Lecture Eight

The Heavenly Stars

Salisbury University

The Properties of Stars

Even with the naked-eye, the night sky is strung with bright pinpoints of light we call “stars.” Along with a dark night sky the unaided eye can easily pick out a few thousand of these pinpoints of light. Astronomers now know that there are in excess of 100 billion stars in our galaxy alone (that is 100,000,000,000 stars!). As you might guess, it would behoove us to study these stars and understand something about them since they are so ubiquitous.

- What are stars?
- How can we determine anything about them?
- How come some are brighter than others?
- How far away are these stars from us?
- How can we use only “observation” of stellar light to know the nature of these objects so remote that their light can take years, centuries, maybe even millennia to reach us?

Stars are remote:

- Nearest star? Sun – 93,000,000 miles away from Earth
- Next closest? 24 trillion miles away? Proxima Centauri! (Not Alpha Centauri!)

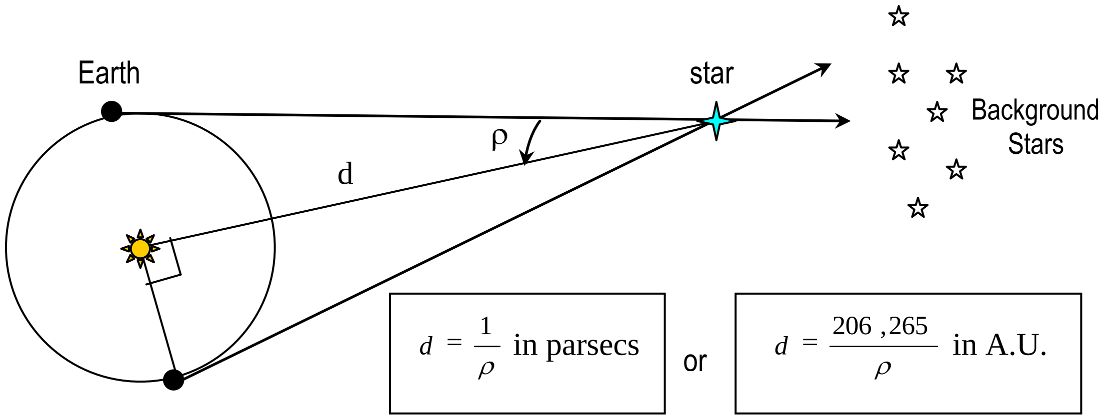
Parallax

Measuring distances to stars: - The most straightforward way of measuring distance is using an effect that we ourselves use every day to judge distances to the objects around us. Parallax.

Analogy: Hey, what do you mean I use parallax every day? I hate trigonometry! Ah, but you do it without knowing it to survive the day. We have an innate ability to judge distance that is what mathematicians call “trigonometric parallax.” To illustrate, hold your arm out straight in front of you. Now stick up your thumb. (Aayyayaaaaa!). Now look at your thumb at the end of your outstretched arm, first with only your left eye closed, then with only your right eye closed. When you wink your eyes back and forth notice that your thumb shifts position with respect to more distance objects behind it. Hey! Now experiment and notice that the amount of shift your view your thumb to have will depend on how far away it is from your face. You are judging the distance to your thumb (and other objects) all the time in this way. This is the reason most living (Earthly) beings have more than one eye, so they can judge distance (with parallax!).

You’ve just made the observation that the larger the parallax angle (ρ), the smaller the distance (d) to the object you are observing.

Stellar parallax



$$d = \frac{1}{\rho} \text{ in parsecs}$$

or

$$d = \frac{206{,}265}{\rho} \text{ in A.U.}$$

Figure 1: The farther the object, the smaller the parallax angle (ρ). ρ is measured in seconds of arc.

Parallax is used to measure the distances to some nearby stars. Most other stars are so far away that observing a star from opposite sides of the Earth will produce a parallax angle much, much too small to detect. Because of this one must use the largest baseline possible. The largest one that can be easily used is the orbit of the Earth. In this case the baseline is the distance between the Earth and the Sun ➔the **Astronomical Unit** (A.U.) or 149.6 million kilometers! The parallax angle *p* is one-half of the total angular shift. The apparent change in position of an object due to a change in the location of an observer.

