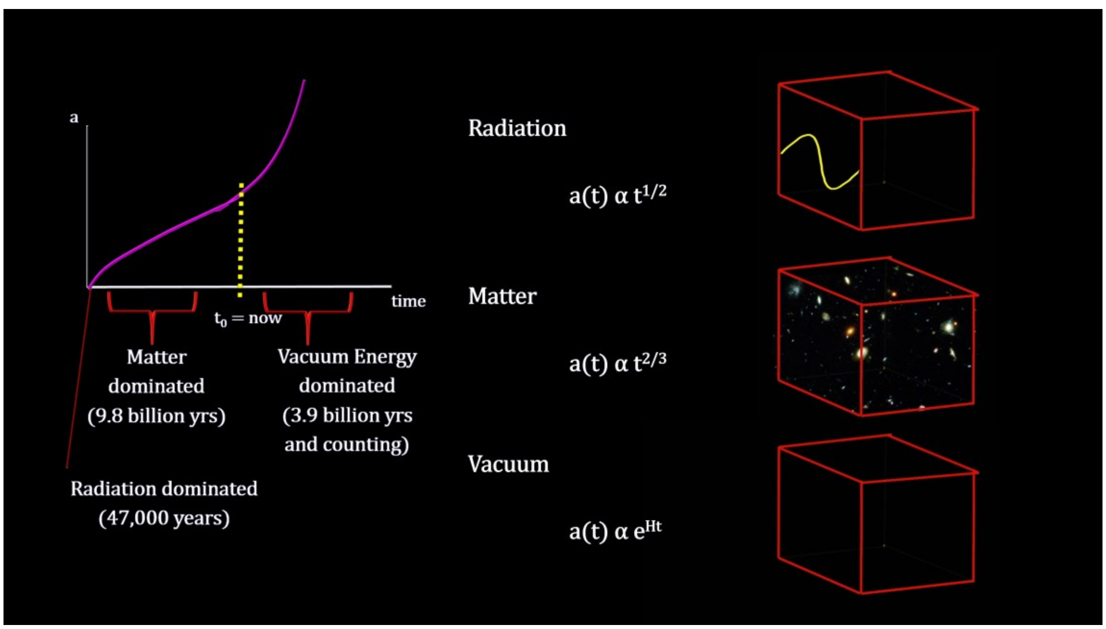
n = energy level

$\hbar$ = (Planck's constant)2π

$\omega = 2\pi$(frequency)

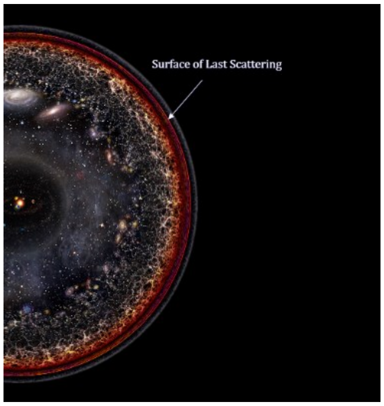


We have seen that radiation and matter in the universe are diluted as space expands. But zero-point vacuum energy does not dilute. In fact, the total amount of vacuum energy increases with the volume of the Universe. In a small Universe, it would have little impact. But today, it is estimated to be almost 70% of the energy density of the Universe. This zero-point quantum vacuum energy is called 'Dark Energy'. And it is enough to force the Cosmos into its accelerating expansion.



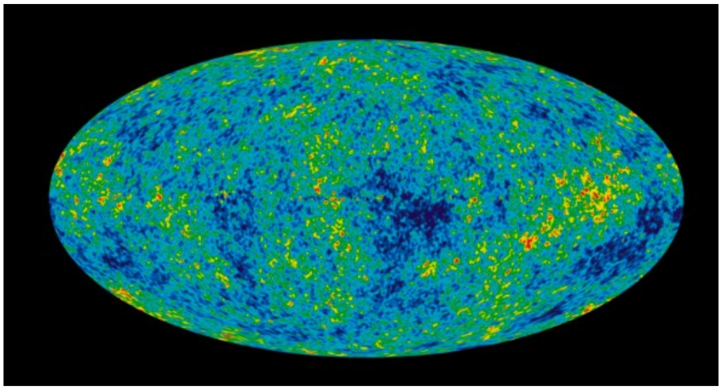
Surface of Last Scattering

As we observe the space around us, we see our solar system, our galaxy, and our local group of galaxies first. We then see significant numbers of large well-formed galaxies in our local supercluster and nearby superclusters. The further out we see, the further back in time we go. And the further back in time we go, the more we notice a reduction in the size and structure of the galaxies. Eventually, we reach as far as the first galaxies to ever form from the first stars that started to shine. Before that, there was just hydrogen and dark matter. No light was being created for us to see.



As we look back in time, we are also looking back at an ever-shrinking volume because the Universe was getting smaller. And its temperature was getting hotter. Eventually, it reached 3000º K. At that point, hydrogen atoms began to disassociate into protons and electrons, and space became opaque. Coming back the other way, the surface where the transition from opaque to transparent occurred is called the Surface of Last Scattering. At that time, all the photons in the Universes were released.

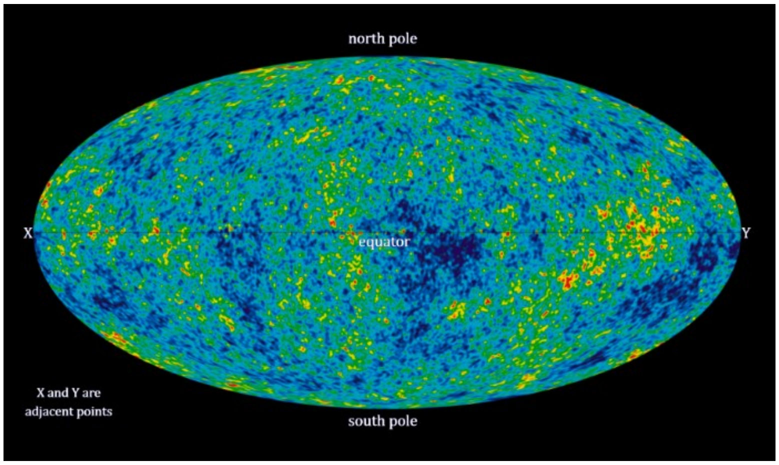
Those photons are still with us today. We see them all across the sky in tremendous numbers. They are the Cosmic Microwave Background (CMB) photons. And they tell us a great deal about the past, present and future of the Universe.



