Chapter 10

Stars

Introduction

Left to right: Double Cluster in Perseus, Albireo (top), alpha and beta Centauri (bottom), Betelguese, Polaris

Without stars, the Universe would be dark. Stars are suns. They provide light and heat for the planets around them. In fact, planets are merely the byproducts of the formation of stars, so without stars, there wouldn't be any planets either. Without stars, the Universe would contain only cold, dark gas—plus the invisible dark matter.

A star is a hot ball of hydrogen gas that gives off light. One of the most important things we want to know is how much light a star gives off. In order to determine that, however, we need to know the distance to the star. Once we measure the distance, we will also be able to calculate the size of the star. You may have noticed that stars have different colors. That is because they have different temperatures; the temperature in turn has a big effect on the energy output. One other important characteristic of the star is its mass. We will learn how to measure that as well. In the next chapter we will see that the mass determines the entire life history of the star.

Constellations

Traditionally, the brighter stars in the sky were organized into animal or human figures --the **constellations.** The constellations that modern astronomers use have their origins in ancient Babylonia. Constellations like Taurus the Bull can be seen in inscriptions that are five thousand years old. Ancient Greek astronomers learned the Babylonian constellations, gave them new names, and added a few of their own. The classical constellations were listed by the Greek astronomer Ptolemy in his star catalog about the year 150 A.D. An example is the constellation of **Orion**, which dominates the winter sky. Orion was pictured as a hunter holding a bearskin shielf in one hand and a club or sword in the other. Hanging from his belt is a scabbard (that's the thing the sword goes in). (See Figure 1.) Ptolemy's catalog included 45 constellations that are considered the classical ancient constellations. In the period between 1500 and 1800, astronomers added another 50 or so constellations. Some of them filled in gaps between the ancient constellations; others organized the stars near the South Celestial Pole that can not be seen from northern Africa. Most of the modern constellations are little known because they don't contain any bright stars. Most of them are named after inanimate objects, like **Sculptor** (the Easel) and **Antlia** (the Pump). The largest constellation, **Argo** (the Great Ship), has been divided into three groups, **Puppis** (the Poop), **Vela** (the Sails), and **Carina** (the Keel). Today 88 constellations are officially recognized.

A particularly important group of constellations are the 12 constellations of the **zodiac**. These are the constellations that the Sun appears in as the Earth orbits around the Sun over the course of the year. In English there are usually known be their Latin names, **Aries** (the Ram), **Taurus** (the Bull), **Gemini** (the Twins), **Cancer** (the Crab), **Leo** (the Lion), **Virgo** (the Virgin), **Libra** (the Balance Scales), **Scorpius** or **Scorpio** (the Scorpion), **Sagittarius** (the Archer), **Capricornus** (the Sea-Goat), **Aquarius** (the Water Bearer), and **Pisces** (the Fish). Additionally, the way the modern astronomers draw the boundaries between the constellations, the Sun goes through a thirteenth constellation, **Ophiuchus** (the Serpent Bearer), located between Scorpius and Sagittarius.

A constellation is not the same as a star cluster. Star clusters are groups of stars that are close together in space, all at about the same distance from the Sun. The stars in a constellation, in contrast, are all at different distances and are not usually associated with each other. The one exception is the constellation of **Coma Berenices** (Berniece's hair). This is a classic constellation that we know today is a true star cluster.

Distance and parallax

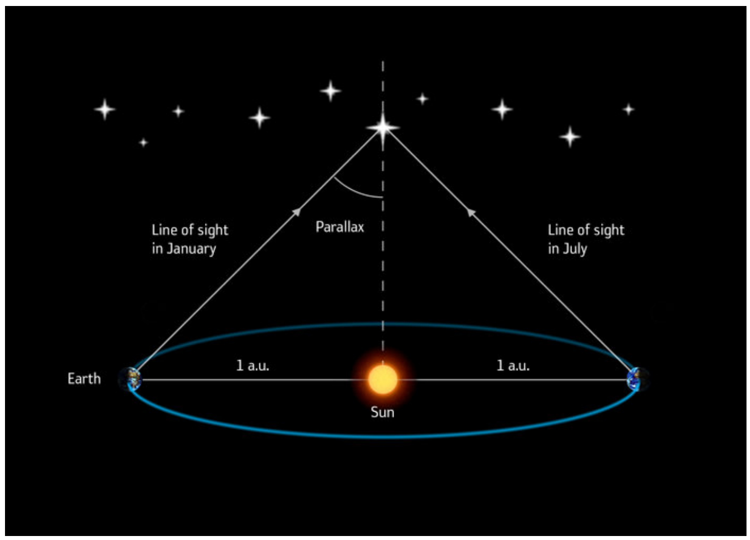
Before we can learn about the properties of a star, we need to know its distance. Otherwise, we do not know if we are looking at a dim object that is relatively nearby or a bright object thata is far away. Unfortunately, determining the distance to a star is not easy. There are two basic methods for measuring the distance to a star:

1) parallax
2) inverse square law

One unit of distance useful for stars is the **light-year (LY)**, the distance that light travels in a year (about 10 trillion km). Until recently, only stars that are less than about 1000 LY away were suitable for the method of **stellar parallax.** This method is based on the motion of the Earth around the Sun over the course of one year. Because of the Earth's motion, nearby stars will shift position back and forth relative to the background of distant stars (see the figure). This slight shift is called the **parallax.** The shift back and forth always takes exactly one year, since that is how long it takes the Earth to go around the Sun. The effect depends on distance:

The greater the distance, the smaller the parallax.

At a great enough distance, the parallax is too small to measure. This is why the method is limitied to nearby stars.



The parallax is measured in seconds of arc. Recall:

a circle = 360°

1° = 60′ (minutes)

1′ = 60″ (seconds).

A star 3.26 LY away has a parallax of 1″. This distance is called a **parsec (pc).** Sirius, for example, is 2.6 pc away or 8.6 LY. If the distance is measured in parsecs, the formula for calculating the distance has a simple form:

distance(pc) = 1/parallax(“)

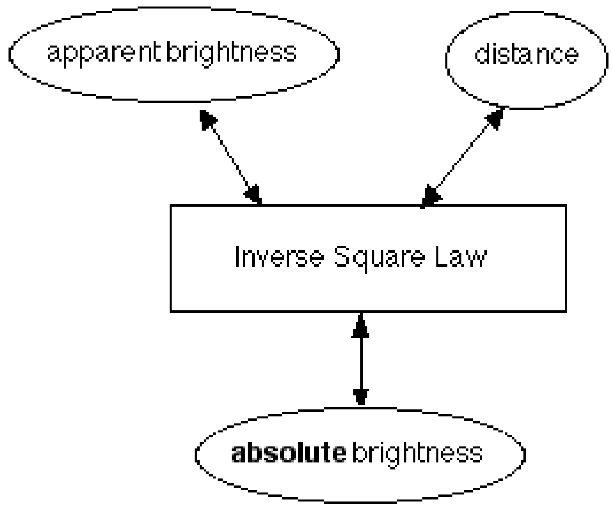
This equation says that a star that has a parallax of 1″ is at a distance of 1 parsec and that as the parallax increases, the distance decreases. In mathematical terms, *the distance is inversely proportional to the parallax.* In other words, a great distance means a small parallax and a large parallax means a small distance. As it happens, even the nearest stars are so far away that their parallaxes are all less than 1 second of arc. This is a small distance, about the size of a dime seen from a mile away. If you have ever seen the double star Castor in a telescope, the two stars of this pair are about 2″ apart.

The star with the largest parallax is **Proxima**, whose parallax is 0.743″ of arc. This is also the single nearest star to the Sun ("proxima" is Latin for "the closest one"). The formula above tells its distance: 1.35 pc, or just more than 4 light-years. It is just slightly closer than **alpha Centauri,** a bright double star in the southern sky, and is probably a distant member of the alpha Centauri system. Alpha Centauri itself can be seen from locations south of latitude 30° N, such as Baja California del Sur, New Orleans, or southern Florida. Proxima, in contrast, is a **red dwarf,** a faint kind of star, and cannot be seen without a telescope.

If the parallax of a star is smaller than 1/1000 second, it cannot be measured precisely by ground-based telescopes. Until this century, if the star was more than 1000 pc away, its distance could not be measured using the method of parallax. The European Hipparchos and Gaia space telescopes can measure the parallax of stars thousands of parcecs away, but even with these satellites, the method of parallax cannot be used for the most distant stars. Another method must be used.

Brightness and distance

The next step in learning about stars is to measure their brightness. There are two measures of brightness, the **apparent brightness** and the **absolute brightness**. Basically, the difference is that the apparent brightness is how bright the appears to us in the sky, whereas the absolute brightness is how much light the star gives off. In this context, "absolute" means "without regard to distance". Given a star of a certain absolute brightness, its apparent brightness is determined by its distance. The closer it is, the greater its apparent brightness. The apparent brightness is connected with the absolute brightness and the distance by the inverse square law.



