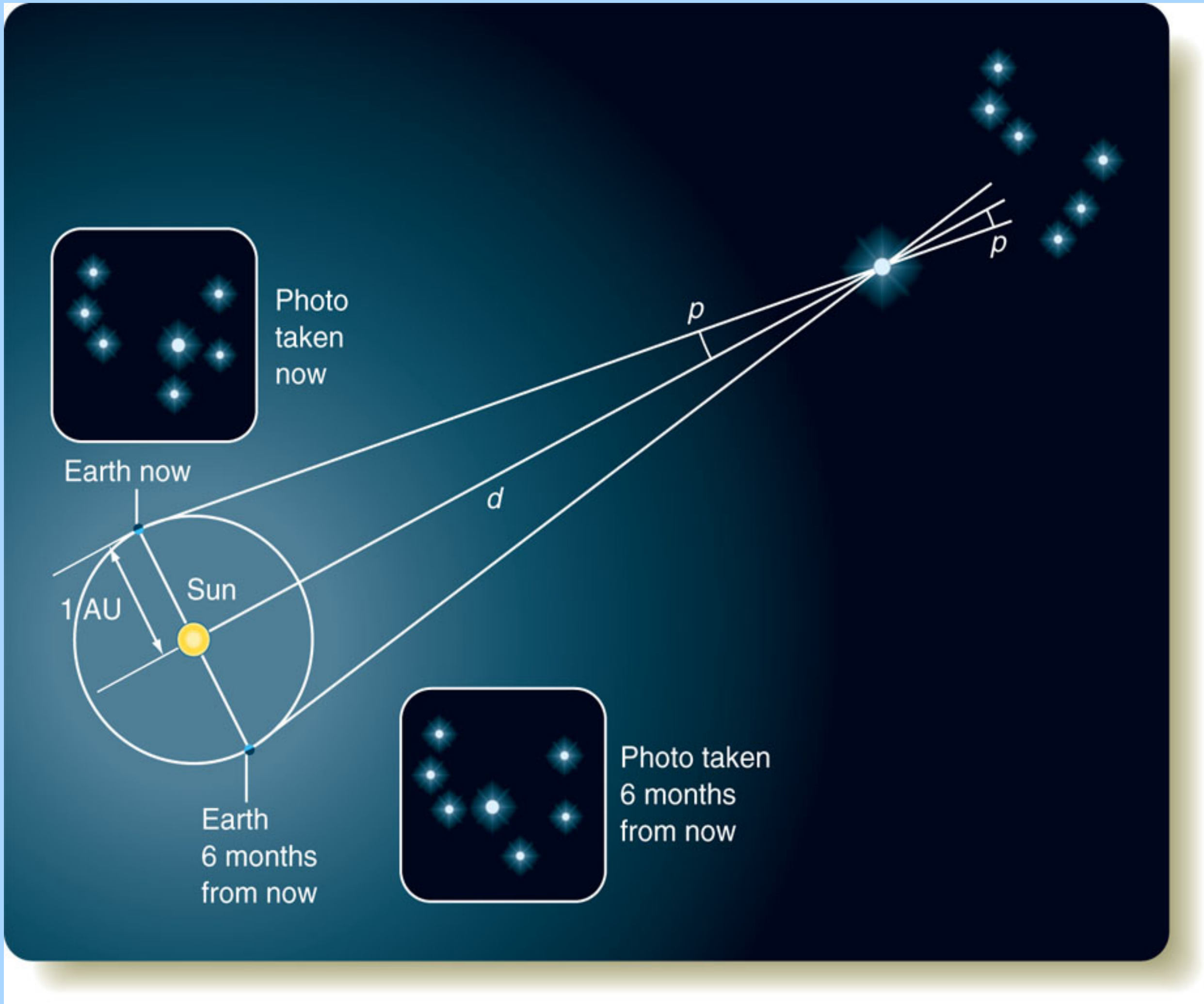
Basic Properties of the Stars

The Sun transforms protons into helium nuclei

a) in its core
b) in the core and radiative zone
c) in the core, radiative zone, and convective zone
d) in the core, radiative zone, convective zone, and photosphere.

The Sun-centered model of the solar system laid out by Copernicus in *De Revolutionibus* (1543) made a very specific prediction: that the nearby stars should exhibit parallax shifts with respect to the distant background of stars. Tycho Brahe improved positional measures from +/- 10 arc minutes to as good as +/- 1 arc minute, but he could measure no parallaxes. This implied either that the stars were more than 3000 Astronomical Units away, or that the Earth was stationary and did not orbit the Sun. It took nearly 300 years after Copernicus' death for the first trigonometric stellar parallaxes to be measured.



If angle p = 1 arc second, the nearby star is at a distance of 1 parsec = 206,265 Astronomical Units = 3.26 lt-yrs.

The word *parsec* is short for “parallax of one second of arc”.

If the radius of the Earth's orbit subtends an angle of 1 arcsec at a distance of 1 parsec, then at a distance of 2 parsecs, 1 AU subtends an angle of 0.5 arcsec. At 3 parsecs 1 AU subtends an angle of 1/3 of an arcsec. Thus, the distance in pc of a star is simply the reciprocal of the parallax in arcsec:

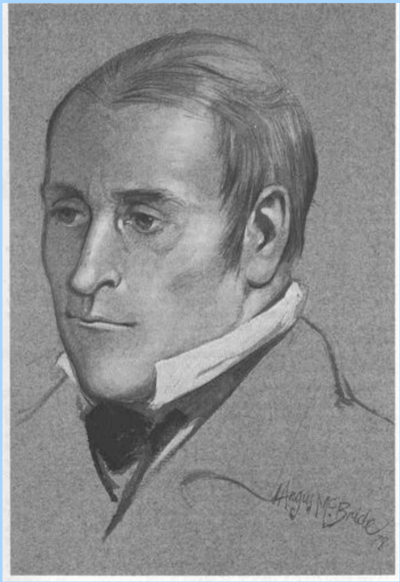
$$d\ (\text{pc}) = 1/p\ ('')$$

A star is at a distance of 12 parsecs. What is its trigonometric parallax?

A. 12 arc seconds
B. 1.2 arc seconds
C. 0.12 arc seconds
D. 0.083 arc seconds

The trigonometric parallax of a star is 1/22 of an arc second. How far away is it?

a. 1/22 of a light-year
b. 1/22 of a parsec
c. 22 light-years
d. 22 parsecs



T. Henderson
(1789-1844)

F. W. Bessel
(1784-1846)

W. Struve
(1793-1864)

In the 1830's Henderson measured the parallax of α Centauri. Bessel measured the parallax of 61 Cygni. Struve measured the parallax of α Lyrae (Vega). All values were one arc second or less.

Values of parallax measured by these 3 astronomers

Struve α Aquilae 0.181 +/- 0.094 arcsec (1822)
modern value is 0.195

Struve α Lyrae 0.125 +/- 0.055 arcsec (1837)
later revised to 0.2613 +/- 0.0254 (1839)
modern value is 0.130

Bessel 61 Cyg 0.3136 +/- 0.0136 arcsec (1838/9)
modern value is 0.286

Henderson α Cen 1.16 +/- 0.11 arcsec (1839)
modern value of 0.768

Henderson and Struve were lucky. Two of the brightest stars in the sky (α Cen and Vega) gave measurable parallaxes. Why did Bessel choose to work on a much fainter star? (Actually, 61 Cyg is a double star system made of a star of apparent magnitude 5.2 and another of magnitude 6.1.) It was because 61 Cyg had a very large motion across the line of sight. This implied that it might be a very nearby star (system).

The number of arc seconds per year (or arc seconds per century) that a star moves with respect to the distance background of stars or galaxies is called the star's **proper motion**.

Proxima Centauri (courtesy Adric Riedel, GSU)

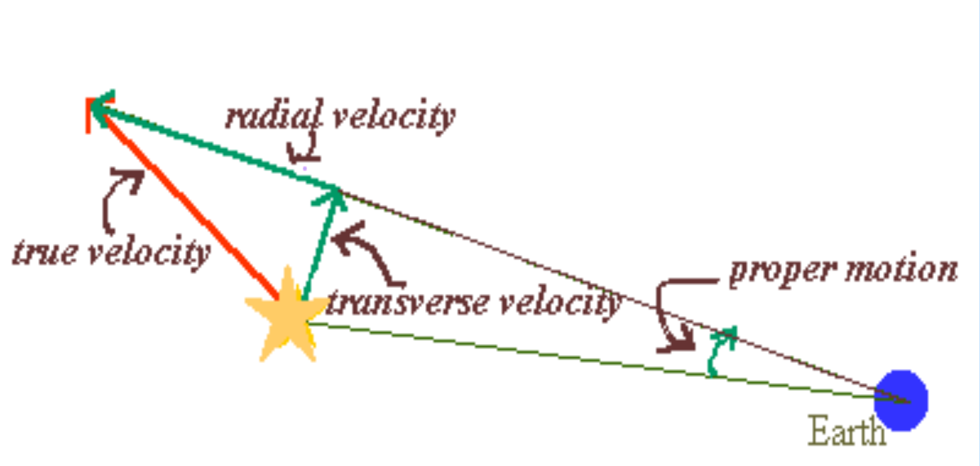


Figure 1: *The components of the velocity of a star.*

The **radial velocity** is measured from the Doppler shift of the lines in a star's spectrum. The **transverse velocity** can be determined from the star's **proper motion** and its distance.

The relationship between **transverse velocity** and **proper motion** is as follows:

$$v_T = 4.74\, d\, \mu \;,$$

where v_T is the transverse velocity (measured in km/sec), d is the distance in parsecs, and μ is the proper motion in arc seconds per year. The numerical factor comes from

(km/sec) / [parsecs X arcsec/yr] =

(km/pc) / [(sec/yr) X (arcsec/radian)] =

$(206265 \text{ X } 149.6 \text{ X } 10^6)/[3.156 \text{ X } 10^7 \text{ X } 206265] = 4.74$

So, a star at a distance of 10 parsecs that has a proper motion of 1 arcsec/year has a transverse velocity of

$$v_T = 4.74 \text{ x } 10 \text{ x } 1 = 47.4 \text{ km/sec}$$

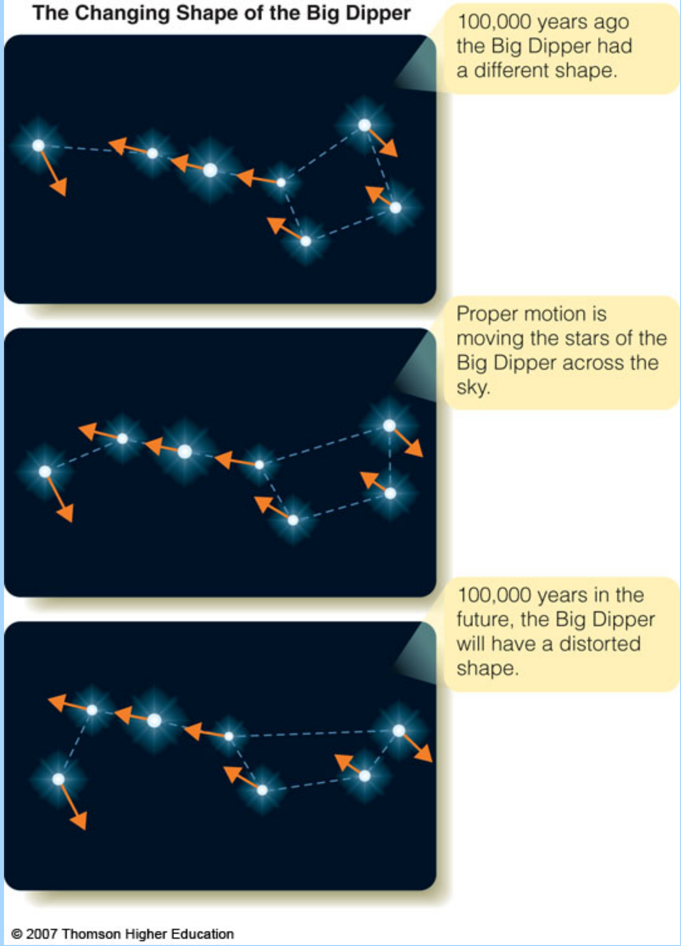
If the stars move sideways in random directions by a few tenths of an arc second per year, or a few arc seconds per year, what is one of the long term consequences of this?

a. they will all eventually escape the galaxy
b. they will all eventually be captured by the black hole at the center of our Galaxy
c. their radial velocities are mostly zero
d. the constellations will change shape over tens or hundreds of thousands of years.