Guess what? The Astronomical Unit is not a sufficient distance to be used because stars are that much farther away. The A.U. is just not large enough. It is, therefore, more convenient to measure some stellar distances (d) in **parsecs**; a star with a parallax angle of 1 second of arc (ρ = 1arcsec) would be at a distance of 1 parsec. (Thus, also 1 parsec = 206265A.U.)

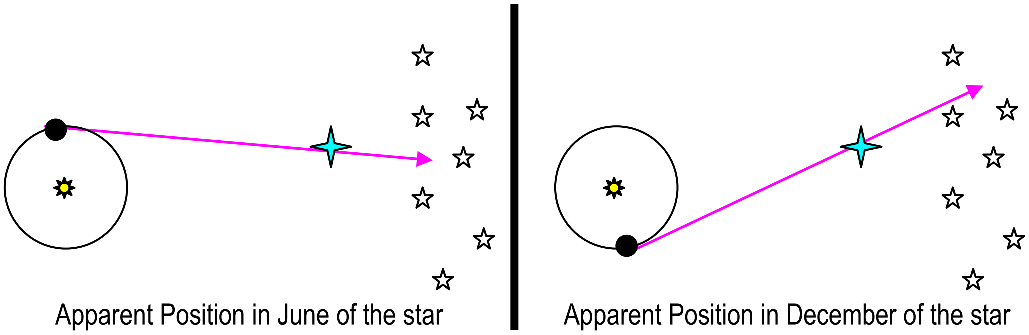


Figure 2: Notice that the star's position has shifted against the background stars as the year progresses.

Making a point: Remember earlier in our discussions about the rise of astronomy, specifically **Tycho Brahe**, Copernicus, & Ptolemy – they failed to measure stellar parallax of any stars because the parallax angles are so very small. All stars (even the nearest ones) have parallax angles that are less than 1 second of arc, meaning that even the closest star will be more than 1 parsec away! (Closest star = Proxima Centauri = 0.772 arcsec = 1.30 parsecs distant! The parallax of Proxima Centauri is comparable to the angular diameter of a dime seen from a distance of 2 miles.)

A question you might be wondering about? Stellar parallax is the "apparent" motion of stars caused by the Earth's orbital motion around the Sun. But, stars are not fixed objects and they too do move through space. As a result, stars change their positions in the sky over time. (Constellations are actually temporary alignments of stars in the sky!) These motions, however, are sufficiently small, so much so, that changes in the positions of stars are not noticeable over a human lifetime (or many human lifetimes).

Brightness of Stars: Stellar Magnitude Scale

Hipparchus – "Magnitude Scale" (2100 years ago) – Done with naked-eye observations.

- The smaller the magnitude the brighter. (Negative numbers too!)
- The larger the magnitude the dimmer.
- He accomplished this by picking a standard star (Vega 0.0) and assigning this star as the common standard by which to compare.

Intrinsic Brightness: Absolute Visual Magnitude

- (M_v) – magnitude the star would have if it was 10 parsecs away by standard. The scale is counter-intuitive. The more negative the magnitude the brighter the star. The more positive the magnitude the dimmer the star.

Apparent Brightness: Apparent Visual Magnitude

- (m) – magnitude the star appears to have. This quantity depends on the distance the star is away from us.

Magnitude Quantification:

- 1.0 step in magnitude ➔ $(2.512)^1$ = 2.512 times in brightness
- 2.0 steps in magnitude ➔ $(2.512)^2$ = 6.31 times in brightness
- 3.0 steps in magnitude ➔ $(2.512)^3$ = 15.85 times in brightness
- 4.0 steps in magnitude ➔ $(2.512)^4$ = 39.82 times in brightness
- 5.0 steps in magnitude ➔ $(2.512)^5$ = 100.0 times in brightness
- … … … … … … …
- 10 steps in magnitude ➔ (100)(100) = 10,000 times in brightness
- 15 steps in magnitude ➔ $(100)^3$ = 10^6 times in brightness

For example:

Vega 0.0 Arcturus –0.1 Sirius –1.5 Altair 0.8 Deneb 1.8

Hey! Neat! The human eye is actually a great “logarithmic detector.”

What can we learn from apparent and absolute magnitudes? How about distance! If we compare the absolute to what apparent brightness a star has we can then surmise the distance the star must be located. The result is given by;

$$\boxed{m - M_V = -5 + 5\log(d)}$$

The Colors of Stars

We have already seen, and you have witnessed, one of the first things you can notice is difference in the apparent magnitudes of stars in the nighttime sky. Another, and perhaps more tantalizing, observation you can attempt to make is to notice the different colors of the stars. Colors? Oh yes, stars shine in the varied rainbows of colors in the visual spectrum. Some stars appear redder, some yellowish (like or Sun), others bluish!