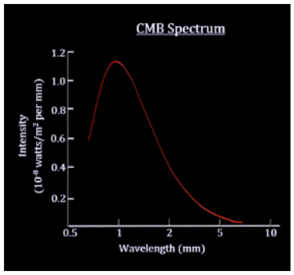
[Music:** @32:18 Mozart - Clarinet Concerto in A from the album The Most Relaxing Classical Music, 1997**]

CMB Radiation

Here's a projection of the celestial dome – the sky – as seen by the Planck satellite. It is the most detailed map ever created. [And it factors out our orbit around the Sun, the Sun's orbit around the center of the galaxy, and the orbital motion of our galaxy around the center of the Local Group, as well as the Local Group's motion in the direction of the Hydra cluster. It comes to 630 km/s. That's 0.2% of the speed of light (1.41 million miles per hour).]



The key observation is that the light fits the blackbody radiation curve almost perfectly. [Its mean wavelength is around 2 mm, and its peak intensity has a wavelength of 1 mm. That's in the microwave range. That's why we call it cosmic microwave background radiation.]



This gives us the temperature of the radiation today. It is 2.725 K. We know that at decoupling it was 3000 K. So, the temperature has been reduced by a factor of 1,100.

Wien's Formula

$$T = b/\lambda_{max} = b/1.0634\text{ mm} = 2.725\text{ K}$$

Where

$$b = \text{Wien's Constant}$$
$$= 2.8977685 \times 10^{-3}\text{ mK}$$

[We also know that the ratio of the current temperature to the temperature at decoupling is equal to the ratio of the current scale factor to the scale factor at decoupling.] So, the Universe has expanded by a factor of 1,100 times since decoupling.

$$\lambda_{today} / \lambda_{decoupling} = a_{today} / a_{decoupling} = T_{decoupling} / T_{today}$$

$$= 3000\text{ K}/2.725\text{ K} = 1100$$

The blackbody radiation formula also gives us the number density of CMB photons. There are over 400 million of them in every cubic meter of space throughout the cosmos. This is a thousand times more than all the photons from all the starlight ever created by all the stars in all the galaxies for all the billions of years that stars have been shining.

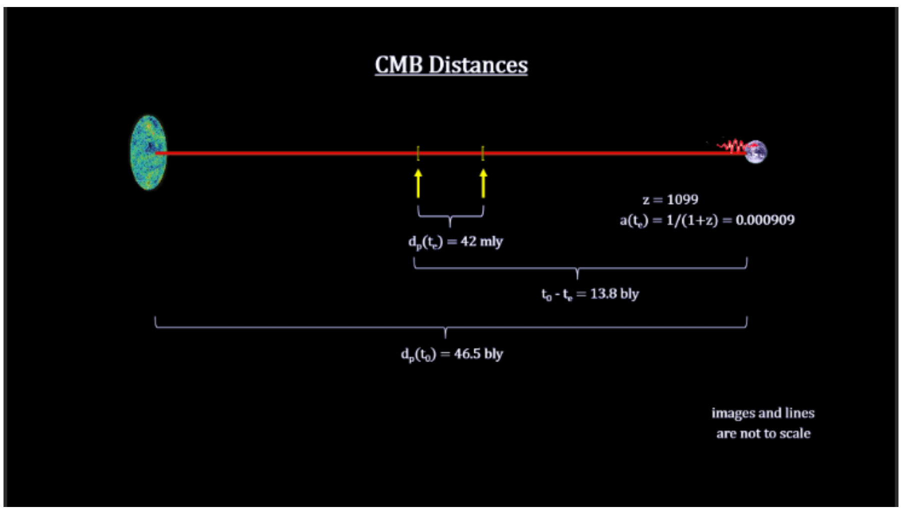
$$n_{\gamma,0} = \varepsilon_{\gamma,0} / E_{mean}$$
$$= 0.2606 \text{ MeV m}^{-3} / 6.34\text{x}10^{-4}\text{eV}$$
$$= 4.107\text{x}10^{8} \text{ m}^{-3}$$

Where

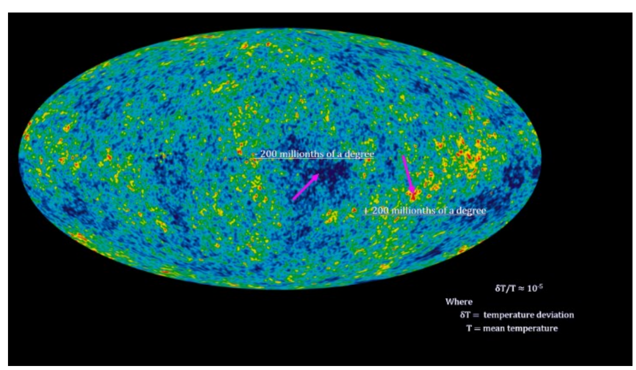
$\varepsilon_{\gamma,0}$ = current energy density

E_{mean} = current mean photon energy

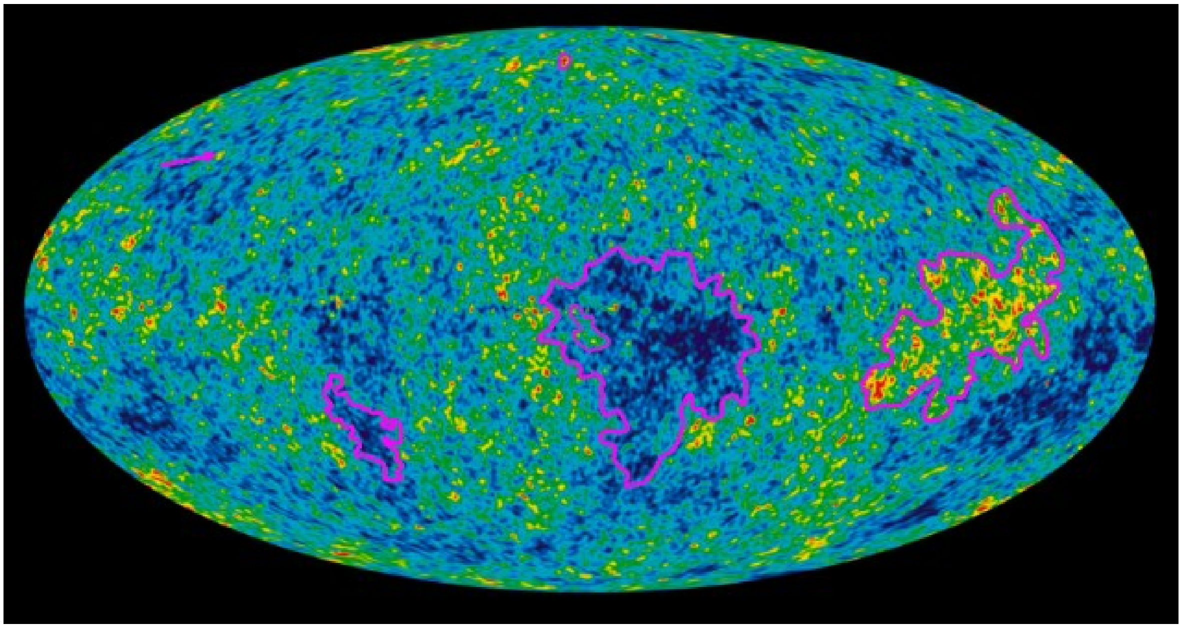
The CMB redshift tells us that the light we see now was only 42 million light years away from our location when it was emitted. It traveled for just under 13.8 billion years to reach us, and its starting location is now 46.5 billion light years away – making the diameter of the visible universe 93 billion light years.