61 Cygni has a proper motion of 5.28 arcsec/yr and a distance of 3.5 pc. Its transverse velocity is 88 km/sec, roughly 3 times the speed of the Earth orbiting the Sun.

61 Cyg is also a binary star with a period of 659 yrs.

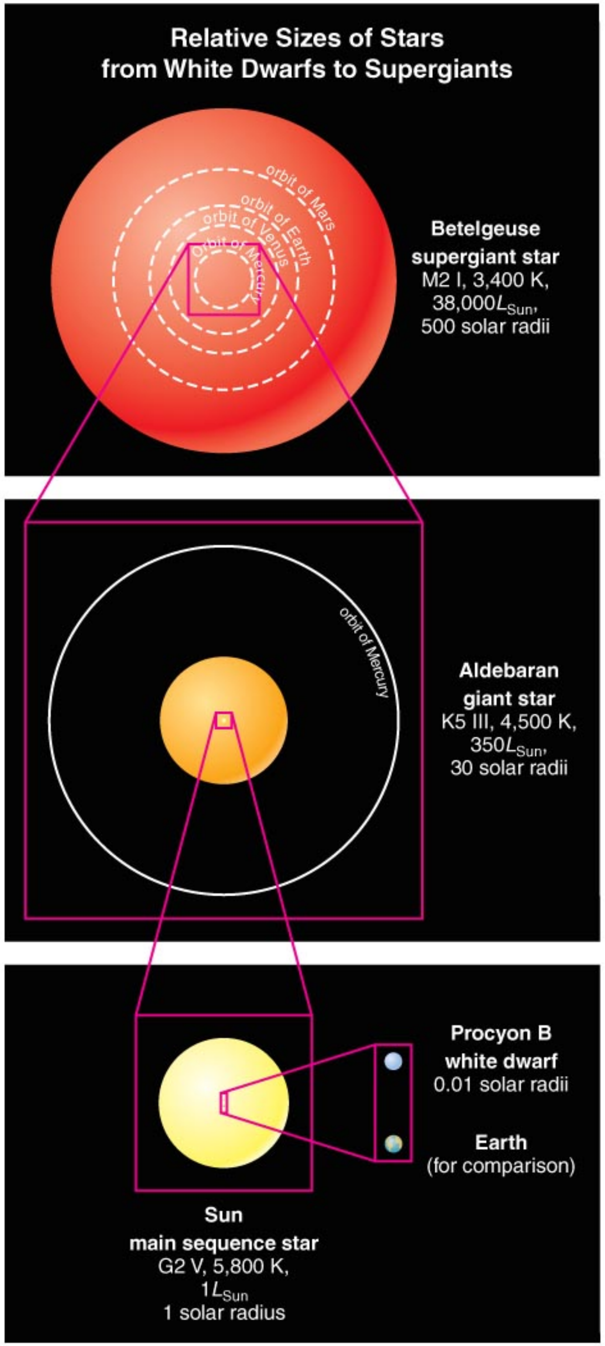
Over the course of hundreds of thousands of years, the proper motions of the stars will cause the constellations to change shape.



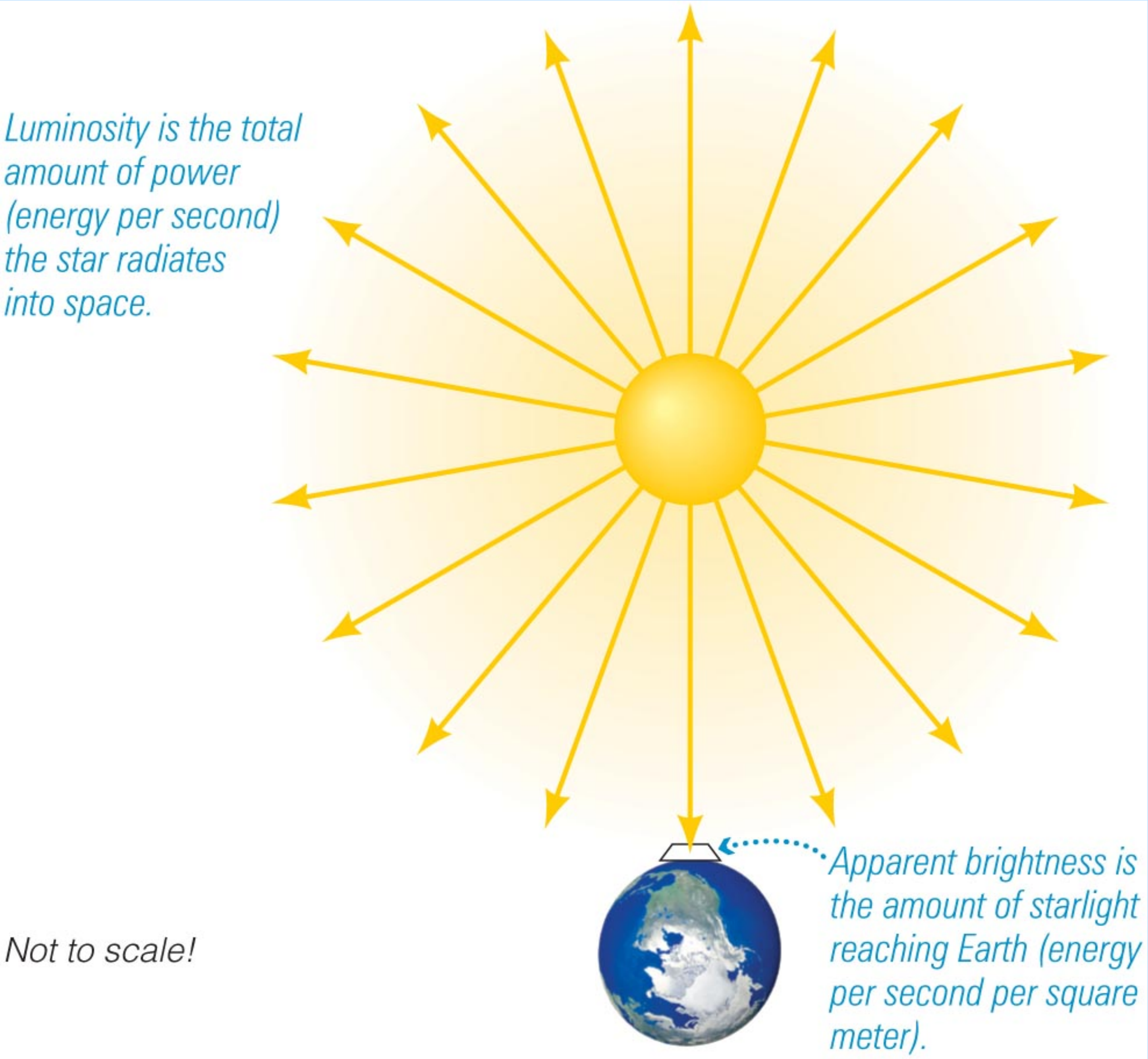
Barnard's star has a proper motion of more than 10 arcsec per year.

A star gives off an amount of light related to its photospheric temperature and its size. There is an incredible range of stellar **luminosity**. This is because stars range in size from white dwarfs (typically 2 percent the size of the Sun) to supergiants that may be as large as the orbit of Mars. Also, their temperatures range from 3000 deg K to 30,000 deg K.

How bright a star appears to us depends on the luminosity of the star and its distance.

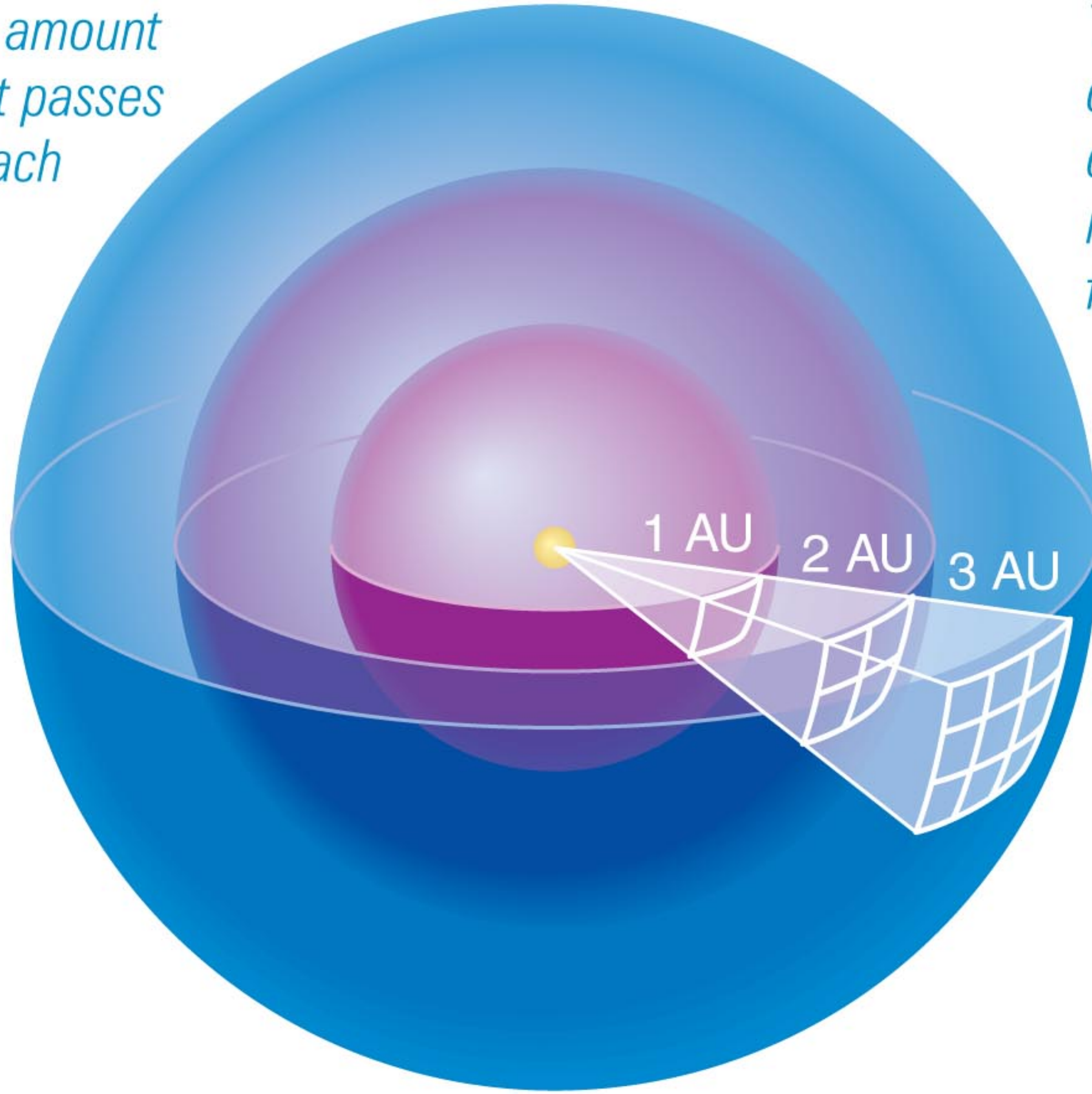


There is a wide range in the sizes of stars.


