1 Stellar Evolution

How is it that we can know so much about stars despite the fact that we can not travel to them?

1.1 Stellar Models

Stars are simple objects.

Using the laws of physics and computers, we learn much.

Four Laws of Stellar Structure

1. Hydrostatic Equilibrium - The weight of each layer is balanced by the pressure in that layer.
2. Energy Transport - Energy moves from hot to cool by radiation, convection or conduction.
3. Continuity of Mass - Total mass equal the sum of the shell masses, no gaps allowed.
4. Continuity of Energy - Total luminosity equals the sum of the energies generated in each shell.

The Equations 4 coupled differential equations

$$\begin{aligned}
\frac{dM}{dr} &= 4\pi r^2 \rho \\
\frac{dP}{dr} &= -\frac{GM}{r^2}\rho \\
\frac{dL}{dr} &= 4\pi r^2 \rho e \\
\frac{dT}{dr} &= \frac{-3}{16\pi ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L}{r^2}
\end{aligned}$$

The Output A table of values

$\frac{R}{R_\odot}$	T	$Density$	$\frac{M}{M_\odot}$	$\frac{L}{L_\odot}$
	$\left(10^6 K\right)$	g/cm^3		
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13.	0.63	0.99
0.20	9.3	36.	0.34	0.91
0.10	13.1	89	0.073	0.40
0.00	15.7	150	0.00	0.00

1.1.1 Understanding the Main Sequence

All stars are not the same.

We try to understand high mass stars, average stars, and low mass stars using stellar models.

One of the most fundamental relationships that is known about main sequence stars is

The Mass - Luminosity Relation This relates the rate of thermonuclear fusion to the star's mass.

The luminosity of the star (in solar luminosities) is due to the rate at which hydrogen is being fused into helium and in the process converting mass into energy.

$$L = M^{3.5}$$

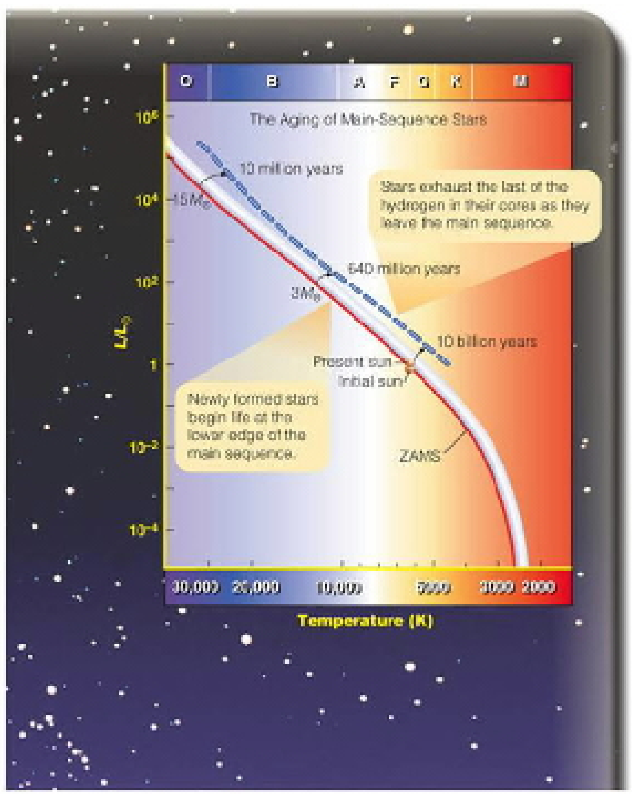
High mass stars emit tremendous amounts of energy. Low mass stars emit small amounts of energy.

High mass stars convert more mass into energy every second than a low mass star. Even though they have more mass, they use up their fuel in a shorter amount of time.

Zero Age Main Sequence - ZAMS

Main Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Approximate Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9



Life Expectancy The time that a star is on the main sequence depends on two things:

1. The amount of hydrogen available for converting to helium

2. The rate at which hydrogen is being converted to helium

If T is the life expectancy of a star in solar life-times then

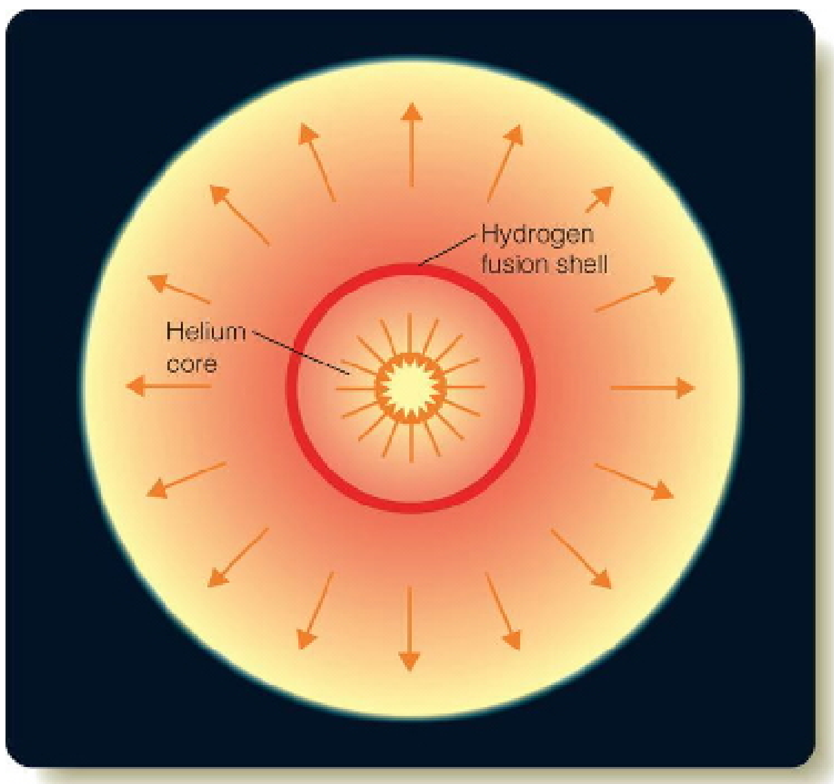
$$T = \frac{M}{L} = \frac{M}{M^{3.5}} = \frac{1}{M^{2.5}} = M^{-2.5}$$

