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 stars 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*** *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. Mozart wrote this*

in 1779. It reflected improvements in the technical capabilities of orchestras at the time and represents a crossover between a symphony and a concerto. In this segment, we are utilizing increased telescope capabilities and crossing over and beyond what parallax can do for us.]

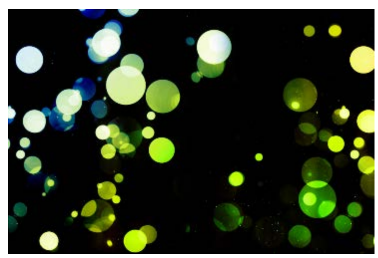
Welcome to our segment on distant stars. By distant, I mean stars that are so far away that parallax doesn't work anymore. Stars like this one, Monocerotis. In order to know how far away Monocerotis is, we'll need a new way to determine distance.

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.

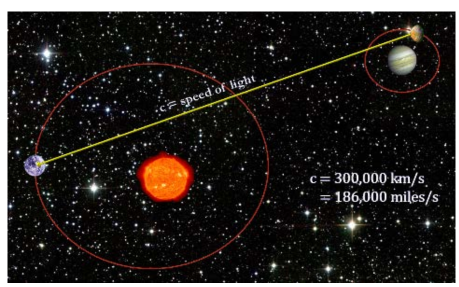
Light

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

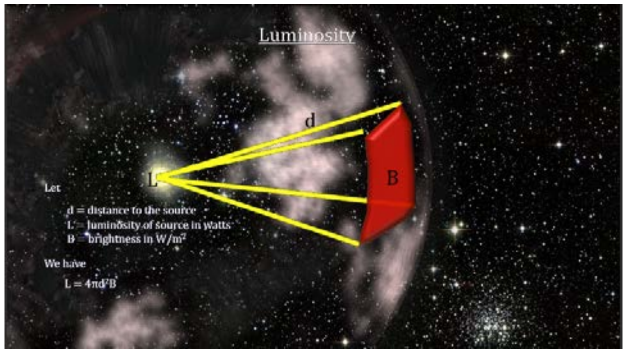
We know that light is electromagnetic radiation created by moving electrons.



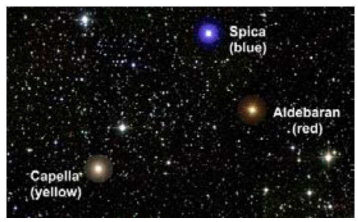
With help from Jupiter's moon Io, we know that light travels across empty space at 300,000 km/s (that's 186,000 miles/second).



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:

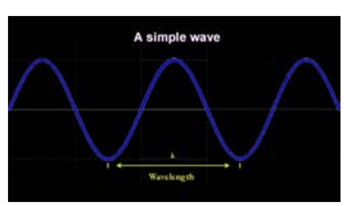
We can view it as a particle or photon. Or we can view it as a wave that can interfere with itself.

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.

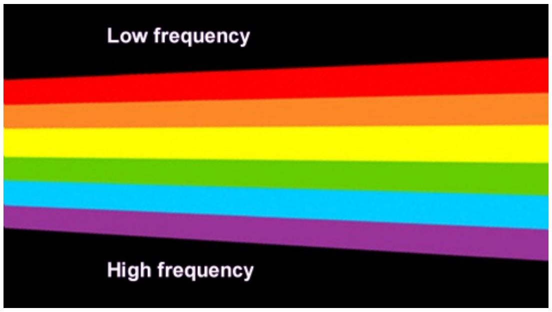
The Electromagnetic Spectrum

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.

$E = hv$

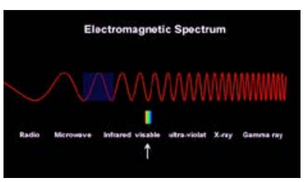
Where: E = energy

v = frequency

h = Planck's constant

$= 6.63 \times 10^{-34}$ joule-sec

[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.

Radiation 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.

<u>Star Color</u>

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.

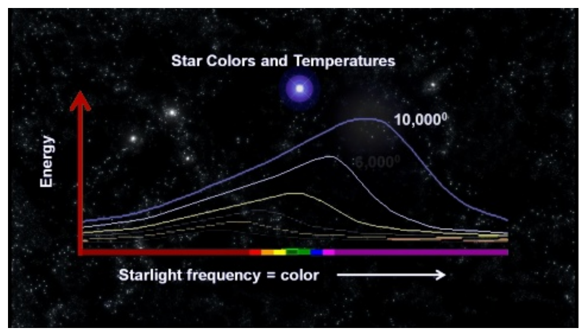
Take a look at this iron rod as it heats up. See how it goes from red hot at the outer edges, through yellow to white hot at the center. If we could get it hot enough, you'd see it turning blue.