Luminosity is the total amount of power (energy per second) the star radiates into space.
Apparent brightness is the amount of starlight reaching Earth (energy per second per square meter).
Not to scale!

The same amount of starlight passes through each sphere.

The surface area of a sphere depends on the square of its radius (distance from the star) . . .



. . . so the amount of light passing through each unit of area depends on the inverse square of distance from the star.

So – a 100 Watt light bulb viewed at 200 meters is one-fourth as bright as the same 100 Watt light bulb viewed at 100 meters.

Recall that Hipparchus set up the system of stellar **apparent magnitudes**. A 1st magnitude star is brighter than a 2nd magnitude star, which is brighter than a 3rd magnitude star, etc. In the 19th century the magnitude scale was more precisely defined. If two stars have an apparent luminosity ratio of 100, they have apparent magnitudes that differ by exactly 5 magnitudes. So we receive 100 times as many photons per second from a 1st magnitude star compared to a 6th magnitude star.

Absolute Magnitudes

As we just stated, the magnitude scale is set up so that two stars with a ratio of luminosities of 100 will differ by five magnitudes. Another way of expressing this is:

$$m_2 - m_1 = 2.5 \log_{10}(\ell_1/\ell_2)$$

If $\ell_1 = 100\ \ell_2$, $m_2 - m_1 = 2.5 \log(100) = 2.5 \times 2 = 5.0$.

Now consider some star observed at two different distances.

Let it have apparent magnitude m and luminosity ℓ at distance d. And let it have apparent magnitude M and luminosity L at some other distance D.

Since the apparent luminosity of a star decreases proportional to the inverse square of the distance, the ratio of the luminosities of the stars is equal to the reciprocal of the ratio of the distances:

$$(L / \ell) = (d/D)^2$$

Combining the last two equations:

$$m - M = 2.5 \log (L / \ell) = 2.5 \log (d / D)^2$$

$$= 5 \log (d / D)$$

$$= 5 \log d - 5 \log D$$

If we let D = 10 pc, since log 10 = 1, this all becomes

$$m - M = 5 \log d - 5 \qquad \text{or}$$

$$M = m + 5 - 5 \log d$$

If we consider apparent visual magnitudes, we have

$$M_V = m_V + 5 - 5 \log_{10} d$$

We call M_V the "absolute visual magnitude" of the star. d is the distance of the star in parsecs.

Thus, if we know the apparent magnitude of a star and its distance, we can calculate the apparent magnitude it would have at a distance of 10 pc. If we determine the distances to many, many stars and measure their apparent magnitudes too, we can convert all the apparent mags to absolute mags and directly compare the *intrinsic bright-nesses* of the stars.

Consider two stars of identical size and identical photospheric temperature. So they both give off the same amount of total light each second. One star is at a distance of 25 parsecs and has an apparent magnitude of 5.0. The other one is at a distance of 50 parsecs and has an *apparent* magnitude of

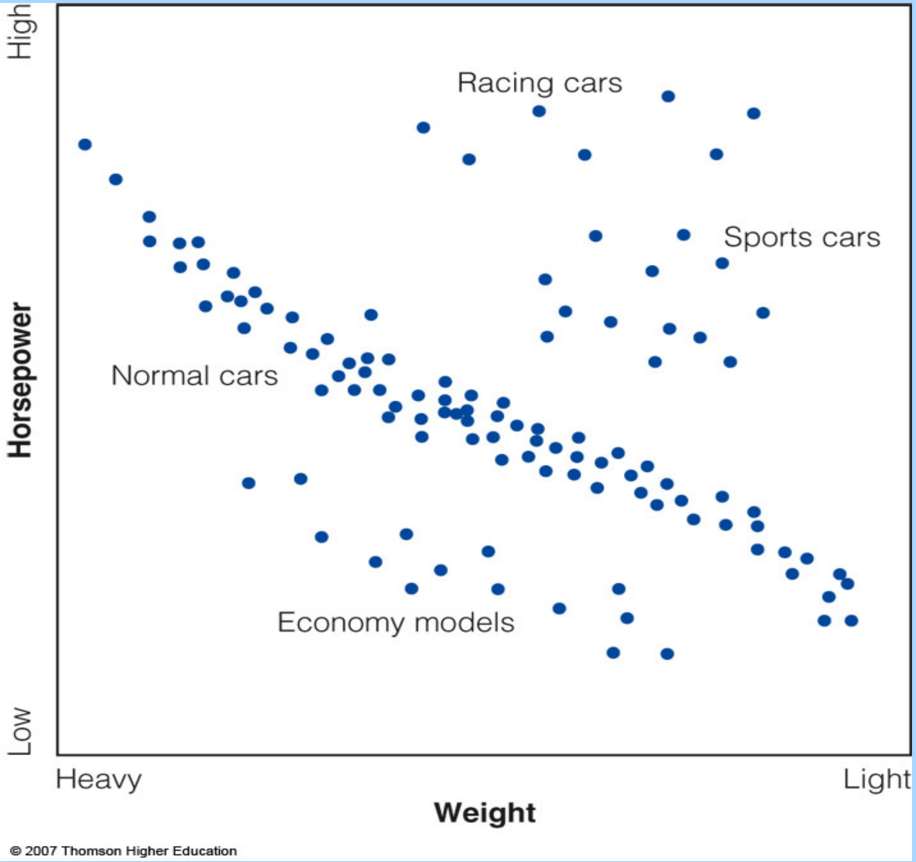
A. 5.0 (e.g. the same)
B. fainter than 5.0 (e.g. 6.5)
C. brighter than 5.0 (e.g. 3.5)

The Sun's absolute visual magnitude is $M_V = +4.8$. That is to say, if it were at a distance of 10 parsecs, it would have an apparent magnitude a little brighter than 5.

How bright would the Sun be if it were at a distance of 100 pc? You'll need $M_V = m_V + 5 - 5 \log_{10} (d_{pc})$.

A. Apparent mag 4.8
B. Apparent mag 9.8
C. Apparent mag 14.8
D. Apparent mag 104.8

As an aside, let us consider the horsepower of cars vs. their weight. For most cars there is a correlation of these two parameters.

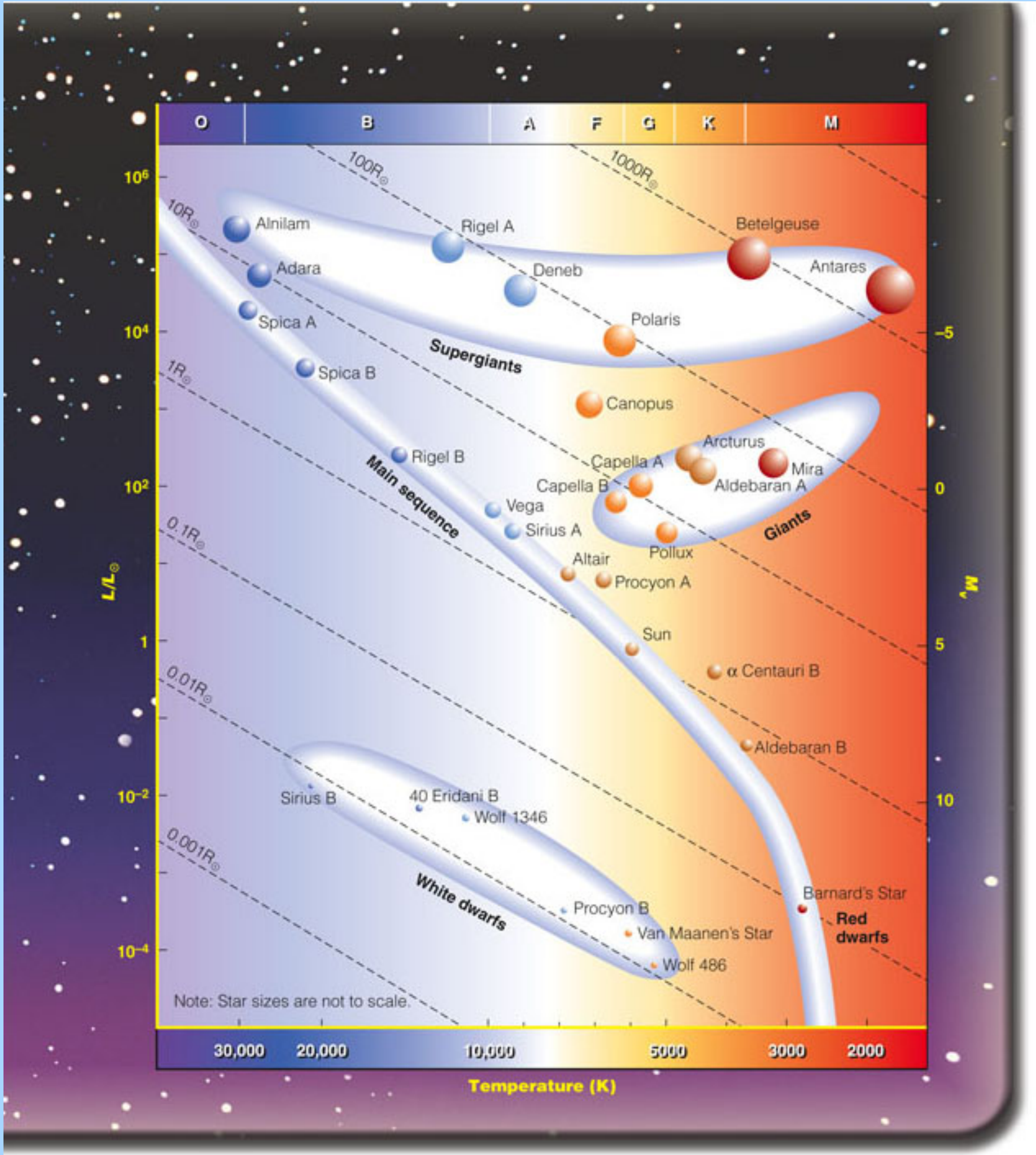


E. Hertzsprung
(1873-1967)

H. N. Russell
(1877-1957)

By the second decade of the 20^{th} century, astronomers had determined the distances to roughly 200 stars. The Danish astronomer Hertzsprung and the American astronomer Russell noted that a majority of stars had absolute magnitudes that correlated with their spectral types. In a plot of M_V vs. spectral type most stars traced out a band from the upper left of the diagram to the lower right. Astronomers call this the **main sequence**.