Hey, what is going on here? Well, remember blackbody radiation? What did we learn? Let me remind you a bit about black body radiation. Well we learned;

- A dense object (stars?) emits electromagnetic radiation according to its temperature.
- The hotter the object the “brighter” and the shorter (“bluer”) the wavelength at which most of the energy is emitted.
- The cooler the object the “dimmer” and longer (“redder”) the wavelength at which most of the energy is emitted.

Stars behave nearly as blackbody radiators, thus when we are deciphering the colors that we see for a star we are also learning something about its temperature (in a specific place). **A star’s color depends on its surface (photospheric) temperature.**

Well, unfortunately, the human eye is a rather poor color sensitive device especially at the low levels of light that most stars have in the sky. [In reality, we are not good at picking out the colors of a few stars when they are very bright in the night sky.] To measure the surface temperatures of stars, astronomers use a light and color sensitive device (CCD) and employ a technique called **UBV photometry**. (U filter ~violet, B filter ~blue, V filter ~red).

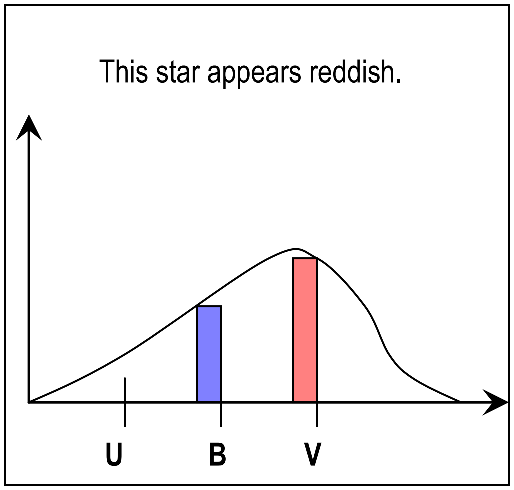


Figure 3: A spectrum of a star that favors the redder portion of the visible spectrum.

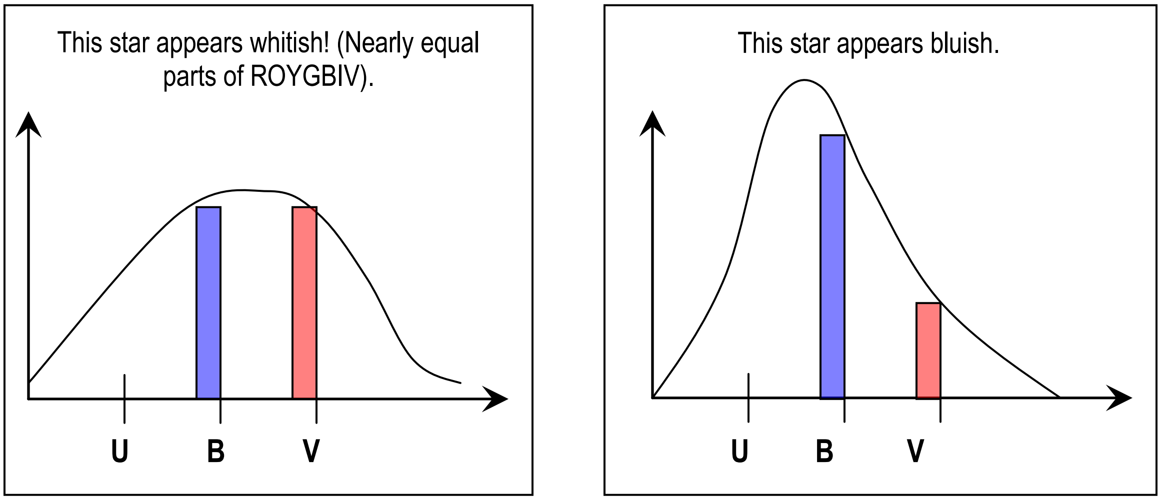


Figure 4: A spectrum with nearly equal portions of blue and red will appear whitish in color, but one that favors bluer wavelengths will appear bluish.