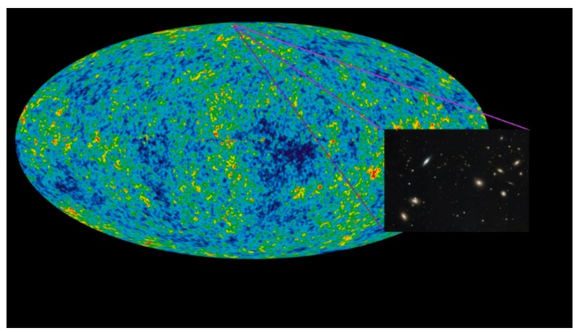
The Planck satellite measurements detected small amounts of temperature deviation. The image uses color to show variations from the average with blue for -200 millionths of a degree through green and yellow to red for +200 millionths of a degree. That temperature deviation comes to 1 part in 100,000. These temperature deviations come from equally small mass density deviations in the plasma at the time of decoupling.



We see large structures, small even tiny structures, and giant structures. We even see structures within structures at every scale. In other words, they're quite fractal in nature.



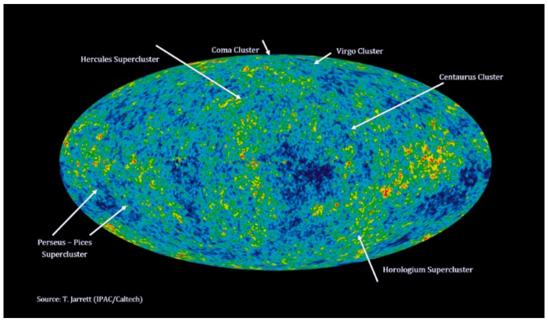
These small-scale differences in the CMB are what lead to the large-scale structures such as galaxy clusters, filaments and voids that we see today. For example, a very tiny spot of red on the Surface of Last Scattering, representing a small decrease in mass density in that region, will have expanded 1,100 times to the size of the Coma Cluster today.

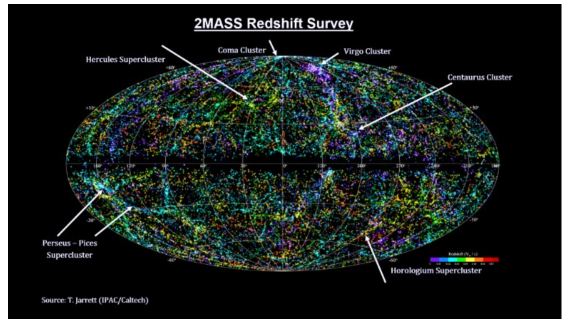


[The fact that there is a Cosmic Microwave Background with all these characteristics, is one of the most important pieces of evidence we have that verifies and validates our current Big Bang model of the universe.]

Fabric of the Cosmos

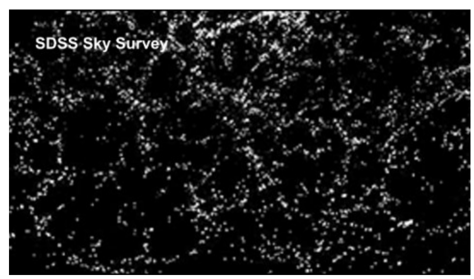
Just how the Universe evolved from small scale matter deviations at the time of decoupling to filaments of superclusters and vast voids can be explained by a physical process called Caustics. Originally developed to explain light behavior, it works just as well for protons and dark matter.



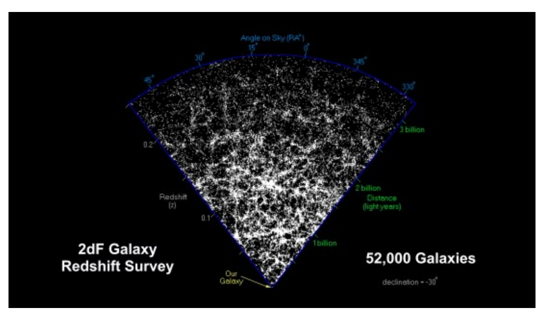


I see this phenomenon in my own back yard. The lines at the bottom of a swimming pool are examples of caustics caused by small waves on the water's surface.

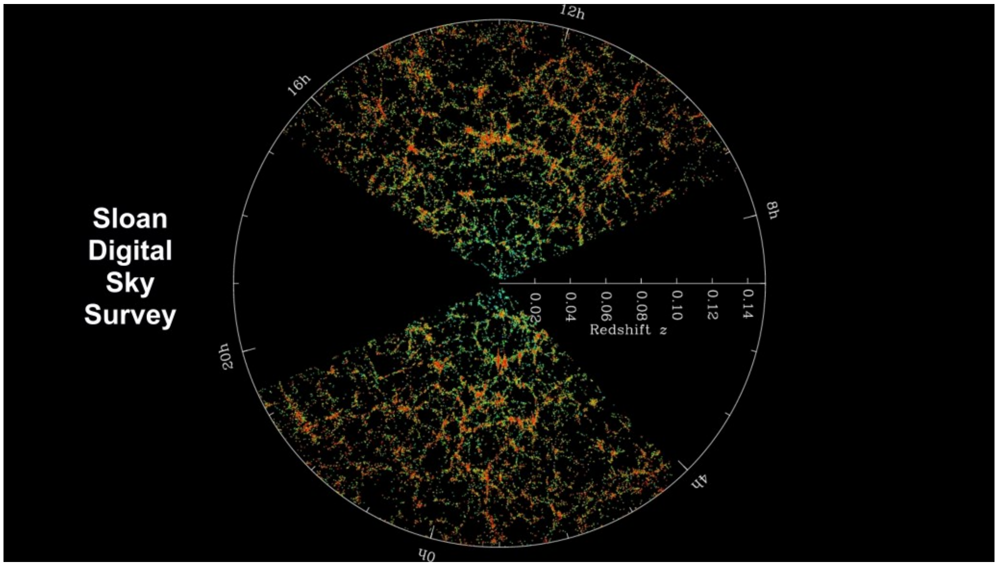
And, when we extend this to three dimensions, we get curved surfaces with increased density that intersect along lines that intersect at points. This is the web like pattern we see in the large-scale Universe.