They noted, however, that at a given temperature there were stars on the main sequence and stars with intrinsic luminosities which were much greater.



The Hertzsprung-Russell diagram (HR diagram).

It is a plot of the intrinsic luminosities of the stars vs. their photospheric temperatures.

If two stars have the same temperature, each square meter gives off the same amount of light ($E = \sigma T^4$). If one of the two stars has 100 times the luminosity of the other, it must have 100 times the surface area, or 10 times the diameter.

Hertzsprung and Russell realized that the stars at the top right of the diagram were much, much larger than the stars on the main sequence with the same temperatures.

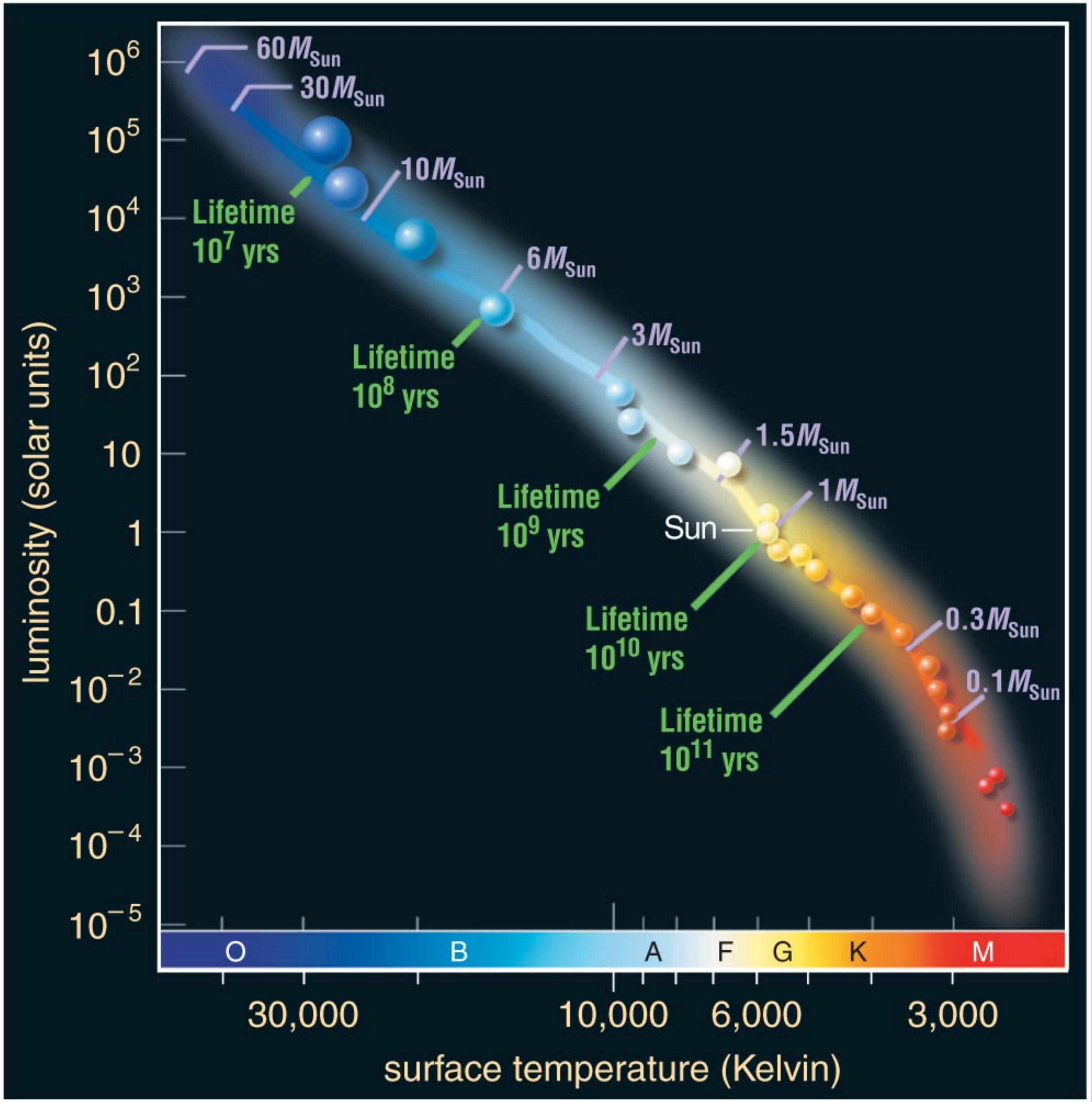
The stars in the upper right and the top of the diagram are **giant** stars and **supergiant** stars. In the lower left of the diagram we find **white dwarf stars**, which are 2 percent the size of the Sun.

The H-R Diagram is

a. A plot of H vs. R
b. A plot of the distances of stars vs. their temperatures
c. A plot of the luminosities of stars vs. their temperatures
d. A plot of the masses of stars vs. their ages

Consider the Hertzsprung-Russell Diagram. Stars spend most of their lives as

a. giant stars
b. supergiant stars
c. main sequence stars
d. horizontal branch stars



Note that the main sequence is a mass sequence and a temperature sequence. Also, the less mass a star has, the longer it lives.

Consider main sequence stars that convert hydrogen into helium using the proton-proton cycle. The luminosity of the star is a measure of how many Joules of energy it gives off per unit time. The total energy given off in the main sequence lifetime of the star is:

luminosity (J/sec) X lifetime of star (sec) = total energy put out over its lifetime (J)

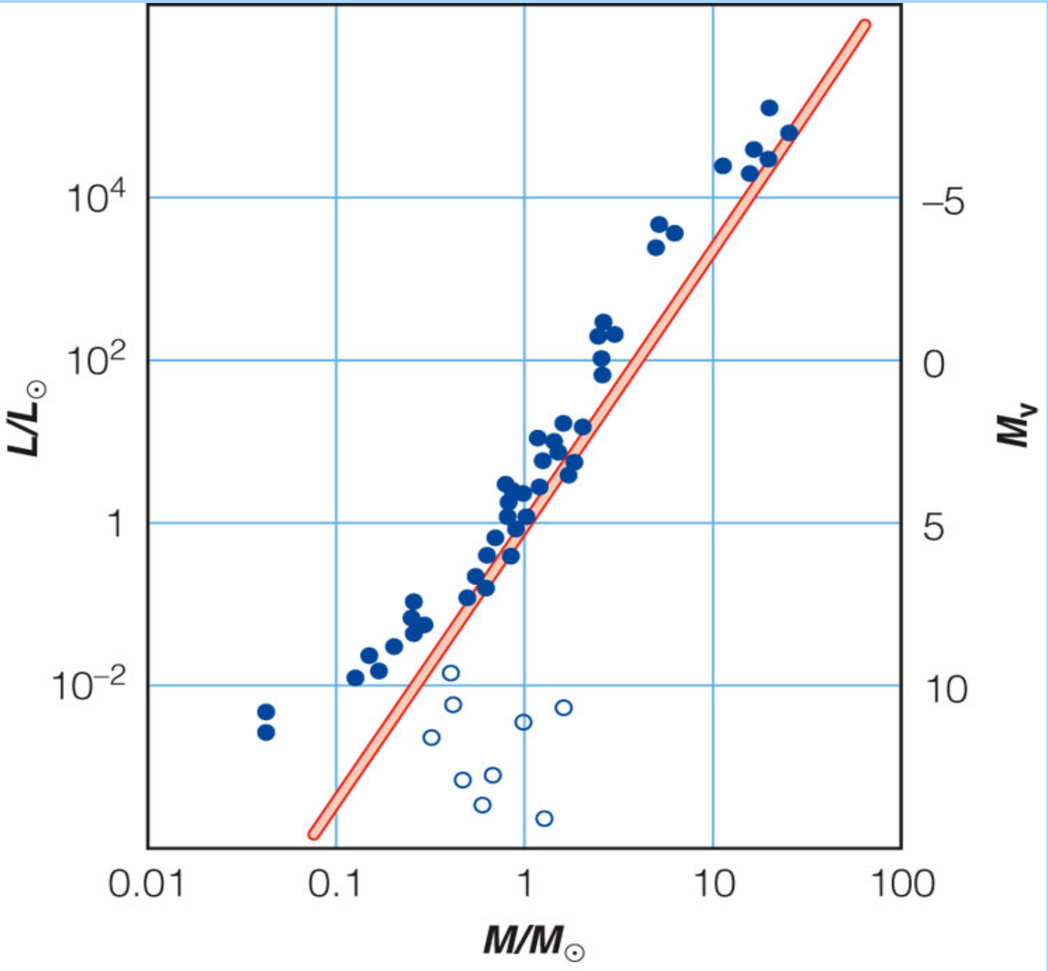
= mass of star X (fraction of mass converted into energy) X c^2

So the luminosity times the lifetime of the star is proportional to the mass of the star (LT is proportional to M).

Therefore, the lifetime of the star is proportional to the mass divided by the luminosity (T is proportional to M / L).

If we use the main sequence lifetime of the Sun as our time reference, and the mass and luminosity of the Sun as our mass and luminosity references, the main sequence lifetime of a star is equal to

$$T_* / T_{Sun} = (M_* / M_{Sun}) / (L_* / L_{Sun})$$



Over a wide range of mass the luminosity of main sequence stars is proportional to the 3.5 power of the mass:

$$L = M^{3.5}$$

(The open circles represent white dwarf stars.)

