Shining Light on the Stars: The Hertzsprung-Russell Diagram

Produced by: University of Toledo FullDome Studio

It is two hours after sunset one winter evening and the stars shine brilliantly in the crystal cold air. At first glance, all of the stars may look similar, but if you look more carefully, you'll begin to see subtle differences between them. While most stars look white to us, many are actually subtle shades of blue, yellow, and even red.

Let's consider the constellation of Orion the Hunter that sits majestically in the South. The star Betelgeuse that forms his right shoulder has a distinct red/orange hue. In contrast, the star Rigel which forms his left leg has a noticeable blue color. Capella, the brightest star in the constellation of Auriga, the Charioteer, is yellow like our Sun.

A star's color is related to one of its most important properties: its surface temperature. Consider our three stars again. Red stars like Betelgeuse are the coolest with surface temperatures of about three or four thousand degrees Kelvin, where Kelvin degrees come from a temperature scale related to the Celsius scale. Yellow stars like Capella and our Sun are a bit warmer at roughly 6,000 degrees Kelvin and blue stars like Rigel are the hottest with surface temperatures of over 10,000 degrees. This may seem backwards, but a star's color works like the colors of fire: a blue or white color indicates a much hotter temperature than red.

Another important property of a star is its intrinsic brightness, or luminosity. Luminosity is a measure of the total amount of energy that a star emits. A star's luminosity does not determine how bright it appears to us, because stars with the same luminosity can appear brighter or fainter, depending on their distance from Earth.

At the turn of the last century, two astronomers, Ejnar Hertzsprung and Henry Norris Russell, realized independently that if you plotted the luminosity of stars versus their temperatures on a graph, the stars didn't fall in random places, but instead grouped together, forming curious patterns. These patterns were later used to unlock many mysteries surrounding the origins and lives of stars, and the Hertzsprung-Russell, or HR, diagram continues to be one of the most important tools that astronomers have to study stars.

In this graph, surface temperature runs along the X axis, but instead of increasing to the right, temperature increases to the left. Luminosity runs along the Y axis increasing toward the top. The Sun lies here on the HR diagram as it has a surface temperature of about 6,000 degrees Kelvin. Stars have temperatures both cooler than the Sun and much hotter than the Sun, even beyond 40,000 degrees Kelvin.

The range of power that stars produce is also incredible: the most luminous stars have luminosities a million times greater than the Sun, and the least luminous stars are as much as one one-million times fainter.

Here is where Betelgeuse, Rigel, and Capella lie on our HR diagram. Capella is actually a binary star composed of two similar stars, so we label them Capella A and B. Rigel is the hottest of the four stars while Betelgeuse is the coolest at 3,200 degrees Kelvin. All four stars, however, are more luminous than our Sun; in fact, Rigel is approximately 125,000 times as luminous.

If we draw a line through Orion's three belt stars and follow that line down and to the left we find the brightest star in the sky, Sirius which is in the constellation of Canis Major—the large dog. While Sirius looks very bright to us, intrinsically it isn't nearly as bright as Rigel or Betelgeuse — only about 25 times higher than the luminosity of the Sun. It is located here on our HR diagram.

Just north of Sirius is the star Procyon in the constellation of Canis Minor—the small dog. Procyon has a faint bluish/white tint which is a result of its 6,500 degree Kelvin surface temperature. Its luminosity is about seven times that of the Sun so it falls on the HR diagram here.

Back at Orion, if we draw a line through his belt moving up and to the right we find a bright orange colored star called Aldebaran, located in the constellation of Taurus the Bull. It is about five hundred times the luminosity of our Sun, with a surface temperature of about 3,900 degrees Kelvin, so it is located here on the HR diagram.

The stars Castor and Pollux form the heads of the Gemini twins. They appear to be about the same brightness but clearly show different colors. Castor appears bluish/white and is actually a binary star composed of two nearly identical stars. In contrast, Pollux has a noticeably orange tint corresponding to a temperature of 4,700 degrees Kelvin but is somewhat more luminous than Castor at about 40 times the luminosity of our Sun. Both of these stars fall here on our HR diagram.

What about the other bright stars visible in the nighttime sky? What patterns do they form on the HR diagram? Notice that all of the stars are more luminous and mostly hotter than our Sun. Does this mean our Sun is the least luminous type of star? To answer this question, we first have to take a tour of the stars in the solar neighborhood.