By collecting distances to thousands of galaxies in a narrow strip of the sky, it is possible to produce a slice of the universe, like this one from the 2dF Galaxy Redshift Survey. In 2003, this survey looked out into the universe to 3.5 billion light years.



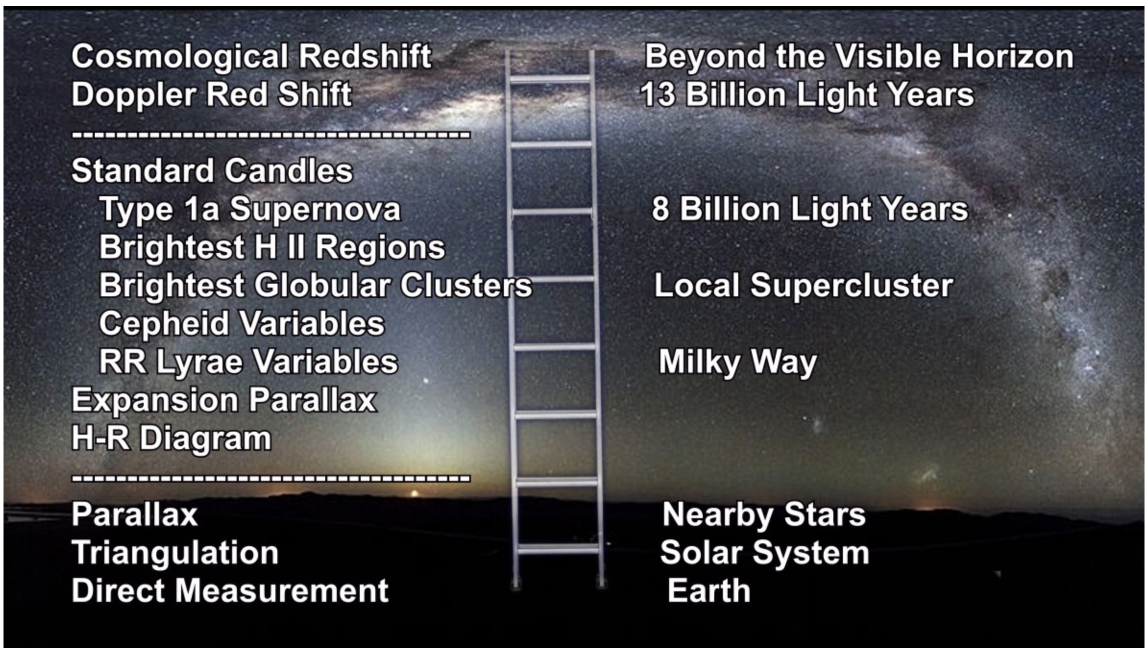
Between 2000 and 2008, the Sloan Digital Sky Survey (SDSS) conducted one of the most ambitious and influential surveys in the history of cosmology. Over eight years of operations it obtained deep, multi-color images covering more than a quarter of the sky and created a 3-dimensional map containing more than 1 million galaxies. These are the color enhanced slices through the SDSS 3-dimensional map of the distribution of galaxies. Earth is at the center, and each point represents a galaxy. Galaxies are colored according to the ages of their stars, with the redder, more strongly clustered points showing galaxies that are made of older stars. The outer circle is at a distance of two billion light years. The region between the wedges was not mapped by the SDSS because dust in our own Galaxy obscures the view of the distant universe in these directions.



Working with the Virgo Consortium of scientists and the Max-Planck Institute in Germany, SDSS put every data point into a supercomputer and created the largest 3D image ever created. Here we are zooming into and panning across that image. Here you cannot see individual galaxies or even galaxy clusters. What we can see are superclusters linked together in filaments or walls in a gigantic cosmic web. In this view to the cosmos, the great Virgo Supercluster is just a dot. There are more stars in the universe than there are grains of sand on all the beaches of Earth. This is the big picture of our universe as we understand it today.

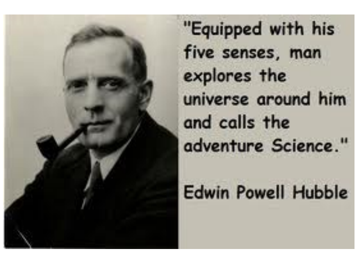
Cosmic Distance Ladder Review

We've come a long way from our start triangulating and directly measuring sizes in my backyard in our segment on the Earth. In this segment, we split 'redshift', our final rung of the cosmic distance ladder, into two parts. The original was based on the doppler effect. The second is cosmological redshift based on the expansion of the universe. (It is important to remember that this kind of redshift can only provide distance information if we have a cosmological model for the expansion. And we do. It's called the lambda cold dark mater benchmark model. It is covered in depth in the "How Old Is It" video book.)



How far away is it - Conclusion

All this reminds me of Edwin Hubble's own words in 1936. They are still appropriate today:



"Thus, the explorations of space end on a note of uncertainty - and necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary – the utmost limits of our telescopes. There we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial. The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation."

Credits - Research

If you recall in the preface, I mentioned that I'd be back with the credits. Here I'll list all the places where I accumulated video clips, pictures, text, and information across books, websites, papers, and broadcast media. All the stuff I used to put together "How far away is it".

But even more important, I'd like to spend a few minutes talking about the key books and websites that guided the development of the video book. These will be the places where you can do additional research into areas of astronomy touched on in this video book. After the credit roll, I'll give you my final thoughts.