Combining the previous two equations, the main sequence lifetime of a star is a simple function of its mass:

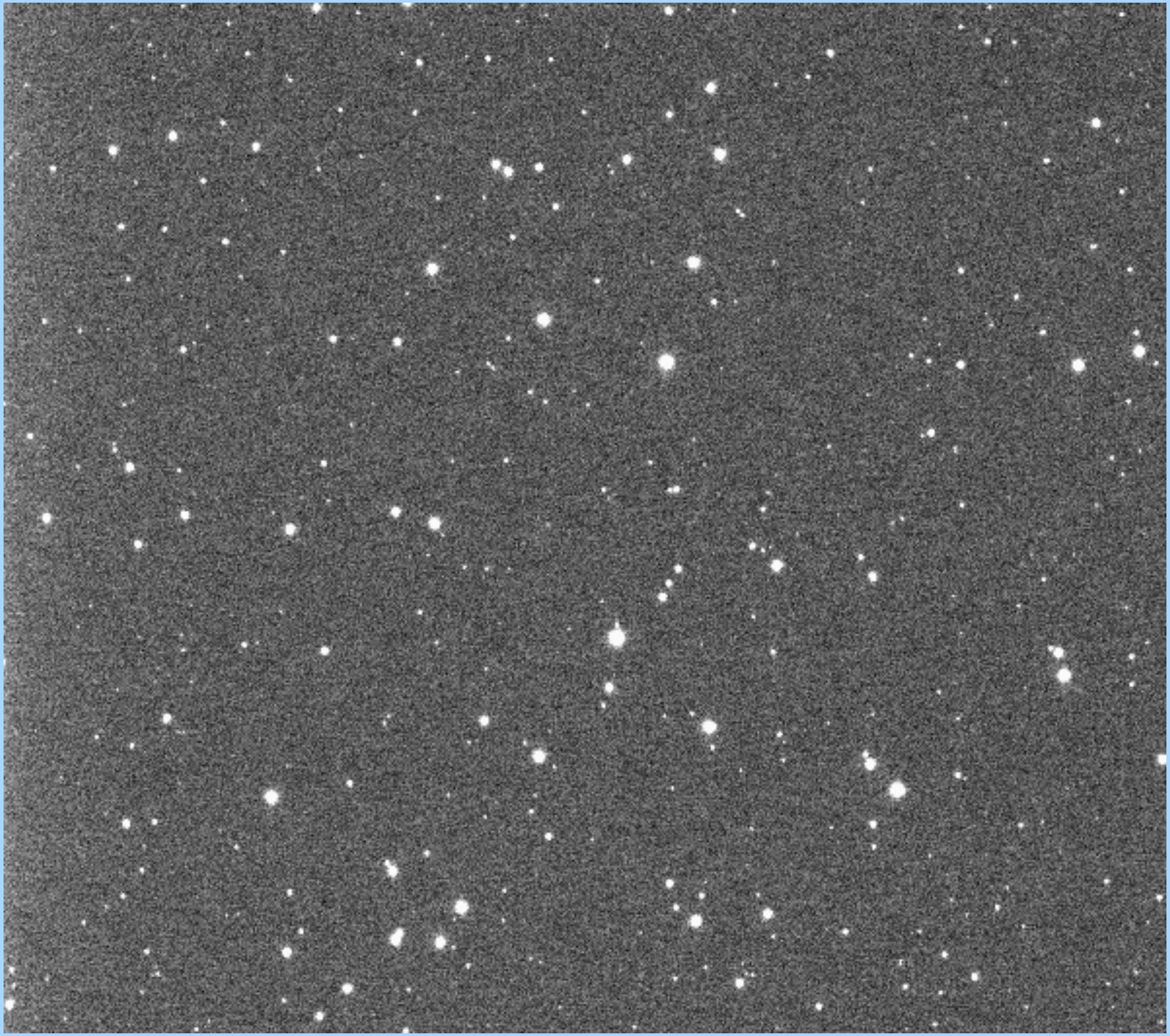
$$T_* / T_{Sun} = (M_* / M_{Sun})^{-2.5} \quad \text{or}$$

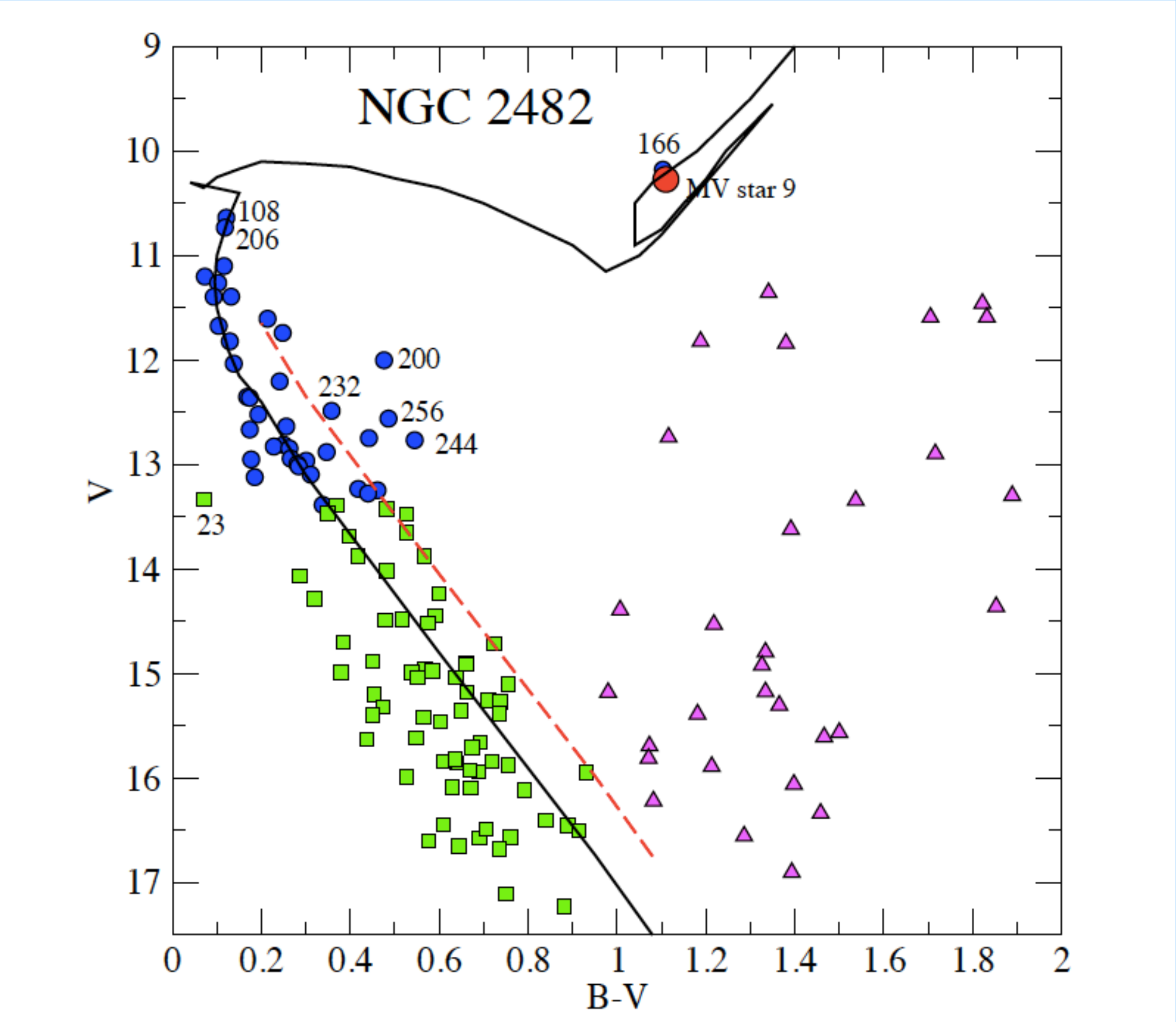
$$T_* = (M_* / M_{Sun})^{-2.5} \text{ X } 10 \text{ billion yrs}$$

The Sun will be a main sequence star for a total of 10 billion years. A star with 10 solar masses will last only 30 million years. A star with 0.25 solar masses can last 320 billion years.

Hot stars are blue, and soon they are through....

The field of the open star cluster NGC 2482 (114 stars)