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.



<u>Wien's Displacement Law</u>

Let: λ_{max} = peak wavelength
T = surface temperature
W = Wien's constant
= $2.9\text{x}10^{-3}$ meters-kelvin

We have: $\lambda_{max} = W/T$
$T = W/\lambda_{max}$

For the Sun: λ_{max} = .0000005 meters
= yellow
T = 5,800 kelvin

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.

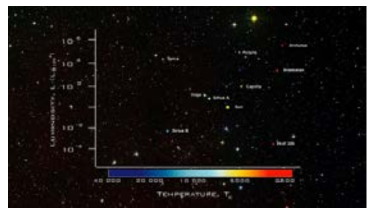
It's that simple.

The Hertzsprung - Russell diagram

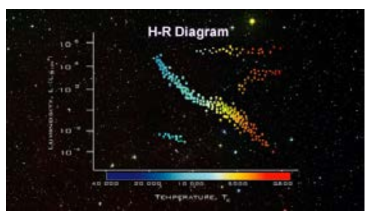
Now that we know star temperatures via their color, and luminosity via their parallax distance, we can build the diagram I mentioned in the introduction.

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.

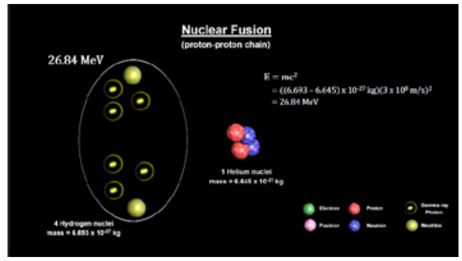
But in order for the H-R Diagram to do this:

- 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

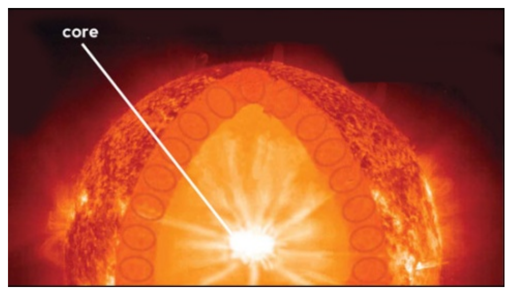
In our segment on star birth nebula, we'll cover how stars form from giant hydrogen clouds collapsing under the force of gravity. They start "shining" once the pressure and temperatures at their core reaches the levels needed to support hydrogen fusion.

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.

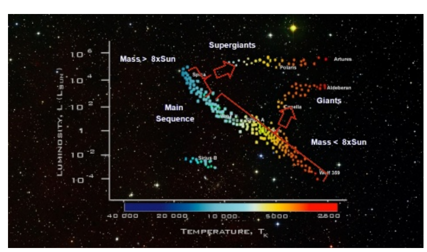
The more hydrogen there is in the collapsing cloud, the more massive the star. The more massive the star, the more intense the pressure in its core. The more intense the pressure, the higher the temperature. The higher the pressure and temperature, the faster the Hydrogen fuses into Helium. The faster 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.



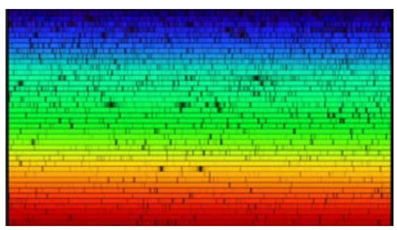
When a Red Giant, with a mass less than 5 times the mass of the Sun, runs out of fuel, it explodes and leaves behind a dim hot tiny star called a White Dwarf. We'll discuss this process more in our next segment on Planetary Nebula.

We'll cover the end-game for more massive stars in our segment on Supernova.

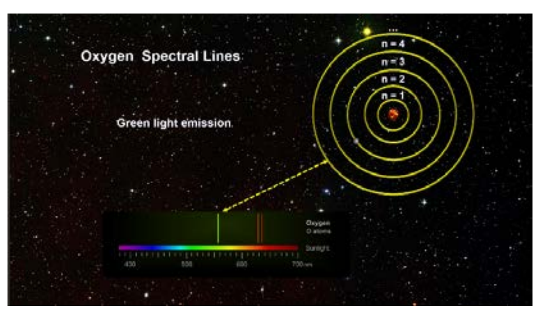
Spectral Analysis

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.