Measuring apparent brightness

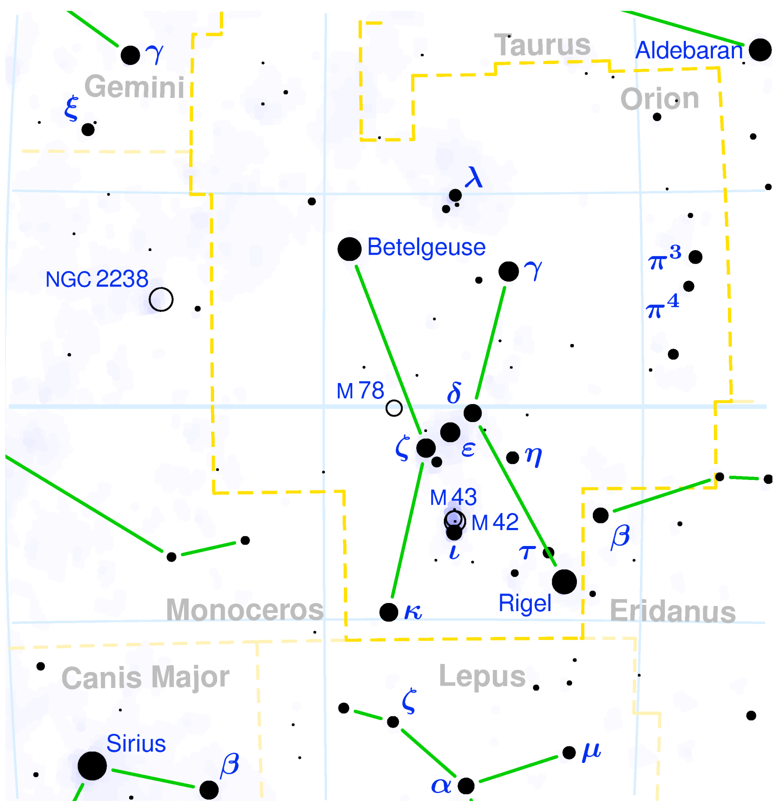
The apparent brightness of a star is how bright it appears in the sky compared with other stars. In principle, the **apparent brightnes**s is the amount of energy from the star that falls on 1 square meter each second. It is measured in watts per square meter (W/m^2). The apparent brightness of the Sun defined this way is 1400 W/m^2.

For all other stars, the apparent brightness is a tiny number, difficult to measure precisely. So in practice, astronomers specify the brightness of a star by comparing it to a standard star. For many years, the standard star was Polaris.

The actual method astronomers use to specify the brightness of stars, is the **magnitude scale**, which will be discussed later on. For the purposes of understanding the Inverse Square Law, it is easier to use a method I call the Polaris Unit scale. The **Polaris Unit** is the apparent brightness of Polaris. So you would say that the apparent brightness of Polaris is 1.0 Polaris Unit. We'll use PU as the abbreviation for Polaris Unit. A star that is twice as bright as Polaris has an apparent brightness of 2 PU, and so forth. Here are some familiar stars from the winter sky:

Star	Apparent brightness (PU)
Polaris	1
Rigel	5.2
Sirius	23.8
Canopus	11.9
π3 Orionis	0.3
Aldebaran	2.8

Compared with Sirius, the brightest star of the night sky, at 24 PU, the faintest stars you can see in a dark sky have a brightness of about 0.024 PU. Thus, Sirius is a thousand times brighter than the faintest stars you can see without a telescope. The Sun's apparent brightness on this scale, in contrast, is about 300,000,000,000 PU: the Sun is 300 billion times as bright as Polaris!



Absolute brightness

The **absolute brightness** of a star is defined as the apparent brightness the star would have if it were at the standard distance of 10 parsecs. There is nothing special about 10 parsecs, it's just a convenient number that was selected arbitrarily. The Sun's absolute brightness, on the PU scale, is 0.072 PU. That means that if the Sun were moved to a distance of 10 pc, it would have an apparent brightness of 0.072 PU, about 1/14 that of Polaris. The Sun would be visible to the unaided eye in a dark sky, but would be lost among hundreds of stars of similar or greater brightness.

Let's take a look at the absolute brightnesses of our example stars:

Star	Absolute brightness (PU)
Polaris	170
Rigel	3250
Sirius	1.7
Canopus	1100
π^3 Orionis	0.2
Aldebaran	11

Looked at this way, Sirius, on the one hand, no longer seems so outstanding; it's much fainter than Canopus, fainter even than Polaris. On the other hand, Rigel is revealed as a true powerhouse — one of the brightest stars in the galaxy! Even obscure π^3 Orionis gives off three times as much light as the Sun.

If Rigel is instrinsically so much brighter than Sirius, it is clear that it must be many, many times farther away. Our goal is to figure out how far away it really is.

Estimating the distance

It's easy to estimate the distance to a star by comparing its apparent brightness (b) with its absolute brightness (B). If b equals B, then the star must be 10 parsecs away, by definition of absolute brightness. With that in mind, complete the following table, using greater than or less than.

Brightness	Estimated Distance
b > B	less than 10 pc
b = B	10 pc
b < B	greater than 10 pc

Inverse Square Law

In order to calculate the distance precisely, you must use the inverse square law. The basic idea is easy:

If a star is x times farther away, it is x^2 times fainter.