Stellar Spectra

There is a lot of information hiding in individual stellar spectra besides color! We can also learn much about the chemical composition of stars by investigating the spectral lines that show up in the spectra.

The spectra of stars reveal their chemical compositions as well as the surface temperatures. A spectrometer is used with the star's light to produce a star's absorption spectra with its particular chemical print. However, Hydrogen, Helium, and a few others are common to most luminous stars. Astronomers have calibrated these commonalities into "**spectral types**."

Annie Jump Cannon

- (scale adopted in 1910) ➔ developed the widely adopted classification scheme.
- Strength of Hydrogen Balmer (to n=2) Lines along with the appearance of other chemical line features
- Adopted Types (based on, partially, photopaper types!)
- This is a surface temperature scale based on spectral lines features.

O B A F G K M		
Early Types	→	Late Types
Hot	→	Cool
Bluish	→	Reddish

The Hertzsprung-Russell Diagram:

A graph that separates the effects of temperature and surface area on stellar luminosities.

- **Ejmar Hertzsprung** (1873-1967) – Copenhagen – Began his career as a Chemical Engineer. While working and independently at the same time…
- **Henry Norris Russell** (1877-1957) – Princeton – Student then professor.

The HR Diagram is much like the same thing as producing a graph of people's height vs. weight.

First, what does the luminosity of a star depend on?

1. Temperature (proportional to T^4)
2. Size (proportional to R^2)
3. Full blown formula? $L = 4\pi R^2 \sigma T^4$

Here we go!

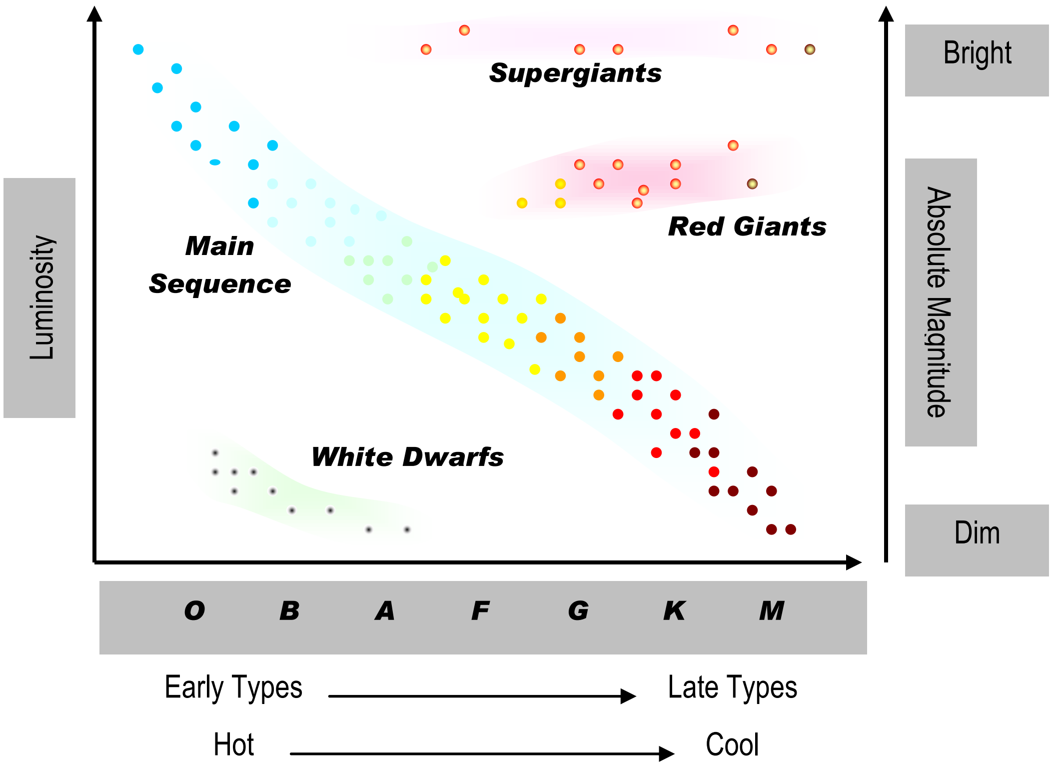


Figure 5: The H.R. Diagram is a simple graph of the relationship between a star's surface temperature and its absolute brightness. However, since the color of a star and the spectral type of a star are related to its surface temperature there is a great deal of flexibility in the graph. There is a lot of information that is contained and/or can be divined from this relationship and graph.