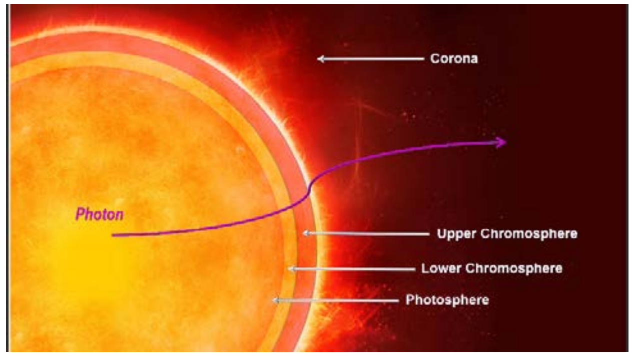
In so doing, he discovered that when he spread sunlight into a spectrum, the spectrum was crossed by great numbers of fine dark lines. He had no idea what these dark lines where, but today we know that they were the key to learning what stars are made of.



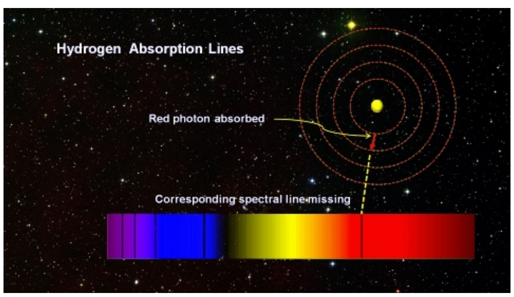
Remember the red and green light of the aurora borealis and the structure of molecules we discussed in our segment on the Heliosphere. The aurora is a good example of light being emitted as electrons change energy levels.



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.

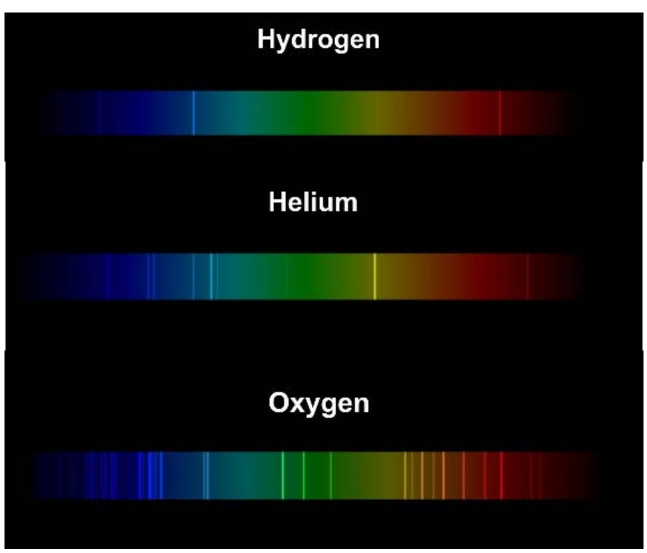


Here's how it works.

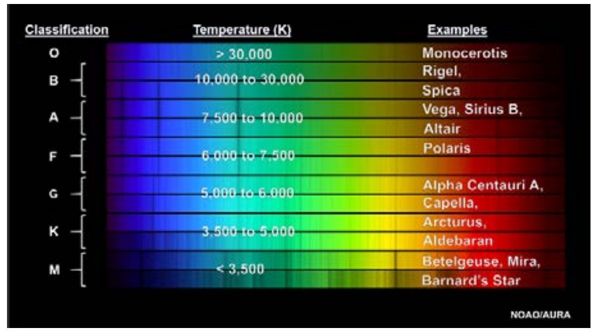


When a photon with exactly the right energy level hits an electron orbiting a nucleus, its entire energy is transferred to the electron which jumps to a higher energy level with a larger quantum number. The photon is eliminated. This creates 'absorption lines' in a star's spectrum as light from the star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

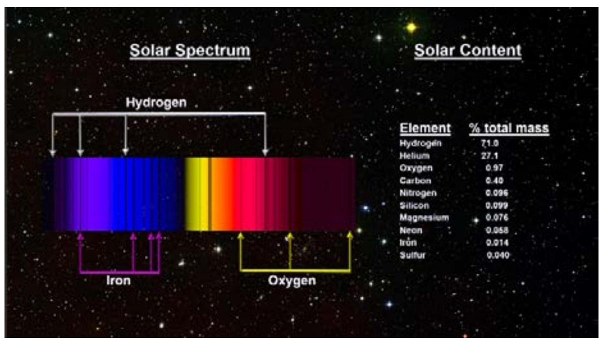
Every atom and molecule has its own spectral line signature. So by observing the absorption lines in a star's spectrum, we can tell what elements are present. **[**Imagine that. Light from stars hundreds of trillions of miles away carries with it information on every element the star is made of!**]**



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 coolest) to 9 (the hottest).] 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.]