If a star is x times closer, it is x^2 times brighter.

In mathematical language,

The brightness of the star is inversely proportional to the square of the distance.

For example:

If the distance is increased 2 times, the star is 4 times fainter.

If the distance is increased 3 times, the star is 9 times fainter.

If the distance is increased 4 times, the star is 16 times fainter.

and so forth.

Example 1: Sirius

Sirius has an apparent brightness = 24 PU and distance =2.6 pc. How bright would it be if it were 10 times farther away?

Solution: If the distance increases 10 times, the star will be $10^2 = 100$ times fainter. Its apparent brightness will go down to 0.24 PU.

Example 2: Rigel

Rigel has apparent brightness = 5.2 PU and a parallax of 0.004 seconds. What is the absolute brightness of Rigel?

Solution: The distance to Rigel is 1/0.004 = 250 pc. The absolute brightness is the apparent brightness the star would have at a distance of 10 pc. It would be 250/10 = 25 times closer. The Inverse Square Law says that if you brought the star 25 times closer, it would be $25^2 = 625$ times brighter. Therefore, the absolute brightness is 625 times brighter than 5.2 PU, or 3250 PU.

Color and luminosity

Stars give off light of all colors, including infrared light, the various colors of visible light, and ultraviolet light. These colors can't all be measured with the same detector, so the apparent brightness of a star is usually measured through a filter that lets through just one color, such as blue or red. Among the colors most often measured are V (yellow), B (blue), U (ultraviolet), R (red) and I (infrared). Because stars are different colors, their apparent brightness depends on the color band you look in. For example, Betelgeuse and Rigil are about equally bright in the V color, but Rigel is much brighter in B because it is much bluer and hotter. Absolute brightness, as well, comes in "flavors" of V, B, R, etc.

Luminosity is the total light output of the star in all colors. It is like absolute brightness in that it doesn't depend on the distance to the star, but unlike absolute brightness, it doesn't vary depending on what color you are using. It represents the light given off in *all colors.*

The stellar magnitude scale

Real astronomers don't use the sensible PU scale. Instead they use the **stellar magnitude** scale. This scale was designed to approximate the star catalog of the ancient astronomer **Hipparchos,** who ranked the stars according to their brightness so that the brightest stars were stars of the **1st magnitude,** stars noticeably less bright were **2nd magnitude,** and so forth. The faintest stars in his catalog were fifth magnitude. So far as we know, the brightness rankings of Hipparchos were just estimates. However, in the 19th century, astronomers defined a brightness scale that approximated the numbers of Hipparchos for the stars in his catalog and that could be extended to fainter stars. This is the stellar magnitude scale. It is a *logarithmic* scale; that is, each step in the scale represents a brightness *ratio.* Specifically, each magnitude represents a ratio of 2.5:

> A 1st magnitude star is 2.5 times brighter than a 2nd magnitude star
> A 2nd magnitude star is 2.5 times brighter than a 3rd magnitude star
> A 3rd magnitude star is 2.5 times brighter than a 4th magnitude star. etc.

On this scale, the faintest star that can be seen without a telescope is magnitude 6. The Hubble Space Telescope can see stars of magnitude 30.

In the magnitude scale, stars brighter than magnitude 1 have a magnitude of 0. You might suppose a magnitude 0 star would be completely invisible, but in fact it is quite bright. Alpha Centauri, Rigel, Arcturus, and Vega are magnitude 0. Two stars (Sirius and Canopus) are even brighter, and so are magnitude -1.

Fractional magnitudes are also used: for example, a star halfway between magnitude 1 and magnitude 2 is magnitude 1.5 (actually $\sqrt{2.5}$ times brighter than magnitude 2). Like PU brightnesses, magnitudes come in different colors: V, B, R, etc.

Absolute magnitudes are defined the same way as previously: the **absolute magnitude** of a star is the apparent magnitude a star would have if moved to a distance of 10 parsecs. The Sun would be a fifth magnitude star at a distance of 10 pc; thus the absolute magnitude of the Sun in +5.

Temperature

Stars shine because they are hot. The brightness of the star and the color of light given off depend on the temperature of the star's surface.

In astronomy, temperature is usually measured in the Kelvin scale, which is preferred because it is based on the lowest possible temperature, **absolute zero.** That is, absolute zero is 0 degrees Kelvin, written **0 K,** and read "zero kelvins." (Absolute zero is -273 on the Celsius scale and -460 on the Fahrenheit scale.) To have some feel for the Kelvin scale, it is useful to remember that room temperature is about 300 K and the Sun's temperature is about 6000 K.