> **[Music:** *Beethoven - Symphony No.9, 'Choral' Final Movement - Here we conclude with Beetoven's "Ode to Joy" climax.* **]**

Hubble

The two primary websites I used for the Hubble images, data, and video clips are hubblesite.org and spacetelescope.org. The Hubble telescope is a joint NASA and European Space Agency (ESA) project.

HubbleSite is the NASA website and SpaceTelescope is the ESA website. You can search for any object at either site by the name I included on the picture in the video book.

I only used a fraction of what is available here. There are thousands of spectacular photographs and each one comes with a wealth of information about the objects seen, methods used, and implications for our knowledge of the Universe. If you are at all interested in learning more about the Hubble Space Telescope's discoveries, these sites are the place to start.

Spitzer and Chandra

I used the Caltech-Spitzer website for the Spitzer Space Telescope infrared images and the Harvard-Chandra website for all the Chandra X-Ray Space Observatory images.

These are wonderful sites for additional research on how new knowledge is being created through discoveries in the extended electromagnetic spectrum.

JPL-Caltech and Goddard

The JPL-Caltech website has a wealth of information about the solar system. Our segment on the Solar System is populated with pictures from this site.

The Goddard Space Flight Center runs a large number of our orbiting space satellites including the Sentinels of the Solar System. You can see the full video here. In addition, Goddard operates the new Fermi Gamma-Ray Space Telescope.

If your research takes you closer to home than these two websites are the place to start.

European Space Agency

The ESA science website and the European Space Organization's Very Large Telescope websites are invaluable sources of information and deep space images. I used these sites for a number of fantastic photographs, primarily in the Milky Way segment.

Hubble Archive

Also, take a look at the Hubble Archive. It has the instructions for going straight to Hubble's raw images database. You can see just what the astronomer sees before the astrophotography techniques are applied. This is where I picked up the Planetary Nebula NGC 2818 photos.

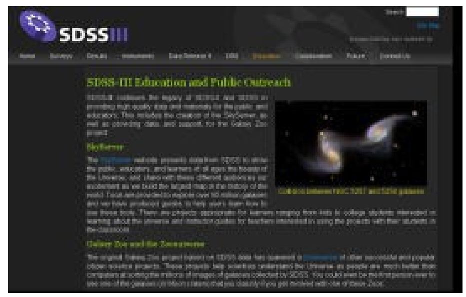
Next Generation

http://www.stsci.edu/jwst/

These next generation space telescopes have their websites up and running now. The next generation discoveries will be published here.

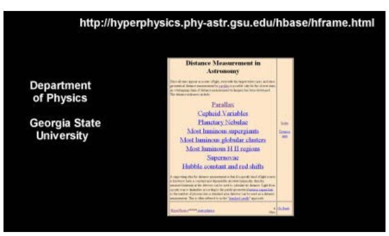
http://www.herschel.caltech.edu

Sloan Digital Sky Survey - http://www.sdss3.org/edu



The Sloan Digital Sky Survey provides tools to explore over 80 million galaxies with guides to help users learn how to use these tools. There are projects appropriate for learners ranging from kids to college students interested in learning about the universe and instructor guides for teachers interested in using the projects with their students in the classroom.
Your participation in these projects actually helps scientists understand the Universe as people are much better than computers at sorting the millions of images of galaxies collected by SDSS. You could even be the first person ever to see one of these galaxies.

Georgia State University -http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html



For information on the cosmic distance ladder and Physics in general, there's no better place than Georgia State University's website.

Atlas of the Universe - http://www.atlasoftheuniverse.com/

The Atlas of the Universe was my top source for galaxy clusters and superclusters in the Virgo Supercluster and Local Superclusters segments.

David Darling's Encyclopedia - http://www.daviddarling.info/encyclopedia.com/

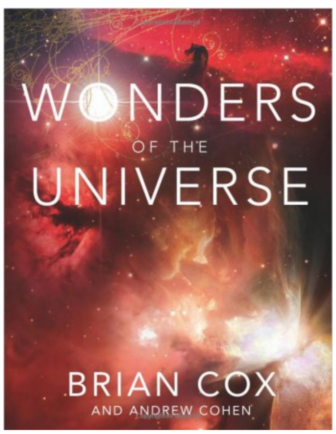
Astronomer [David Darling's Encyclopedia]() of Science is also an excellent source of information.

Astrophotographers

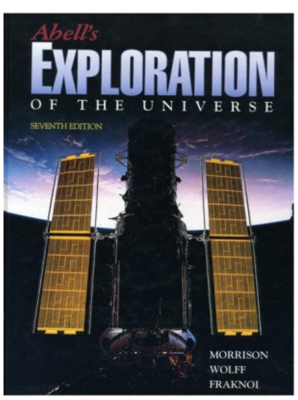
Then there are the wonderful astrophotographers: I used [Rogelio Benal Andreo's]() award winning photographs; [Anthony Ayiomamitis']() fantastic astrophotography; [Robert Gendler's]() wonderful work; and pictures from [Tony Darnell's]() excellent website.

Books

I used two books extensively.



The first was Brian Cox and Andrew Cohen's book "Wonders of the Universe". It pointed me at all the interesting areas to focus on. I don't think I overlooked a single item in the book that was connected to the cosmic distance ladder. The book itself goes into a wide variety of astronomical subjects. I highly recommend reading this book and or seeing the BBC Series "Wonders of the Universe" narrated by Brian Cox himself. It is an excellent update for anyone who has seen the older "Cosmos" series done by Carl Sagan.



The second book was George Abell's second edition of "Exploration of the Universe" published in 1969. This was my lower division astronomy text book. I'm glad I saved it all these years. I used this book for all the foundational information about parallax, the solar system, stars, nebula, galaxies, etc. You may recognize the name Abell. George Abell was the astronomer who cataloged all the star clusters we examined in our sections on the

Virgo Supercluster and the Local Superclusters. His work on this book was so good, that others have taken up the task to keep it alive. Today you can get the 9th edition. If you want to get serious about astronomy, this is the book for you.
We'll end with a list of the Hubble photo's used, websites, video clips, books, papers, and music that were all a part of this video book "How Far Away Is It". Now here are the rest of the credits. Feel free to send comments to howfarawayisit@gmail.com

Thank you for watching.