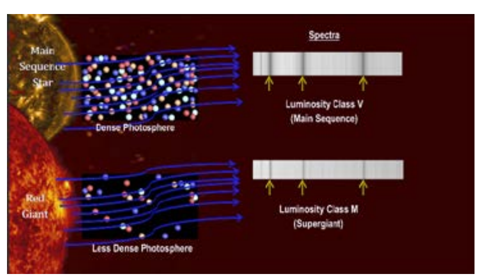


[Music @13:48** Puccini, Giacomo: Crisantemi; Radio Symphonie Orchester Berlin and Riccardo Chailly; from the album "Puccini without Words", 2006**]

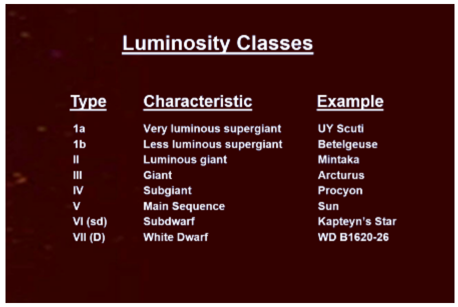
Luminosity Classes

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.

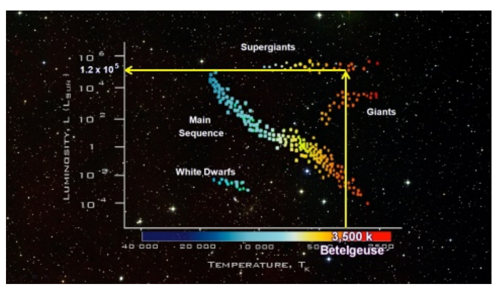


Luminosity Classes

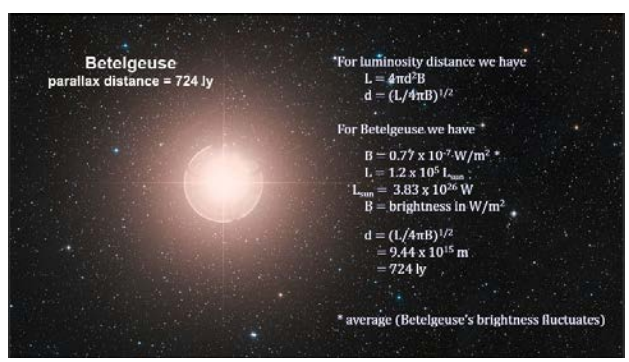
Type	Characteristic	Example
1a	Very luminous supergiant	UY Scuti
1b	Less luminous supergiant	Betelgeuse
II	Luminous giant	Mintaka
III	Giant	Arcturus
IV	Subgiant	Procyon
V	Main Sequence	Sun
VI (sd)	Subdwarf	Kapteyn's Star
VII (D)	White Dwarf	WD B1620-26

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, than 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.

V1331 Cyg - A8 to G5 1,800 ly

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.

UY Scuti - M4Ia (9,500 light years)

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.

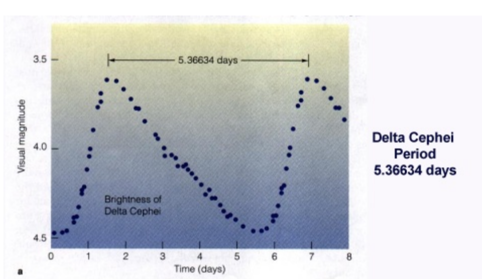
AG Carinae is losing its mass at a phenomenal rate. It's mass to energy conversion is creating powerful stellar winds with speeds of up to 7 million km/hour (4.3 million miles per hour). These powerful winds are responsible for the shroud of material visible in this image.

[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.]