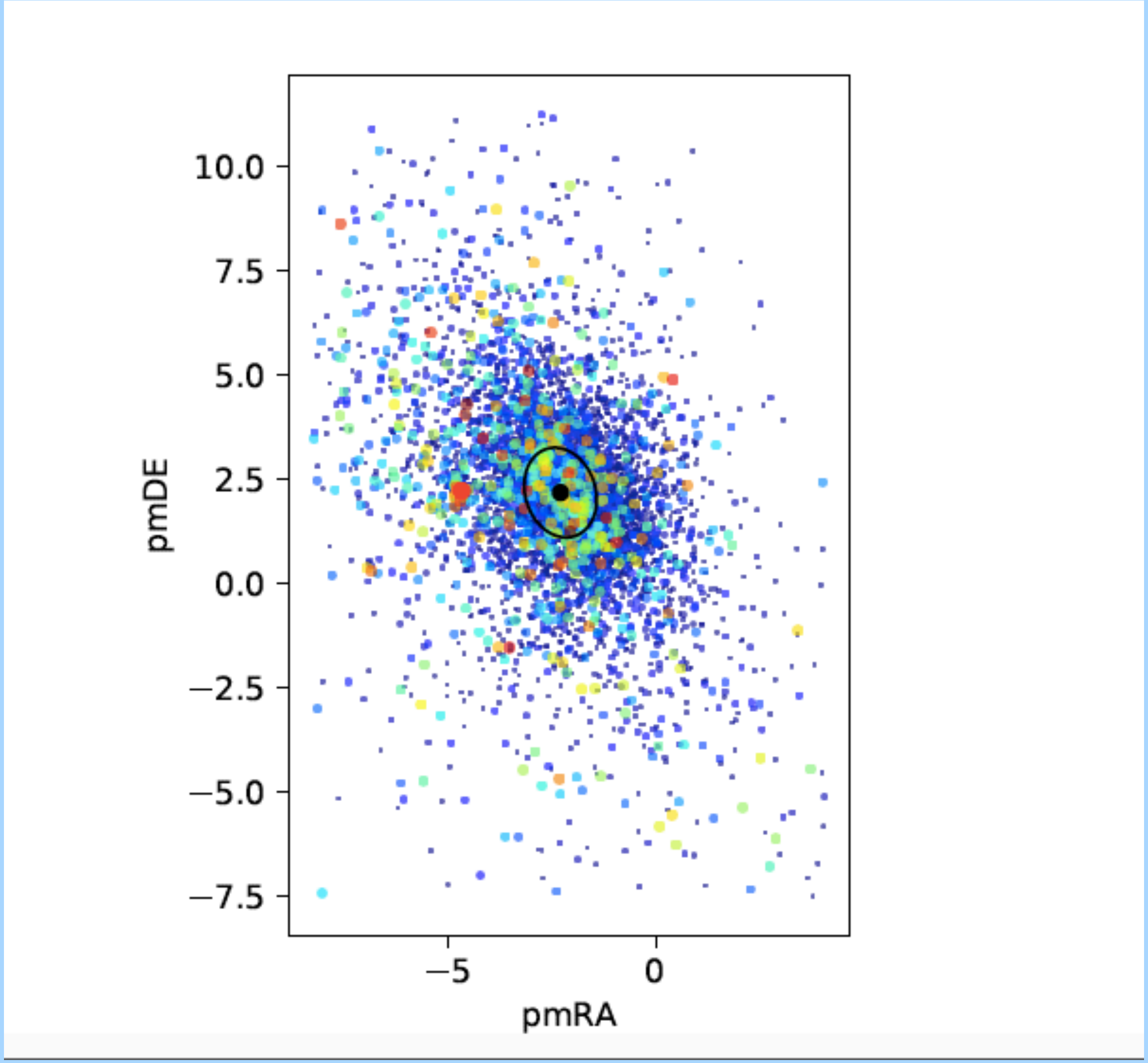


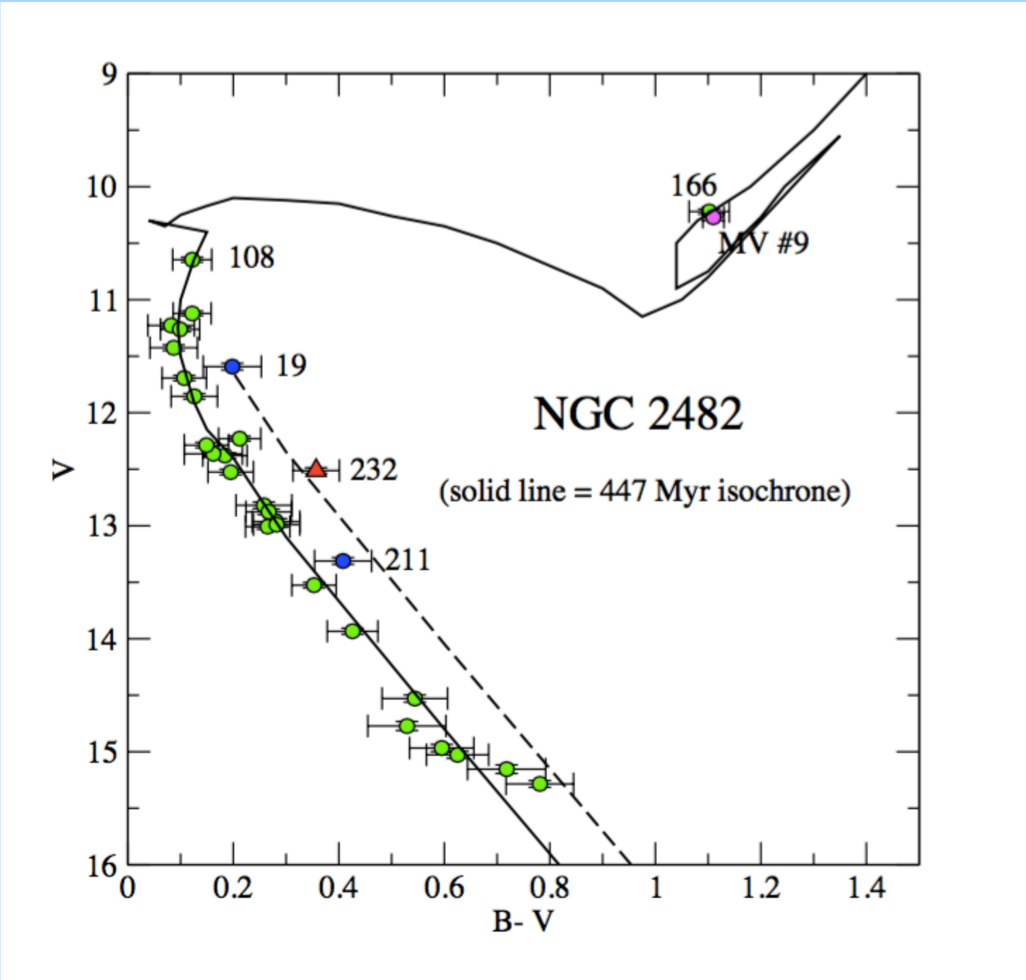
A color-magnitude diagram of an open star cluster can tell us how old it is.

This is data for the open cluster NGC 2482. Stars considerably right of the main sequence are more distant giants.

But why is the MS so fat?

Proper motion data from the Gaia satellite can help us decide which stars are most likely to be cluster members.

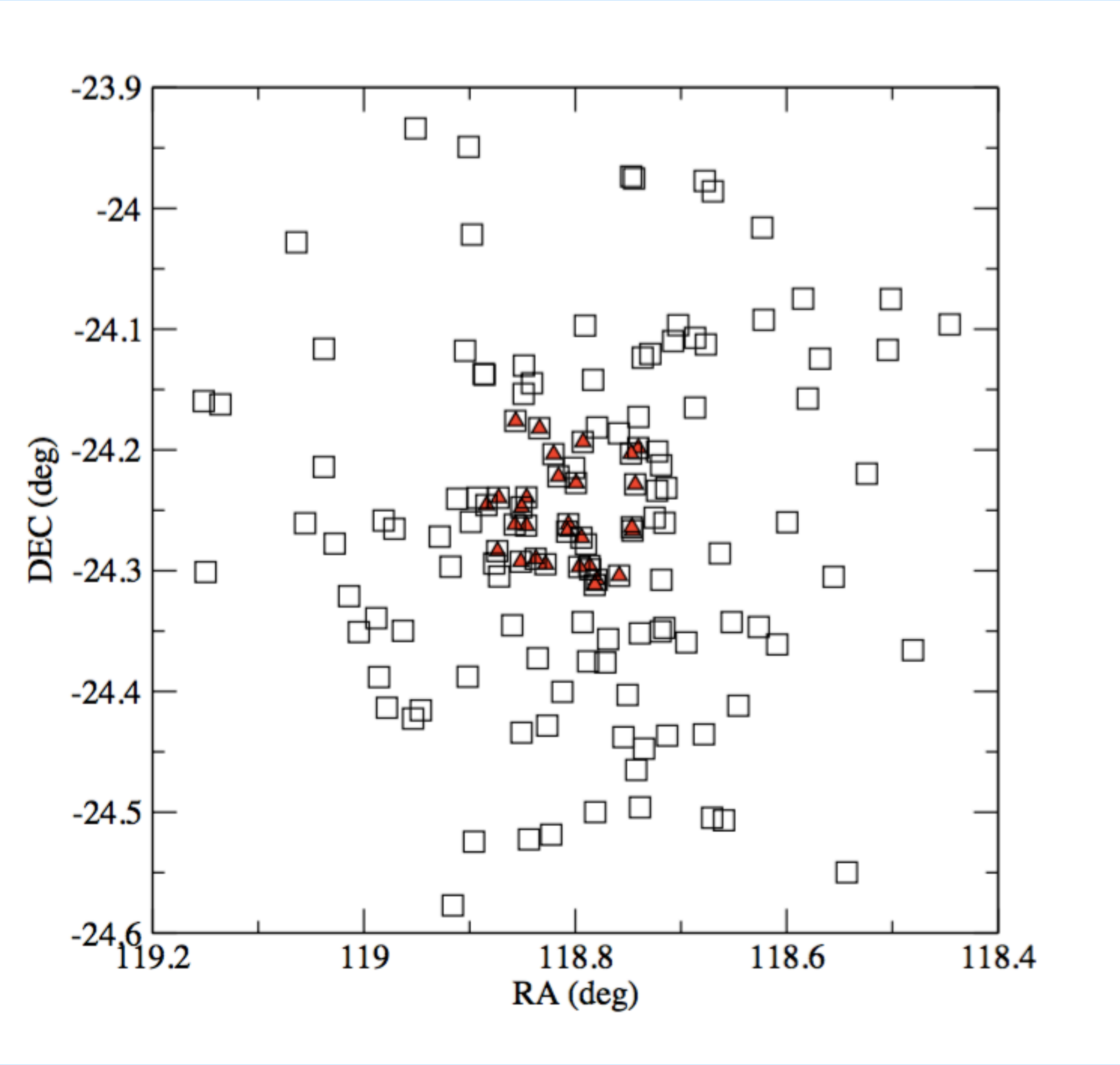




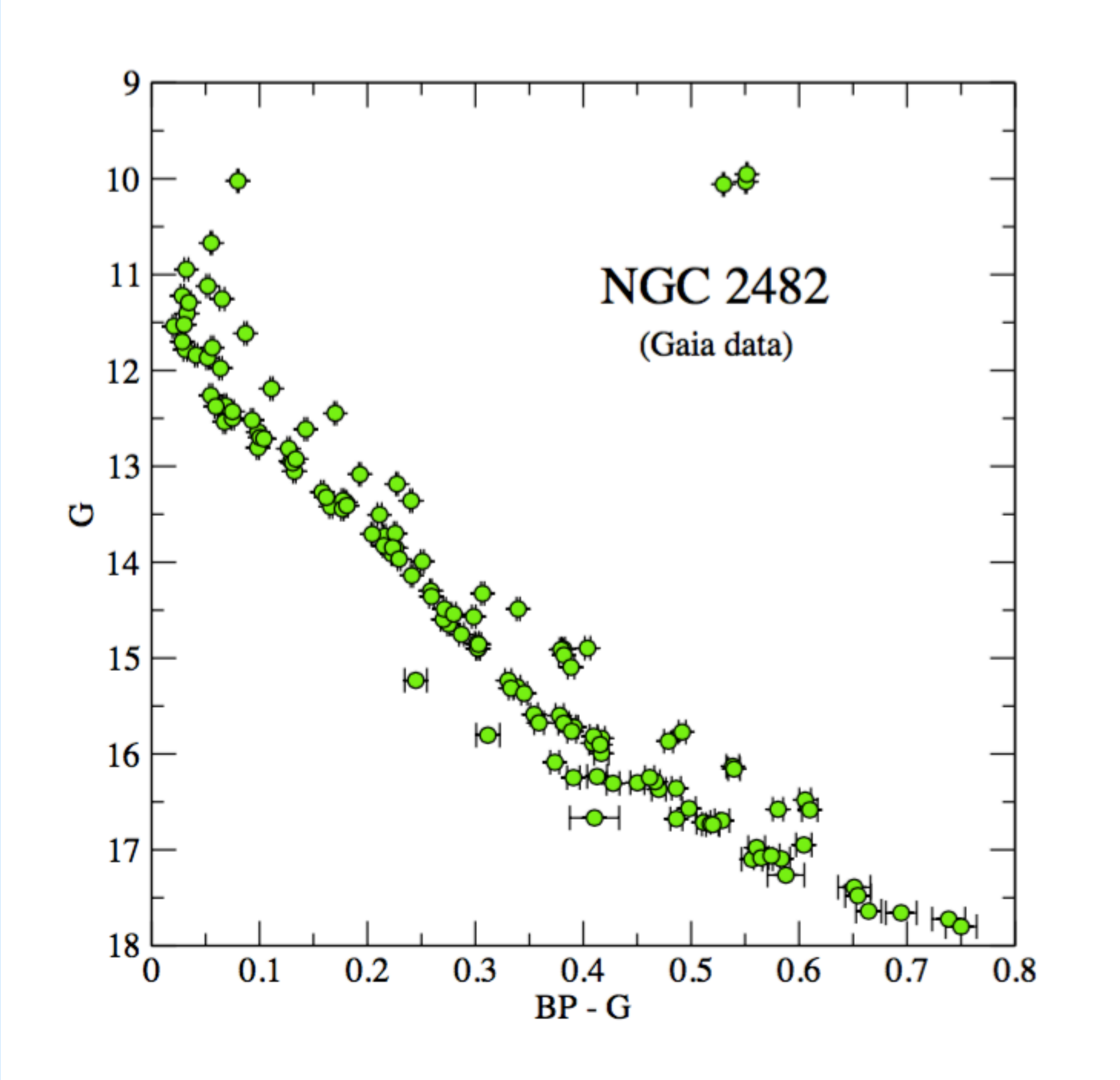
The main sequence tightens up if we plot data only for the 29 stars of the central region that are cluster members..