Thermal Emission

Everything that is not at a temperature of absolute zero (and nothing is) gives off some form of light (electromagnetic waves). Stars give off visible light, planets give off infrared light, and cold gas gives off radio waves. The reason is simple: everything contains electrons, and when you jiggle an electron, it gives off a photon. The harder you jiggle the electron, the higher the energy of the photon. The "jiggling" of the electrons in matter due to its heat continually gives off photons. The higher the temperature of the matter, the more energetic the photons are and the more photons are given off. Recall that high-energy photons have short wavelengths. Thus, thermal emission has two important properties:

1) the hotter the object, the shorter the wavelength of the light given off

2) the hotter the object, the more light is emitted

As applied to stars, this means *the hotter the star, the bluer and brighter the star.*

Another name for thermal emission you may run across is **blackbody radiation.** This term refers specifically to the thermal emission given off by a perfect radiator, that is, an object that is black at all wavelengths. The spectrum given off by this "black body" is described by a theoretical curve called the **Planck Curve** after its discoverer, Max Planck.

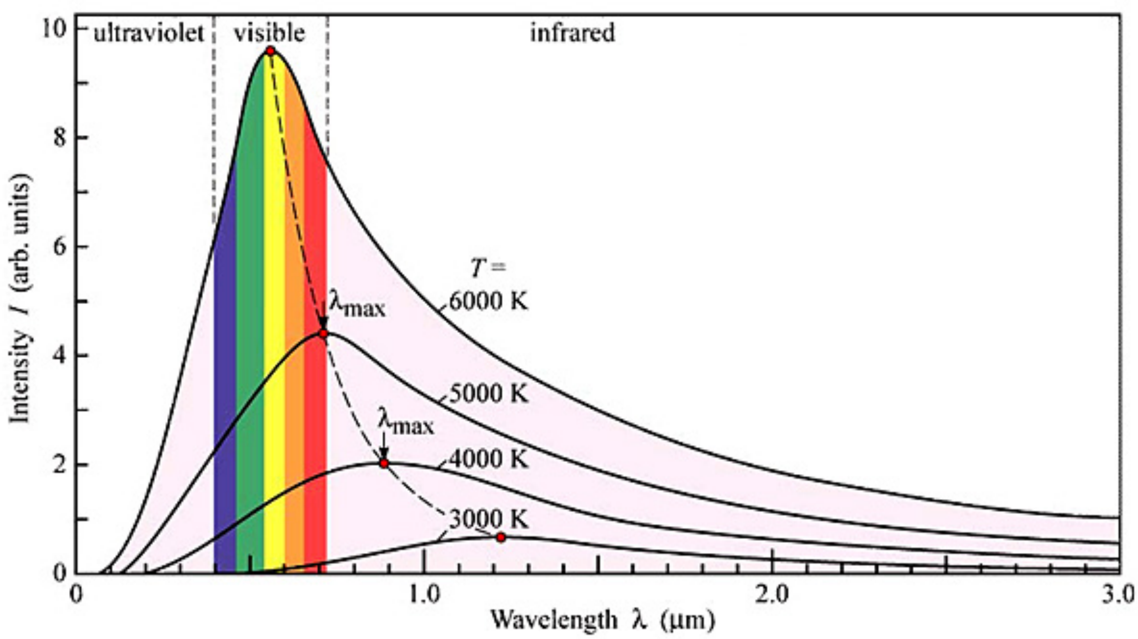
The Planck Curve

The Planck Curve is the spectrum of an ideal radiator, that is to say, it describes the brightness of light given off versus the wavelength of the light. The curve depends on the temperature of the object. Some examples are shown in Fig. ??. Note the following characteristics:

1) the curve is strongly peaked at a wavelength that depends on the temperature.

2) The curve drops off rapidly on the short-wavelength side of the peak.

3) It declines slowly on the long-wavelength side of the peak.



The reason for the peak is that the jiggling electrons are most likely to give off photons with an energy close to the electron's energy, which is determined by the temperature.

The area under the curve is the total energy given off by the star, its **luminosity.** Notice that two things happen as the temperature of the star is increased:

1) The peak gets higher, that is, the luminosity increases *(Stefan's Law)*, and

2) the wavelength of the peak shifts to shorter wavelengths *(Wien's Law)*.

In other words, if two stars are the same size but different temperatures, the hotter star is *bluer* and *brighter.*

Stefan's Law

Stefan's Laws says that the luminosity of a star depends on only two characteristics of the star: its **temperature** and its **surface area** or size. In simple terms,

hotter, brighter

bigger, brighter

Mathematically, Stefan's Law is

$$L = \sigma T^4 A$$

where L is the luminosity, T the temperature, and A the surface area. The Greek letter σ (sigma) is a constant involving the speed of light. The "4" on the T means that the luminosity is extremely sensitive to the temperature: if the temperature goes up 10%, the luminosity goes up 40%; if the temperature doubles, the luminosity increases $2^4 = 16$ times. What this means is, that most of the light in the Universe is given off by hot stars.