Imagine that we are now floating in space above the Earth. The stars visible from Earth's surface can still be seen from this vantage point.

As we slowly move away from the Earth and head towards the Sun, our view of the stars really doesn't change much. But if we artificially increase the brightness of all the stars that lie within a distance of about 25 light years from our Sun, hundreds of new stars that were simply too dim to be seen before suddenly become visible. In total, there are just over 200 accurately represented stars in this spherical volume of space — our small neighborhood in the vast metropolis of stars known as the Milky Way Galaxy.

We are now traveling past our Sun towards the outer reaches of the solar system. You'll notice that many of the nearby stars that we artificially brightened appear red in color. As we learned earlier, their red color shows that their surfaces are much cooler than our yellow Sun.

We are now leaving our solar system on a path to the star Proxima Centauri. At a distance of just over 4.2 light years, or 24 trillion miles, this star is our closest stellar neighbor. The surface of Proxima Centauri appears more mottled than our Sun because red dwarf stars have larger and more star spots. If you look off to the right you can see two other stars nearby. Proxima Centauri is actually a member of a triple star system consisting of Alpha, Beta, and Proxima Centauri. This star, along with most of the other red stars in the solar neighborhood are known as "red dwarf" stars.

Although most of the stars in the Sun's nearby neighborhood are red dwarf stars, there are a handful of hotter yellow and blue/white stars.

One of these neighbors is the star Sirius that we saw earlier. Sirius lies at a distance of about 8 light years from the Sun, and besides being the brightest star visible in the night sky, it is one of the few bluish/white stars in our 25 light year neighborhood. In the background, we see

Sirius' companion, an Earth-size stellar corpse known as a white dwarf. White dwarfs are extremely dense because they contain as much mass as the Sun but in a volume only the size of the Earth. A teaspoon of white dwarf material would weigh 15 tons on Earth! Within our 25 light year neighborhood, there are only a handful of white dwarfs.

This approaching yellow star is known as Sigma Draconis, or the star Alsafi. Unlike the two previous systems we visited, Alsafi is a single star and is located almost 19 light-years from us. Its yellow color indicates that it has a temperature similar to that of the Sun, although it is slightly less luminous. Sigma Draconis is one of the few stars within 25 light years that can be seen from Earth with the unaided eye.

As our closest neighboring stars fade into the distance, we really start to get a sense of just how many red dwarfs there are in the solar neighborhood. We are now roughly 25 light-years, or about 700 trillion miles, from the Sun. We have again artificially increased the brightness of just the stars within 25 light years — our closest neighbors.

Notice just how many of the nearby stars are red dwarfs. This tiny pocket of the Milky Way Galaxy is not unique, so we can assume that the population of stars contained within this volume is representative of the rest of the stars in the Milky Way. This means that most of the stars in the Galaxy are cool red dwarf stars, while hotter and more luminous stars like the Sun, Sirius, or Betelgeuse are far less common. In fact, red dwarf stars outnumber stars like our Sun by a ratio of twenty to one.

Returning to our local neighborhood, we can see how these neighboring stars fall on the Hertzsprung–Russell Diagram.

Remember, the HR Diagram shows the temperatures of stars versus their luminosities. Our Sun is located here on the diagram, and as before, the 122 brightest stars visible in the night sky from Earth are located here. But what about all the stars in the nearby solar neighborhood, most of which are too faint to be seen without a telescope? We immediately see that these two groups of stars lie in completely different parts of the HR diagram. The local group of stars within 25 light years of the Sun are cooler and less luminous than the Sun, while the stars we can see in the night sky are typically hotter and more luminous than the Sun. How do we reconcile this seemingly contradictory result? How can it be that the solar neighborhood seems so unusual compared to the rest of the stars?

The answer is deceptively simple. Red dwarf stars are the most abundant type of star, but are much less luminous than our Sun, so they are not visible from the Earth by eye. In contrast, stars that are much more luminous than the Sun, like Sirius or Betelgeuse, are less common, but, like a bright searchlight, can be seen from great distances. Indeed Hertzsprung himself called these very luminous stars the "whales amongst the fishes" — they're exceedingly bright, but also exceedingly rare. As you continue to study the stars, you will appreciate just how important the HR Diagram is to our understanding of the Universe.