Stellar evolution theory gives a cluster age of 447 +/- 93 million years.

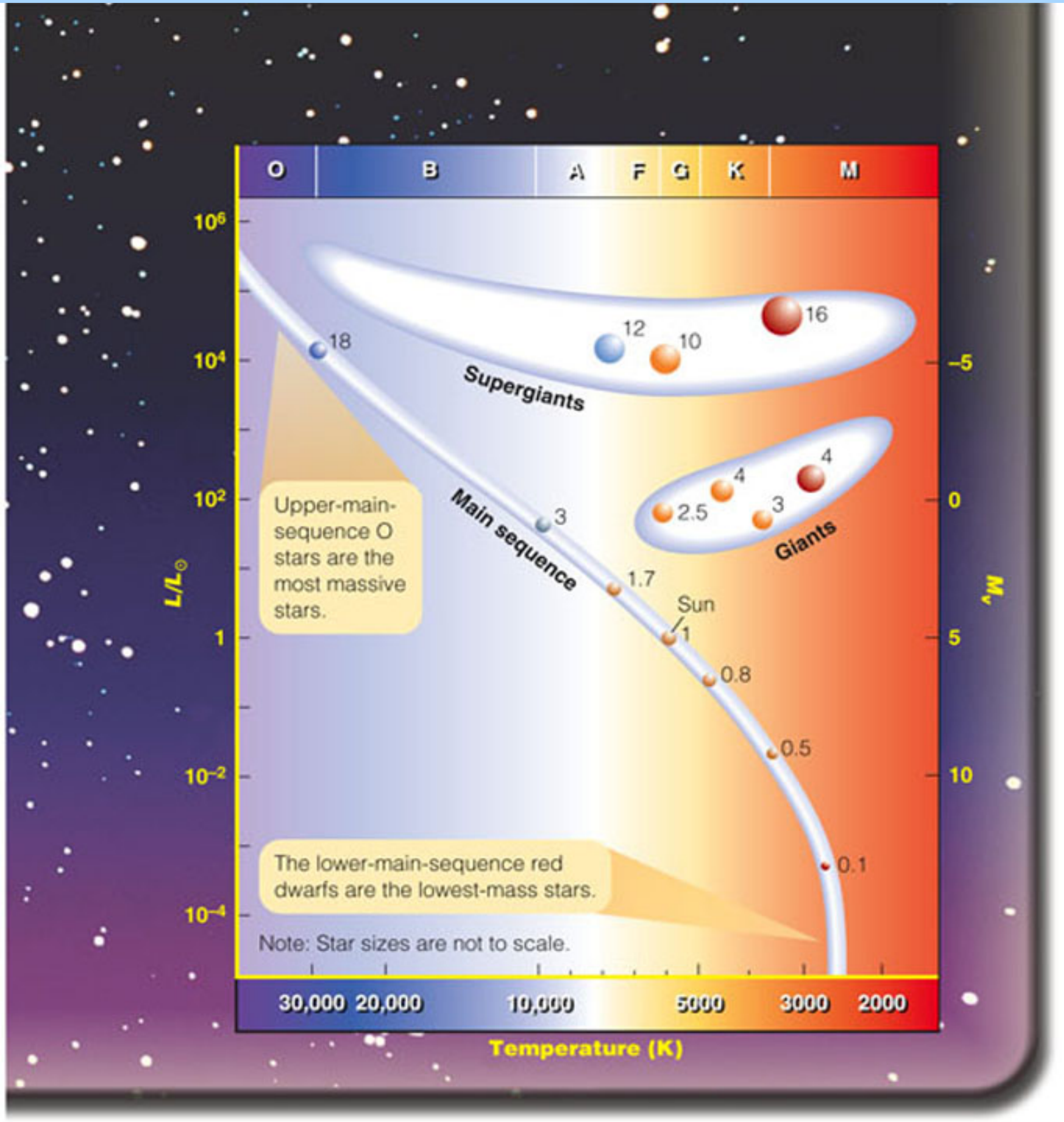
Dr. Zhong Nanshan, famous Chinese epidemiologist



Our imagery of the cluster only covers the central region.



N = 135
members



Giant stars and supergiant stars are former main sequence stars that have used up their core fuel. This leads to changes in size and luminosity.

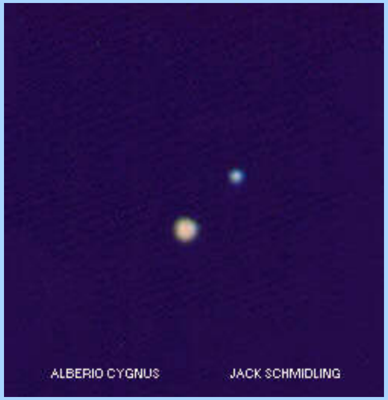
Objects in order of increasing mass

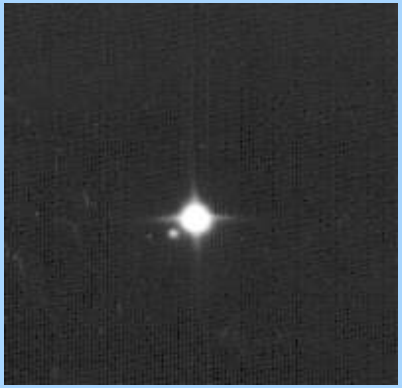
Asteroids	
Jupiter	1/1000 M_Sun
Planets	< 0.01 M_Sun
Brown dwarf stars	0.01 to 0.08 M_Sun
Stars	0.08 to roughly 100 M_Sun

Visual double stars

William Herschel (1738-1822) discovered the planet Uranus in 1781. He also discovered about 1000 double stars, many star clusters and “nebulae”.

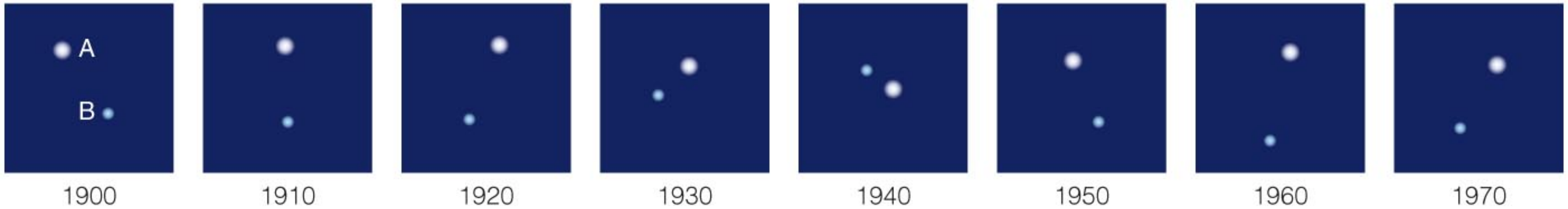
Herschel thought that perhaps there was a very small range of luminosities of stars. So if one saw two stars very close to each other on the sky, he thought that these might be chance alignments. The fainter star might be much farther away. If this were true, then one might make very careful measurements of the angular separation of such a pair of stars and measure the trigonometric parallax of the brighter (presumably closer) star.





β Cygni, Polaris, and γ Andromedae.

What Herschel found instead was that many of these "chance" pairings of stars were not chancey at all. Two stars close together on the sky often orbited each other.



Here each frame represents the relative positions of the components of Sirius over 10 year intervals.

Recall the most general form of Kepler's 3rd Law:

$$P^2 = 4\,\pi^2\,a^3 \,/\, G\,(\,M_A + M_B\,)\ .$$

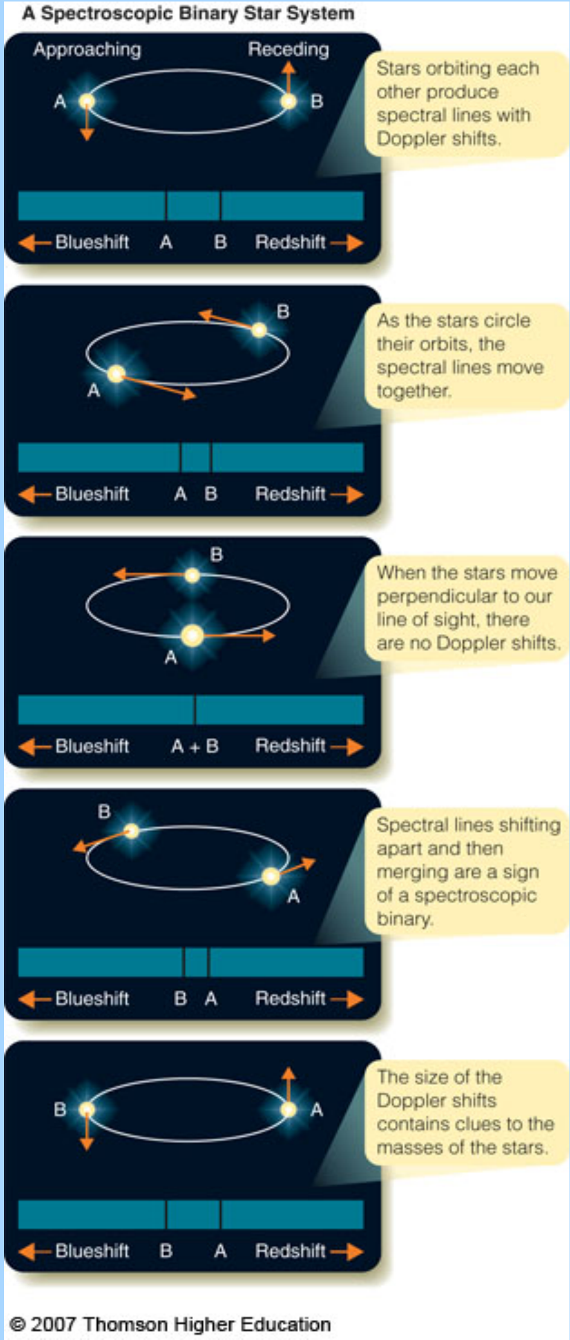
Here P is the period of the orbit of two objects about their center of mass. The orbit size is a, and the denominator contains the sum of the masses of the objects.

From the observations of visual binary stars we get most of our information on the masses of stars. If we have the *sum* of masses from Kepler's 3rd Law and the *ratio* of the masses from the position of the center of mass, we can obtain the individual masses.

Two other kinds of double stars

spectroscopic binaries – revealed by the Doppler shifts of the two stars in a close binary system

eclipsing binaries – revealed by the mutual eclipses of two stars. To see this the observer on the Earth must be close to the plane of the orbit of the two stars.