Hubble Photographs - http://hubblesite.org/

Andromeda Galaxy - M31
Galaxy NGC 300
Stephan's Quintet
Galaxy NGC 4163
Galaxy NGC 4214
Active Galaxy Centaurus A"
Starburst Galaxy NGC 1569
NGC 2976
Grand Design Spiral Galaxy M81
Starburst Galaxy M82
Circinus Galaxy
NGC 253
NGC 3077
Star Birth in Galaxy M83
Pinwheel Galaxy M101
Sombrero Galaxy M104
Barred Spiral Galaxy NGC 1512
Eagle Nebula
Stellar Spire in the Eagle Nebula
Whirlpool Galaxy M51
Spiral Galaxy M74
NGC 5866
I Zwicky 18
Spiral Galaxy NGC 2841
Virgo Cluster Galaxy NGC 4660
Galaxy NGC 3079
Gaseous Bubble in Galaxy NGC 3079
Spiral Galaxy NGC 3949
Starburst Galaxy NGC 3310
Virgo Cluster M87
NGC 4013
NGC 4710
Dusty Spiral Galaxy NGC 4414
Galaxy NGC 1427A
Hanny's Voorwerp, IC 2497
Spiral Galaxy NGC 3982
Barred Spiral Galaxy NGC 1300
Black Hole-Powered NGC 7742
NGC 5584
The Dusty Galaxy NGC 1316
Spiral Galaxy NGC 4319
NGC 3021
NGC 1309
Spiral Galaxy NGC 4622
Polar Ring Galaxy NGC 4650A
Galaxy ESO 510-G13
Galaxy NGC 6782
Galaxy Cluster MACS J0025
NGC 1275
Black Hole ESO 243
Colliding NGC 1410 NGC 1409
The Mice NGC 4676
Spiral Galaxy NGC 4911
Arp 273
Tadpole Galaxy
Interacting Galaxies Arp 147
Abell S0740
VV 340
Hoag's Object Galaxy
2MASX J00482185
COSMOS 3127341
Galaxy Cluster Abell 520
Pandora's Cluster, Abell 2744
COSMOS 1705033
Galaxy Cluster MACS 1206
COSMOS 1161898
COSMOS 2607238
Dust Pillars in the Carina Nebula
Gravitational Lens 0013+2249
Gravitational Lens 0038+4133
Gravitational Lens 0211+1139
Interacting Galaxy 2MASX J091...
Interacting Galaxy Arp 256
Interacting Galaxy ESO 77-14
Interacting Galaxy NGC 454
Interacting Galaxy NGC 6240"
Interacting Galaxy NGC 6786
Dog Star, Sirius and Companion
Star Fomalhaut (HD 216956)
Helix Nebula
Dumbbell Nebula
HH 2
HH 34
HH 47
Orion Nebula
Horsehead Nebula
Orion Constellation
Retina Nebula
S106
Dying Star HD 44179
Cone Nebula
Cygnus Loop Supernova Remnant
Ant Nebula
NGC 6369
NGC 2440
NGC 2371
Kohoutek 4-55
Boomerang Nebula
Crab Nebula
Planetary Nebula SuWt 2
IC 4593
SN 1006
SN 1006 Supernova Remnant
Carina Nebula
Jet in Carina Nebula
Butterfly Nebula NGC 6302
NGC 5315
Trifid Nebula
NOAO Image of Trifid Nebula
Bok globules in NGC 281
Cassiopeia A

NGC 2818
NGC 6791
47 Tucanae
Necklace Nebula
Omega Centauri
Omega Nebula
NGC 3603
Star V838
NGC 3324
Galactic Center Region
Small Magellanic Cloud
Double Bubble
LH 95 in the Large Magellanic Cloud
Supernova Remnant N 63A
Menagerie
Tarantula Nebula - Hodge 301
30 Doradus
Supernova Remnant 0509
Star Cluster NGC 2074
NGC 602, N90
NGC 346
Galaxy Triplet Arp 274
M 66
Dwingeloo 1
Neptune
Venus Cloud Tops
BoRG 58
ESO 576-69
Zw II 28
SDSS J1004+4112
Giant Lensed Galaxy Arc
SN 2002dd
Cygnus Loop Nebula
Packman NGC 281
Pistol Star
Arches Cluster
Quintuplet Cluster
Eta Carinae 1843 Event
Lagoon Nebula
Ultra Deep Field
Galaxy HUDF-JD2
Bubble Nebula NGC 7635
Eskimo Nebula (NGC 2392)
Glowing Eye of Planetary Nebula NGC 6751
NGC 3314
Globular Cluster M80 NGC 6093
Egg Nebula M16
Spiral Galaxy NGC 3370
Cepheid Variables in IC 4182
IRAS 22491-1808
NGC 5189
Spiral Galaxy NGC 4639 w/ Cepheids
NGC 5307
He 2-47
NGC 6543, Cat's Eye Nebula
Rotten Egg Nebula
Planetary Nebula MyCn18
Ring Nebula (M57)
Bow Shock near Young Star LL Ori
Veil Nebula
NGC 1068 Black Hole SN
NGC 4921 in Coma Cluster
NGC 4522
M 66
NGC 7023 Iris Nebula
Abell 370
NGC 7049
Pismis 24 and NGC 6357
Tycho Supernova, SN157
Kepler's Supernova Remnant
NGC 4755 or the Jewel Box
Apr 142

Hubble Archive - http://hla.stsci.edu/

IC 1011 Abell2029
Carina Nebula
ANGST (ACS nearby Galaxy Survey)
COMA (ACS Treasury Survey of Coma Cluster of Galaxies)
COSMOS (Cosmic Evolution Survey)
GOODS (Great Observatories Origins Deep Survey)
Hubble Heritage
UDF (Ultra Deep Field)
APPP (Archive Pure Parallels Program
SGAL (Spiral Galaxies)
Andromeda (Deep Optical Photometry of Six Fields in the Andromeda Galaxy)
Carina (An ACS H-alpha Survey of the Carina Nebula)
CANDELS (Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey
CLASH (Cluster Lensing and Supernova survey with Hubble)
PHAT (The Panchromatic Hubble Andromeda Treasury)
HIPPIES (Hubble Infrared Pure Parallel Imaging Extragalactic Survey)
HUD09 (Hubble Ultra Deep field 2009)
Cepheid Variable Star V1
Light Curve of Cepheid Variable Star V1
Star Field in M31 with V1 included
Hubble's 1923 photo of V1