In plain English, Stefan's Law states that:

1. If two stars are the same size, the hotter star is the brighter star.

2. If two stars are the same temperature, the larger star is the brighter star.

Wien's Law

Wien's Law says that the peak of the Planck spectrum shifts to shorter wavelengths as the temperature increases. Its equation says that

peak wavelength = (3 mm)/T

Example 1. The Cosmic Microwave Background, with a temperature of 3 K, peaks at a wavelength of 3 mm/ 3 = 1 mm.

Example 2. The Sun has a surface temperature of about 6000K. Its peak wavelength is (3mm)/6000 = 3000µm/6000 = 0.5µm,

where 1 µm = a micrometer = a millionth of a meter.

Implications for stars

As applied to stars, these lessons mean that:

1) The temperature and size of a star determine its luminosity.

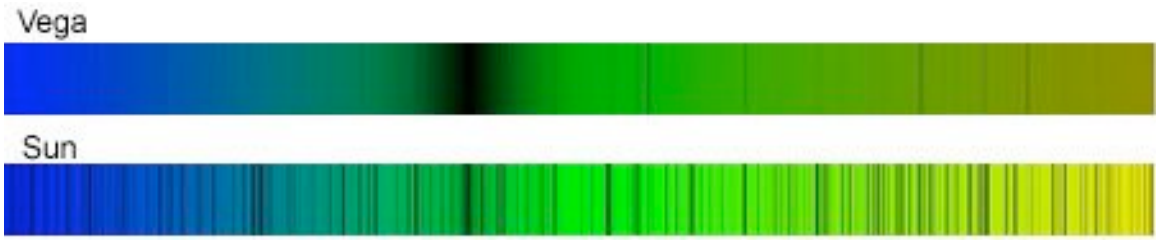
2) Hotter stars are bluer.

3) The brightest stars are big and blue.

Measuring the Temperature

You can use Wien's Law to determine the temperature of a star. All you have to do is use a prism to get the star's spectrum and measure where the spectrum is the brightest. Today, that is done electronically.

A hundred years ago, however, the spectrum was recorded as a picture on film, and it wasn't easy to say where the brightest wavelength was. However, astronomers figured out that the dark lines (absorption lines) in the spectra not only told what elements were in the star but also reflected the temperature, because the temperature affects how dark the lines are. Compare Vega (temperature 10000K) and the Sun (6000K). Vega and the Sun have the same elements in them; the difference is one of temperature.



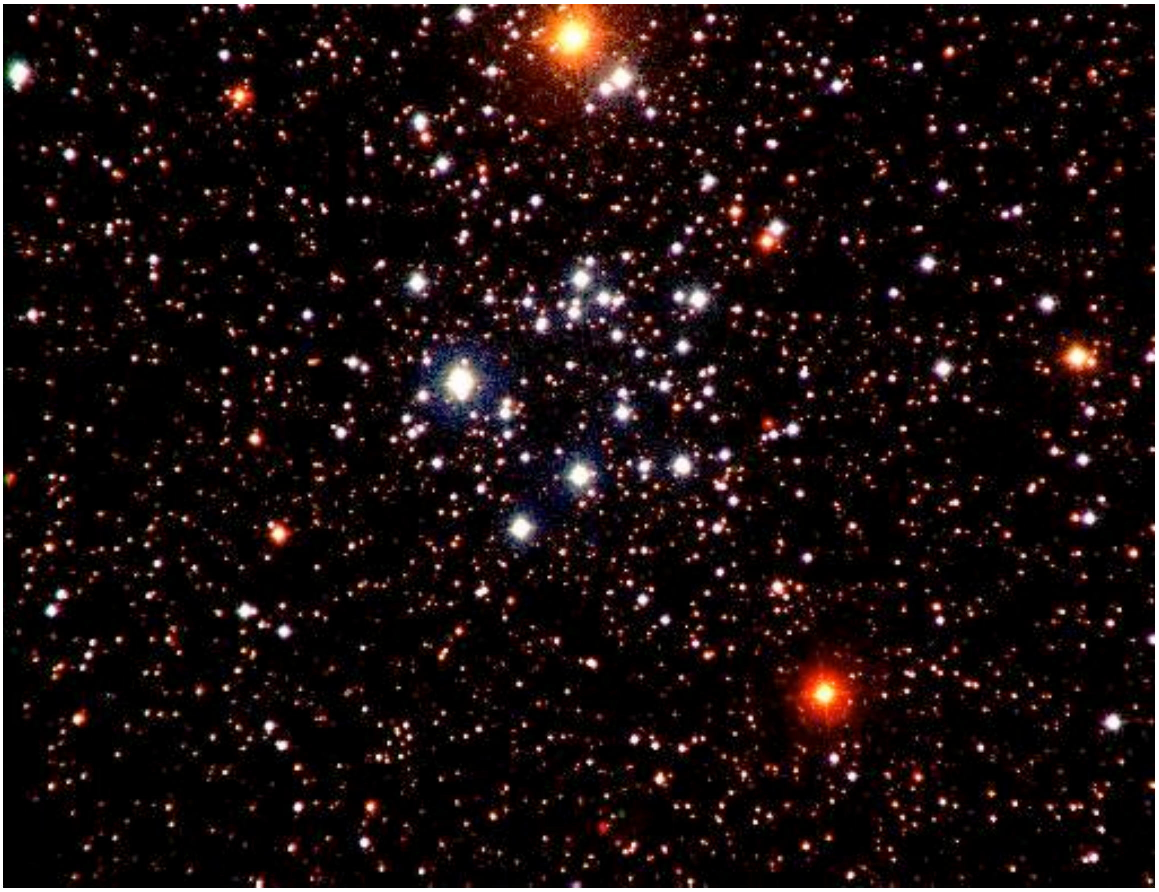
Several different patterns of spectral lines were seen and given letters: A, B, C. etc. Later, the patterns were arranged in order of temperature, from hot to cool: O B A F G K M, which generations of astronomy students have learned by the time-honored mnemonic