A Spectroscopic Binary Star System
Approaching
Receding
A
B
Stars orbiting each other produce spectral lines with Doppler shifts.
Blueshift A B Redshift
As the stars circle their orbits, the spectral lines move together.
Blueshift A B Redshift
When the stars move perpendicular to our line of sight, there are no Doppler shifts.
Blueshift A + B Redshift
Spectral lines shifting apart and then merging are a sign of a spectroscopic binary.
Blueshift B A Redshift
The size of the Doppler shifts contains clues to the masses of the stars.
Blueshift B A Redshift
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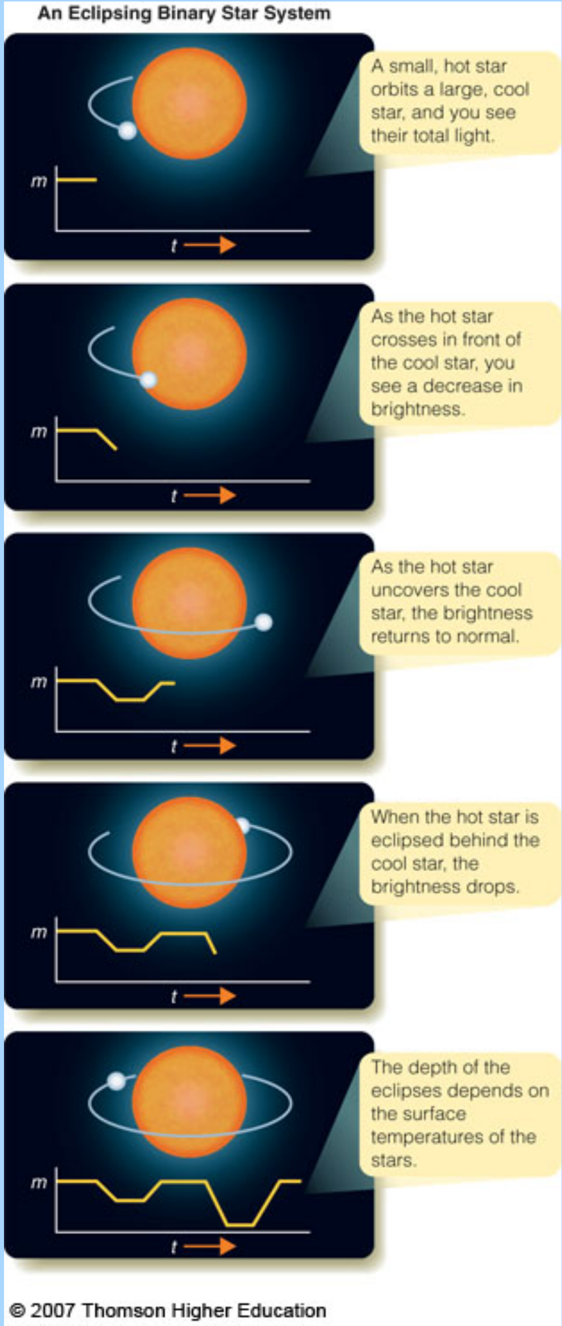
An Eclipsing Binary Star System
A small, hot star orbits a large, cool star, and you see their total light.
m
t
As the hot star crosses in front of the cool star, you see a decrease in brightness.
As the hot star uncovers the cool star, the brightness returns to normal.
When the hot star is eclipsed behind the cool star, the brightness drops.
The depth of the eclipses depends on the surface temperatures of the stars.
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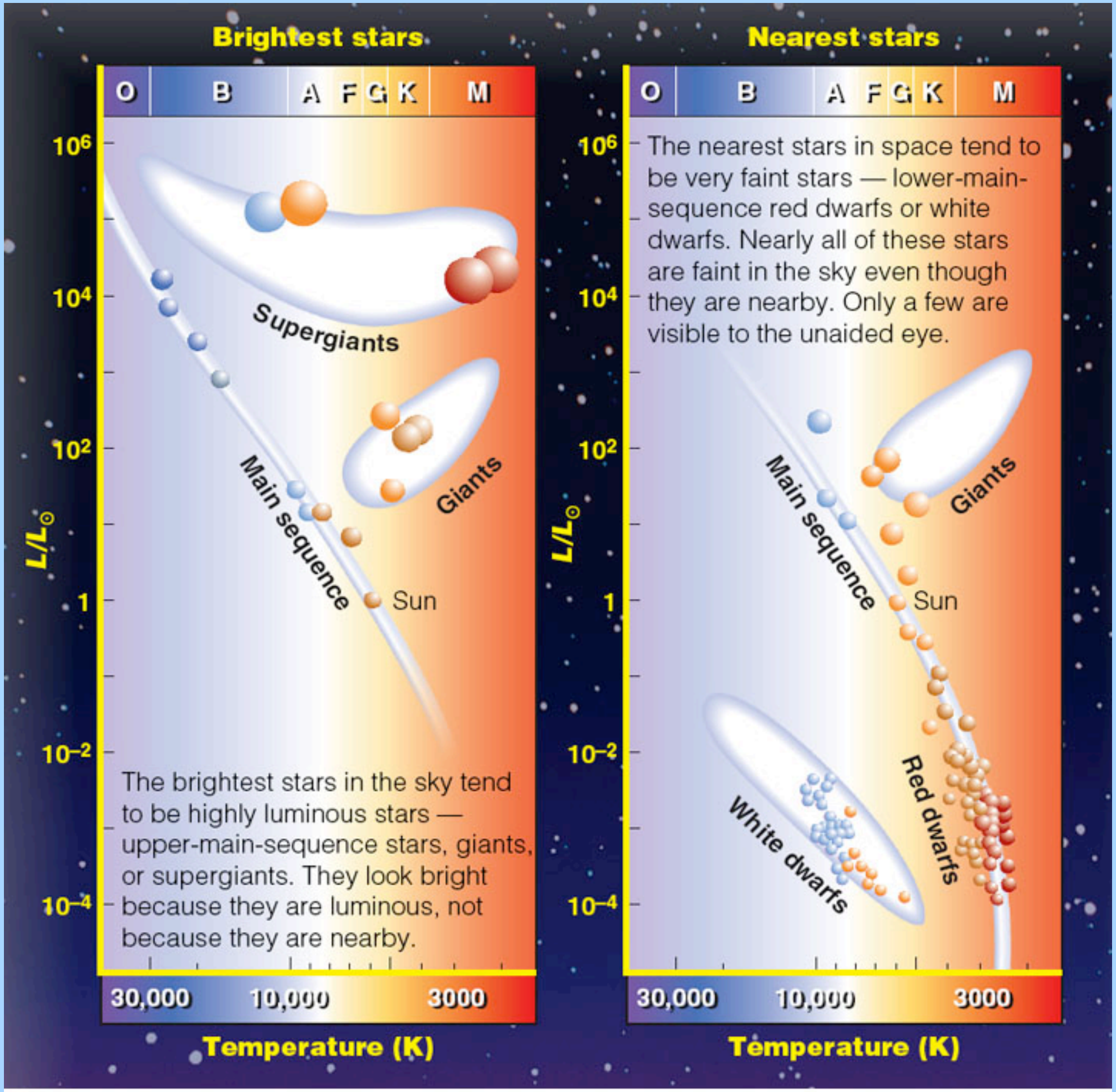
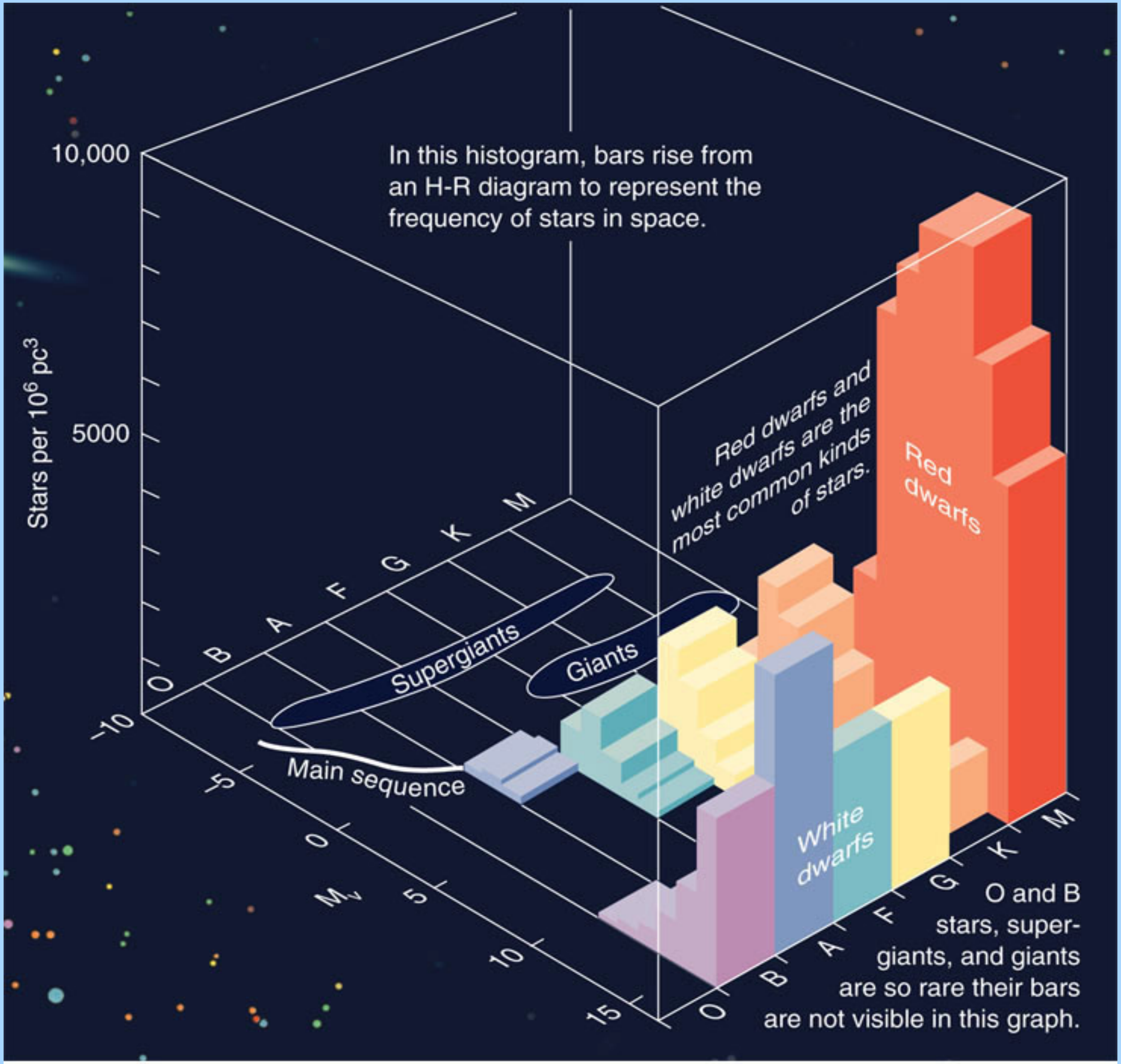


The vast majority of stars are cool orange and red dwarf stars with masses of 0.4 M_{Sun} or less.

Only 1 out of 1000 stars has a mass of 10 M_{Sun} or more.



In this histogram, bars rise from an H-R diagram to represent the frequency of stars in space.
10,000
5000
Stars per 10^6 pc^3
O
B
A
F
G
K
M
-10
-5
0
5
10
15
M_V
Supergiants
Giants
Main sequence
Red dwarfs and white dwarfs are the most common kinds of stars.
Red dwarfs
White dwarfs
O and B stars, super-giants, and giants are so rare their bars are not visible in this graph.