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Venus
Mercury"
Jupiter and Three Galilean Satellites
Saturn's Tumbling Moon Hyperion
Saturn by Voyager 1
Europa
Io In Front of Jupiter
Shoemaker
Saturn's Northern Storm
Shoemaker-Levy 9 Impact
Jupiter
Clumps in Saturn's Rings
Titan's luminous crescent
Quartet of Saturn's moons
Lunar Far side
Ganymede
Itokawa
Comet Halley
Comet Siding Spring
Makemake
Caliban
Ariel
Uranus
Uranus and Ariel
Solar System PDF
Jupiter Ring System
Europa Voyager 2 Closest Approach
Mariner 10's Venus
Pluto and Its Moons
Galileo Journal Translation

Io
Oberon
Voyagers at the Termination Shock
Leonids Meteor Shower
Far Side of the Moon
Voyager 2 Looks at Saturn's Rings
COBE's View of the Milky Way
Heliosheath
HD 278942
Cygnus Loop Nebula
Packman NGC 281
RCW 86
Orion Molecular Cloud
Dark River to Antares
Earth from Mars
Earthrise - Apollo 8
Ozone Layer Hole over Antarctica
Sunlight over Earth
Galileo Images the Moon
The Earth and Moon
Solar flare - time laps
Mars and Elysium
Mars and Syrtis Major
Mars and Acidalia
An Ancient Jovian Storm
Jupiter's Great Red Spot
Miranda as seen by Voyager 2
Star HD 189733
Mira
Voyager in the Bow Shock

Chandra X-Ray Space Observatory - http://chandra.harvard.edu/

Star CH Cyg
SN 1006
Abell 2029 - CI 1011
El Gordo
Perseus Cluster
RCW 103 - SN
NGC 4649 Black Hole
NGC 4696 Black Hole
Cosmos Field
NGC 6240
M81
Abell 520
MACS J0025.4-1222
Abell 2744
Centaurus A, NGC 5128
NGC 4649
NGC1068
Sextans A
NGC 1275
Galactic Center
SN 1006
Tycho's SNR
SNR 0509-67.5
RCW 86

Spitzer Space Telescope JPL/CalTech - http://www.spitzer.caltech.edu/

Lagoon nebula
SN 1006
Galaxy HUDF-JD2 - Near Infrared
Galaxy HUDF-JD2 - Infrared
Sombrero Galaxy
Cosmos Field
XSC Equitorial Projection
Local Volume - Meet the Neighbors
SN 1604
Galactic Center
NGC 281
Fomalhaut
HD 189733b
Milky Way
RCW 86
Rho Ophiuchi

ESO European Southern Observatory - http://www.eso.org/public

Cone nebula
SN 1987A
HIP 13044
Cat’s Paw Nebula (NGC 6334)
NGC 6729
J102915 - oldest star
M 78 in Orion
R Coronae Australis
Orion Nebula - infrared
NGC 2467
Milky Way
HE 1523-0901
Betelgeuse
HUDF-JD2
NGC 3369
El Gordo
Cosmos Field
Abell 2744
SN 1604
SN 1987A
NGC 3603

NASA Goddard Spaceflight Center - http://svs.gsfc.nasa.gov/

Heliosphere Bubbles
Hinode - Sunspots
RHESSI - Solar flares
TRACE - Coronal rain
TIMED - Earth Atmosphere
SOHO - Filament304
STEREO - Coronal mass ejection (CME)
VOYAGER - Stagnation region
Heliosphere to Alpha Centauri

NASA/Goddard Space Flight Center Scientific Visualization Studio

Earth from Apollo 17
NASA Cosmic Distance Scale
Transit of Venus
Incandescent Sun
SDO: Year One

Anthony Ayiomamitis - http://www.perseus.gr/

Vega
Capella
Altair
Antares
Mirach
Deneb
Castor
Polaris
Delta Cephei
Arcturus
T Lyr - Carbon Star in Lyrae
AW Cyg - Carbon Star in Cygnus
Mu Ceph - Carbon Star in Cepheus
Barnard's Star in Oph - Motion Star
61 Cygni AB - Motion Star
Lalande 21185 in UMa - Motion Star
Wolf 359 in Leo - Motion Star
Sigma Draconis - Motion Star
Hypervelocity Star HVS 4
Hypervelocity Star HVS 2

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Milky Way

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Michael Fowler UVa Physics Department
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Serge Brunier
Milky Way from atop the Andes

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Milky Way from Devil's Tower Wyoming

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Rho Ophiuchi
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Richard Crisp
M33 the Triangulum Galaxy
Heart and Soul Nebulae

Local Volume Legacy Survey

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Georgia State University

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M101 Hubblesite.org/newscenter/archive/releases/2006/10/video/a

M83 Hubblesite.org/newscenter/archive/releases/2009/29/video/a

M82 Hubblesite.org/newscenter/archive/releases/2006/14/video/a

M81 Hubblesite.org/newscenter/archive/releases/2008/02/video/a

Stephan's Quintet Hubblesite.org/newscenter/archive/releases/2001/22/video/c

Eagle Nebula Hubblesite.org/newscenter/archive/releases/2005/12/video/b

Whirlpool Galaxy Hubblesite.org/newscenter/archive/releases/2005/12/video/c

CLASH MACS 1206 Hubblesite.org/newscenter/archive/releases/2011/25/video/a

Stages in Galaxy Collisions Hubblesite.org/newscenter/archive/releases/2008/16/video/d

Dozens of Colliding Galaxies Hubblesite.org/newscenter/archive/releases/2008/16/video/c

Milky Way's Future Hubblesite.org/newscenter/archive/releases/2008/16/video/a

NGC 1275 Filaments Hubblesite.org/newscenter/archive/releases/2008/28/video/b

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Arp 273 Hubblesite.org/newscenter/archive/releases/2011/11/video/c

Helix Nebula Hubblesite.org/newscenter/archive/releases/2003/11/video/c

Butterfly Nebula Hubblesite.org/newscenter/archive/releases/2009/25/video/h

Galaxy Triplet Arp 274 Hubblesite.org/newscenter/archive/releases/2009/14/video/b

Hubble_ Zoom MACS 1206 Hubblesite.org/newscenter/archive/releases/2011/25/video/a

Omega Centauri Hubblesite.org/newscenter/archive/releases/2010/28/video/b

Carina Nebula Hubblesite.org/newscenter/archive/releases/2010/29/video/a

Ant Nebula Menzel 3 Hubblesite.org/newscenter/archive/releases/2001/05/video/a

Horsehead Nebula Hubblesite.org/newscenter/archive/releases/2001/12/video/a

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IC 4593 Hubblesite.org/newscenter/archive/releases/2007/33/video/a

Bok globules in NGC 281 Hubblesite.org/newscenter/archive/releases/2006/13/video/a