O Be a Fine Girl/Guy Kiss Me

(Recently, this mnemonic has required revision with the addition of three cooler spectral types: T, L, and Y.) The discovery of the temperature dependence of the spectral types provided a quick way of determining the temperature before the era of electronics.

The H-R Diagram

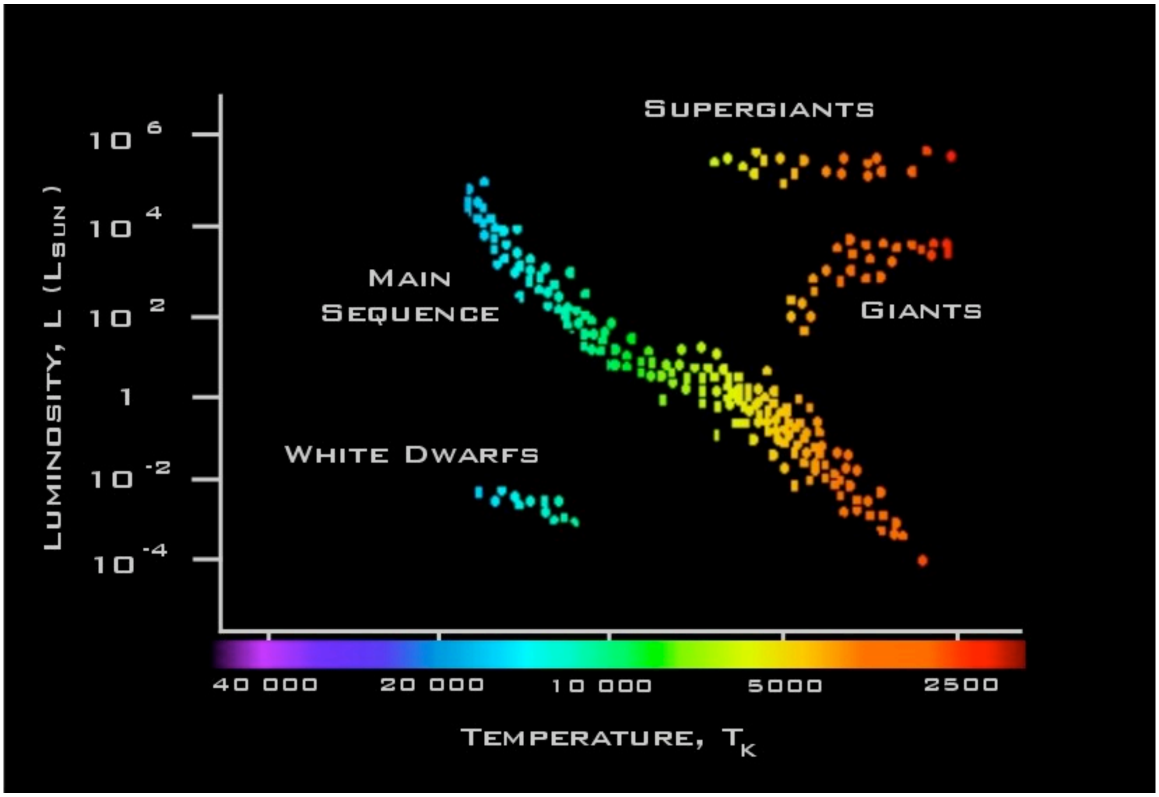
The spectra showed that stars have a range of temperatures, but could not tell us whether they differ in size as well. The problem was, that in order to know the size, you need to know the distance to the star, which is difficult to determine. There was one hint, however, that stars come in different sizes. Star clusters are groups of stars that are all at essentially the same distance. Many open star cluster have a few members that are bright but very red. Since red stars are cool stars and cool stars are dim stars, the only way a red star can be bright is to be very large. We call these stars **red giants.**



The open star cluster M50 with its brilliant red giant stars.