Notice that the pattern above for a graph of Luminosity Vs. Spectral Type is *not random.*

Main Sequence

- Extends from the hot, bright, bluish stars in the upper left to cool, dim, reddish stars in the lower right.
- Size (Radius) if the stars: $R \sim R_\odot$ (or slightly bigger/smaller) ~90% of the stars in space.

Red Giants

- Cool, luminous stars. They are very luminous because of their large size.
- Size $R \sim 100R_\odot$ ➔ but they are only about 0.9% of the stars by number.

Supergiants

- Exceptionally luminous extra large sized stars! (humongous!)
- Size $R \sim 1000R_\odot$ ➔ but they are only about 0.1% of the stars by number.

Where is the missing 9%?

White Dwarfs:

- HOT but faint stars.
- The surface temperatures of these stars are very hot, but since they are so small they are not very luminous.
- Size $R \sim (1/100) R_{\odot} \sim R_{\oplus}$ ➔ but they are only about 9% of the stars by number.

Caution: Do not confuse the size of an object with the mass of an object. Just because an object is large in dimension does not necessarily mean it is also large in mass. For example, you can have a forty foot tall by three foot across marshmallow that looks "large," but that does not mass as much as that of a "small" football sized hunk of lead.

Stellar Information: Some Example Stars

Name	Spectral Type	Temp (K)	Mass	Kind?
Spica	B1	~20,000 K	$13\ M_{\odot}$	M.S. Bluegiant
Sun	G2	~5,800 K	$1\ M_{\odot}$	Main Sequence
Betelguese	M2	~ 3,000 K	$14\ M_{\odot}$	Red Supergiant
Sirius B	A0	~18,500 K	$1\ M_{\odot}$	White Dwarf

Table 1: A set of example stars that can be graphed on the HR diagram along with their specific information.

Mass Ranges of Main Sequence Stars (*ONLY*)

- **Most Massive Stars** ~ 55-100(?) times more massive than the Sun (very rare)
- **Least Massive Stars** ~ 0.1-0.08 times the mass of the Sun. (very common)
- This pattern stretches from the higher mass O,Bs to lower mass K,Ms.

Mass-Luminosity Relationship

The Main Sequence also exhibits a “Mass-Luminosity Relationship.” Simply, a star’s location on the main sequence depends on its mass. The more luminosity a star has the larger its mass. The lower the star’s mass the smaller its luminosity. But this is true only on the main sequence.

The math form of the “mass-luminosity” relation of the main sequence.

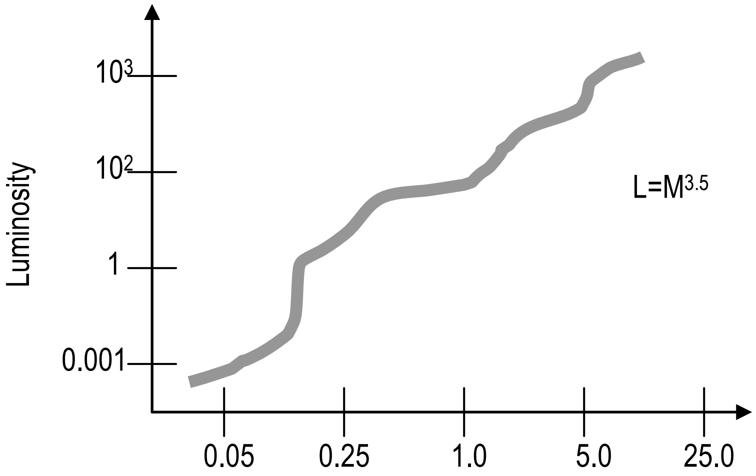


Figure 6: The mass-luminosity relationship is purely and empirical result. The masses of the main sequence stars loosely follow a power law relating the mass to overall luminosity.

- Suppose the mass of a star is 4 $M_\odot$ then

  $L = (4)^{3.5} = (4) \times (4) \times (4) \times (4)^{0.5} = 128$ times more luminous. 128 $L_\odot$
- Suppose the luminosity of a star is 5 $L_\odot$ then

  $5 = (M)^{3.5} \Rightarrow M=(5)^{-3.5} = 1.6$ times more mass. 1.6 $M_\odot$

Note: This was for the main sequence stars only. Giants and super-giants do not follow the mass-luminosity relation very closely. White Dwarfs do not follow this relation at all.