Variable Cephei and RR Lyrae Standard Candle Stars

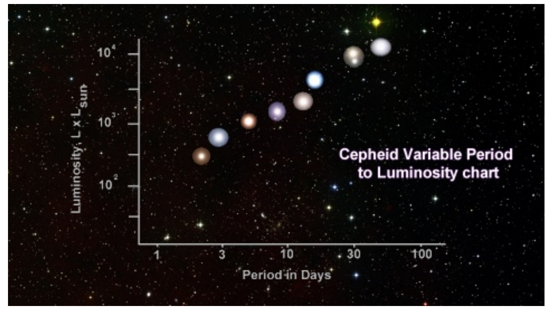
Delta Cephei – F5Ib to G1Ib (887 light years)

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.

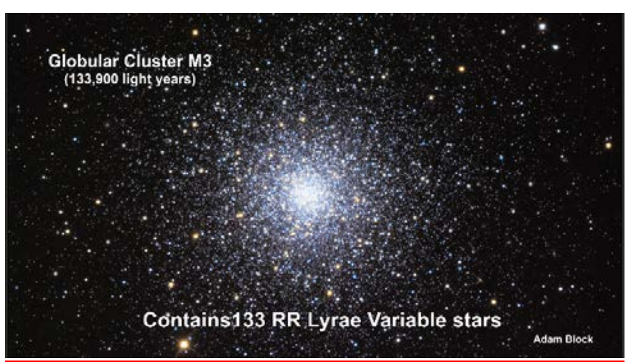
Early in the 1900s, an American astronomer, Henrietta Leavitt, thought to plot Cepheid luminosity cycle periods against luminosity. She found that the period of these stars varied in proportion to their absolute brightness. This was very interesting, because, as we have discussed, once we know the intrinsic 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)

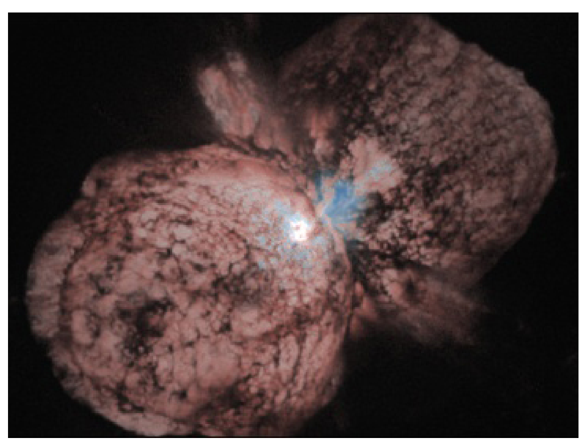
Mu Cephei is a red supergiant star. In fact, it is one of the largest and most luminous stars known in the Milky Way. This star could fit a billion Suns into its volume.

[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

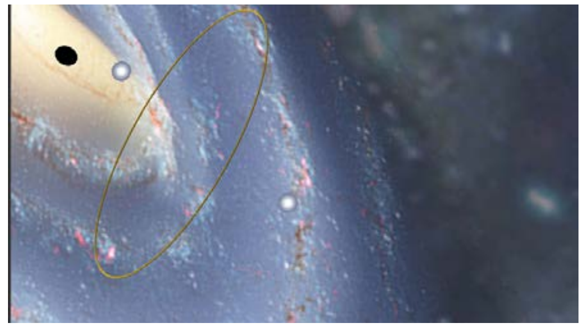
Hubble's latest image of the star V838 Monocerotis [Mon-**o**-ser-o-tis] reveals dramatic changes in the illumination of surrounding dusty cloud structures. The effect, called a light echo, has been unveiling never-before-seen dust patterns ever since the star suddenly brightened for several weeks in 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.

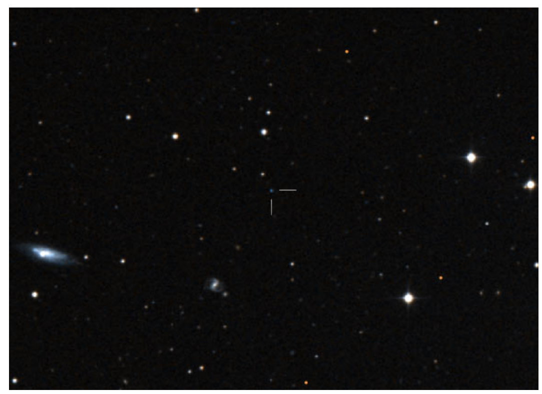
[Based on the speed and position of HE 0437-5439, the star would need 100 million years to have journeyed from the Milky Way's core. Yet its mass — nine times that of our Sun — and blue color mean that it should have burned out after only 20 million years — far shorter than the transit time it took to 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 Strasbourg

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).