Supernova Remnant N 63A Hubblesite.org/newscenter/archive/releases/2005/15/video/a

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Star V838 Monocerotis Hubblesite.org/newscenter/archive/releases/2004/10/video/a

Trifid Nebula Hubblesite.org/newscenter/archive/releases/1999/42/video/a

WFC3 30 Doradus Hubblesite.org/newscenter/archive/releases/2009/32/video/b

Carina Nebula Hubblesite.org/newscenter/archive/releases/2010/13/video/d

Dark Pillars of Carina Hubblesite.org/newscenter/archive/releases/2010/29/video/a

Herbig-Haro object HH 1 Hubblesite.org/newscenter/archive/releases/2011/20/video/m

Herbig-Haro object HH 2 Hubblesite.org/newscenter/archive/releases/2011/20/video/j

Herbig-Haro object HH 34 Hubblesite.org/newscenter/archive/releases/2011/20/video/f

Herbig-Haro object HH 47 Hubblesite.org/newscenter/archive/releases/2011/20/video/b

S106 Hubblesite.org/newscenter/archive/releases/2011/38/video/b

NGC 6791 Hubblesite.org/newscenter/archive/releases/2008/25/video/a

NGC 3324 Hubblesite.org/newscenter/archive/releases/2008/34/video/b

Cepheid variable M1 V1 Hubblesite.org/newscenter/archive/releases/2011/15/video/a

Ring Nebula Hubblesite.org/newscenter/archive/releases/2013/13/video/b/

NGC 5189 Hubblesite.org/newscenter/archive/releases/2012/49/video/b/

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GJ 1214 zoom www.ESO.org/public/videos/eso0950c/

NGC 6729 www.ESO.org/public/videos/eso1109a

J102915 - oldest star www.ESO.org/public/videos/eso1132a

SN 1987A www.ESO.org/public/videos/eso1032b

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Zoom in on Betelgeuse www.ESO.org/public/videos/eso0927a

Zooming in on NGC 3603 www.ESO.org/public/videos/eso1005a

Cat's Paw Nebula (NGC 6334) www.ESO.org/public/videos/eso1003a

Carl Sagan - Pale Blue Dot www.YourTube.com/watch?v=p86BPM1GV8M

City Lights from International Space Station
NASA Astronaut Don Pettit (2002-2008) www.YourTube.com/watch?v=U7WuSP663uU

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International Space Station www.YourTube.com/watch?v=EPyl1LgNtoQ

Plains Milky Way – Dekotalaps www.YourTube.com/watch?v=KySThq5CxLI

A timelapse view of the milkyway from Chile www.YourTube.com/watch?v=JEHm-XUHwNw

Millennium_flythru www.YourTube.com/watch?v=M1vPSwRzAZI

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Milky Way from Chile www.YourTube.com/watch?v=JEHm-XUHwNw

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Music

Johann Sebastian Bach
Cantata No.147 - Jesu, Joy of Man's Desiring
Air 'on the G String'
Zion hort die Wachter

Samuel Barber - Adagio for Strings

Ludwig van Beethoven
Symphony No.9 in D minor Op.125, 'Choral' _ III
Adagio molto e cantabile
Final Movement
Piano Sonata No 14 in C sharp minor - Moonlight

Georges Bizet - Entracte to Act III

Ridolfo Luigi Boccherini - Minuet

Alexander Borodin - Nocturne

James Horner - Braveheart Movie Music
  End Credits
  Main Title

Carl Maria von Weber - Der Freischütz Ouvertüre

Achille-Claude Debussy - Clair De Lune

Clément Philibert Léo Delibes - Flower Duet

Antonín Leopold Dvořák - String Serenade

Edward William Elgar - Enigma Variations Op.36

Gabriel Urbain Fauré - Pavane Op.50

Franz Liszt - Hungarian Rhapsody No. 2

Ramin Djawadi - HBO Series - Game of Thrones - Main Title

Edvard Grieg - Peer Gynt Incidental Music Op.23 - Morning

Louis Armstrong - What A Wonderful World

Pietro Antonio Stefano Mascagni - Intermezzo

Jules Émile Frédéric Massenet - Meditation

Felix Mendelssohn - Violin Concerto in E Minor Op.64

Wolfgang Amadeus Mozart
  Clairinet Concerto in A
  Concerto No_ 10 for 2 pianos & orchestra
  Flute and Harp Concerto in C, K.299 - Andantino
  Piano Concerto No.21 in C 'Elvira Madigan'
  Piano Concerto No_ 20 in D minor
  Sinfonia concertante for violin, viola & orchestra
  The Magic Flute

Johann Pachelbel - Canon in D

Sergei Vasilievich Rachmaninoff
  Piano Concerto No 2 in C minor
  Rhapsody on a Theme of Paganini - Variation 18

Joaquin Rodrigo - Concierto de Aranjuez

Charles-Camille Saint-Saëns - The Carnival of the Animals - The Swan

Alfred Eric Leslie Satie - Gymnopédie No.1

Pyotr Ilyich Tchaikovsky - Capriccio Italien

Twinkle Twinkle Little Star

Vangelis
Conquest Of Paradise
Heaven And Hell 3rd Movement

Antonio Vivaldi -The Four Seasons - Winter Concerto in F Minor

Richard Wagner - Rienzi Overture

Simon Wilkinson - Exodus www.thebluemask.com

Ending

Well that's a wrap except for one last thing.

If you recall in the Preface, I mentioned that I was creating this video book to update those I care about on what we have learned about the Universe while I wasn't looking.

But on reflection, when I review all we've learned and all that we have yet to discover, my thoughts turn to my grandchildren and I'm reminded of the Louis Armstrong lyrics:

I see my grandchildren smile
I watch them grow
They'll learn much more than I'll ever know
And I think to myself
What a Wonderful World

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

Index

David Butler has created a video book of Hubble Space Telescope pictures together with an illustrated explanation of how we know how far away things are from your back yard to the most distant galaxies.

See how:

- triangulation takes us across the world;
- parallax takes us across the solar system;
- standard candles take us across the Milky Way;
- red-shift takes us across the universe.

Learn about the Sentinels of our Heliosphere. See stars, star clusters, planetary nebulae, supernovae, star forming nebula, black holes, orbiting dwarf galaxies, Andromeda, the local group of galaxies,super galaxy clusters, and colliding galaxies.

The video book also contains a segment on credits with websites identified for further research by interested viewers.