About a hundred years ago, two astronomers, Ejnar Hertzsprung in Denmark and Henry Norris Russell in the U.S., started plotting the brightnesses and temperatures or spectral types of the stars in a cluster on a diagram that opened our eyes about the nature of stars. Since they were working independently, both are given credit for the invention of the diagram, which is formally called the **Hertzsprung-Russell diagram**. But everyone calls it the H-R diagram for short.

In the H-R diagram, brightness or luminosity is plotted along the vertical axis. The temperature or spectral type is plotted along the horizontal axis. Perhaps because everyone learned the spectral types in the sequence OBAFGKM, it became conventional to put Type O, the hottest stars, on the left end of the axis and the Type M stars, the coolest stars, on the right end. Nowadays, when the spectral types are usually replaced with temperatures, the hottest temperatures end up on the left and the coolest temperatures are on the right.



The H-R diagram revealed that there are several different kinds of stars that must have a different internal structure. The main kinds are:

1. **Main sequence stars**
2. **Red giants**
3. **Supergiants**
4. **White dwarfs**

Main sequence stars

Main sequence stars on the H—R Diagram run from the upper left to the lower right, that is, from stars that are hot and bright to stars that are cool and dim. The reason for this as that these stars are all roughly the same size, so the difference in brightness is the result of the temperature. 90% of the stars in the Galaxy are

Main Sequence stars. These stars must have something in common. We'll find out what in the next chapter. The Sun is a Main Sequence star.

The stars in the cool end of the Main Sequence, the type M stars, are known as M-dwarfs or **red dwarfs.** More than half the stars in the galaxy are red dwarfs. Most of the Sun's nearest neighbors, including Proxima, the single nearest star to the Sun, are red dwarfs. Nevertheless, they are so faint that not a single one can be seen without a telescope or at least a binocular.

Red giants

Red giants are also called simply giants, because most of them are actually orangish in color. (It would be ridiculous, though accurate, to call them "orange giants.") These are stars that are cool but bright. Stefan's Law tells us that these stars must be very large, because otherwise cool stars are dim. The largest red giants are tens of times as large as the Sun. Examples of nearby red giants are Pollux in Gemini, Aldebaran in Taurus, and Arcturus in Boötes.

Supergiants

The supergiants lie along the top of the diagram, because they are the brightest stars of all — tens of thousands of times as luminous as the Sun. These stars would vaporize any nearby planets. However, they are quite rare; the nearest is Betelgeuse, about 400 light-years away, far enough that we are quite safe. Rigel, also in Orion, is another supergiant. The supergiants vary in temperature from cool to hot; Betelgeuse is a cool red supergiant, while Rigel is a hot blue supergiant. These stars are destined to blow up in a fiery supernova explosion.

White dwarfs

The stars in the lower left corner of the H–R diagram are hot but faint. Stefan's Law tells us that these stars must be quite small, roughly the size of the Earth. Consequently, they are called **white dwarf** stars. For a long time it was an utter mystery why these stars are so much smaller than the Main Sequence stars. Although they are odd, they are not rare: roughly one out of ten stars is a white dwarf. As we shall see in the next chapter, the Sun will someday become a white dwarf.

Mass of stars

The mass of stars (their weight) is measured by observing binary stars, stars that are close enough together that they are bound by their mutual gravitational attraction and orbit around each other. Such pairs are common in the galaxy; about half the stars in the galaxy belong to a binary system. The speed of their orbiting tells us the strength of the gravitational attraction, which itself depends on the mass of the stars. This principle is known as Kepler's Third Law.

mass → gravity → speed → orbital period

We observe the orbital period (usuually many years) and work backwards to calculate the mass. We do need to know the distance to the star system, so we need to measure the parallax.

It turns out that the mass of stars varies quite a bit, but not nearly as much as the size or luminosity. The lightest stars are about a tenth the mass of the Sun; the heaviest, about 100 times as massive.

Among the Main Sequence stars, the least massive stars are the red dwarfs; the most massive are the O and B stars. In fact, it is the mass that determines the temperature and luminosity of a Main Sequence star. In the next chapter, we'll take up the questions:

1. What do the Main Sequence stars all have in common?
2. How are the red giants and white dwarfs are related to the Main Sequence stars?
3. What happens to stars when they die?