Density ranges of Stars (average densities).

- Sun ~ 1.0 grams/cm^3 (The same density of water!)
- Giants ~ 0.01 grams/cm^3 → 0.1 grams/cm^3
- Supergiants ~ 0.000001 grams/cm^3 (That is less than the density of air!)
- White Dwarfs ~ 10,000,000 grams/cm^3

  (1 sugar-cubed size of white dwarf material would weigh nearly 20 tons!)

The Yerkes System

A Refinement to the Spectral Types developed and used in conjunction with the HR Diagram: (Sometimes call the M-K System (Morgan-Keenan)).

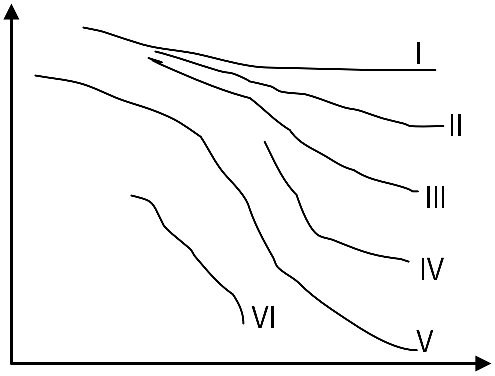


Figure 7: The Yerkes System further categorizes stars into many more stellar types.

Class

- Type I ➔ Supergiant
- Type II ➔ Bright Giant
- Type III ➔ Giant
- Type IV ➔ Subgiant
- Type V ➔ Main Sequence (Dwarf)
- Type VI ➔ SubDwarf
- Under this system the Sun is a “G2-V” type star.

The Main-Sequence Mass-Luminosity Relation:

The Mass-Luminosity relation for * only* the main sequence is straightforward. As you compare stars going up the main sequence the stars become progressively more massive (also larger in diameter size and bluer in surface color).

Note: This relationship works, again, only along the main sequence. The giants and white dwarfs have a range of masses that are characteristics of their own.

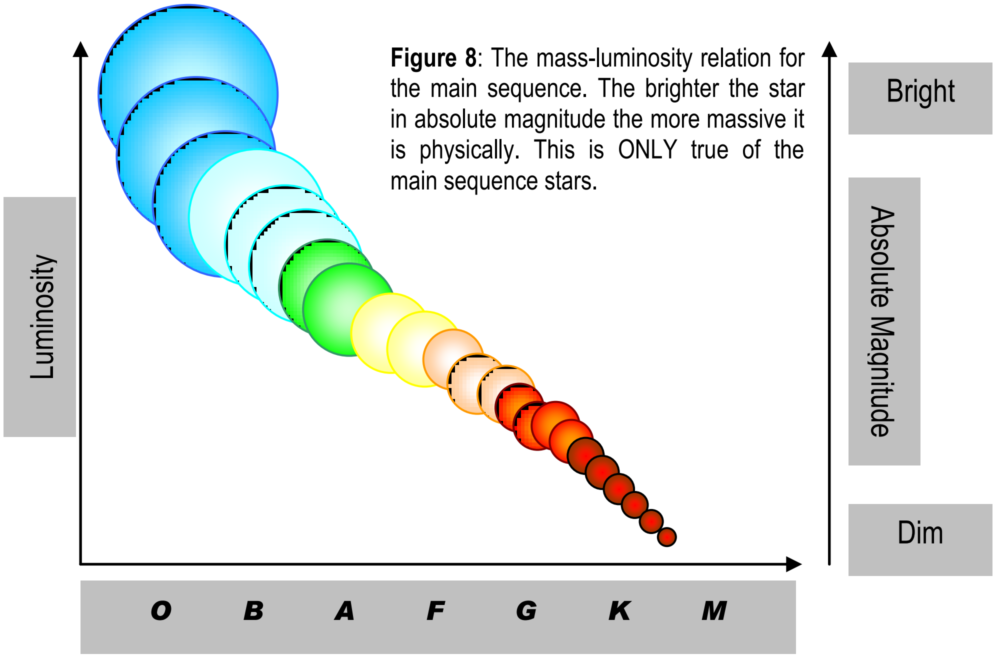


Figure 8: The mass-luminosity relation for the main sequence. The brighter the star in absolute magnitude the more massive it is physically. This is ONLY true of the main sequence stars.