Work an example.

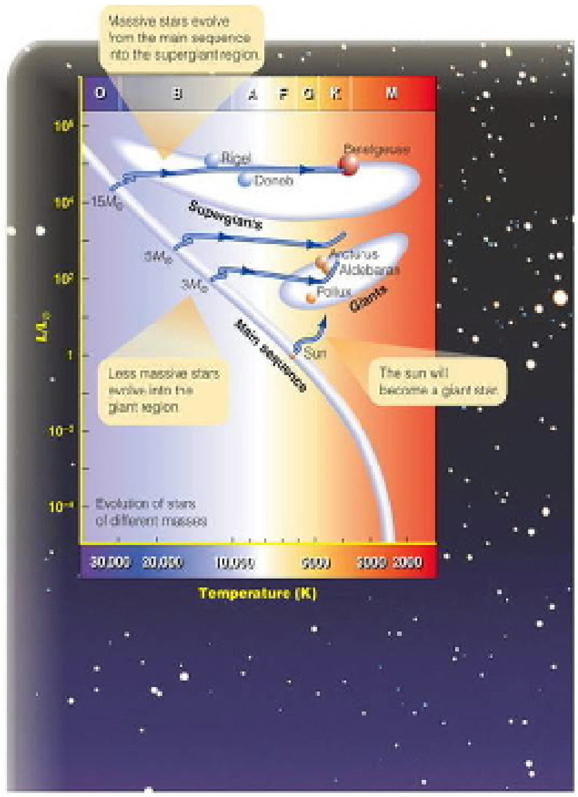
1.2 Post Main Sequence

Mass determines the fate of a star.

Stars are like campfires, ashes accumulate at the center if not mixed.



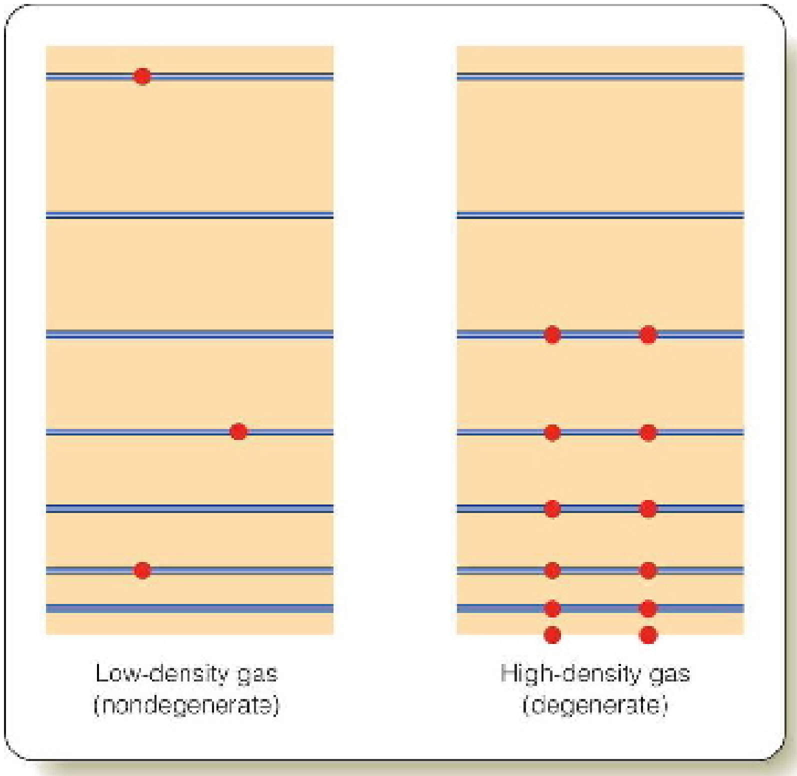
The accumulating helium in the core contracts due to its own mass, causing the core to grow hotter, but not hot enough to fuse helium into carbon. Temperatures are hot enough for a hydrogen shell surrounding the core to continue fusion into more helium. The star is currently overproducing energy, hydrogen in the shell and the conversion of gravitational energy into thermal energy. This overproduction causes the star to expand its outer layers, thereby, cooling them and the star becomes a giant.



How much can the helium core contract?

Degenerate Matter Electron degeneracy - Pauli Exclusion Principle

Fermions can not be in the same energy at the same time in the same place. Helium core contracts to a minimum size and then stops.



A degenerate gas resists compression

Degenerate gas - does not obey the Pressure - Temperature Themostat (pressure does not depend on temperature).

Helium Fusion If the temperature is hot enough, helium fusion can take place.

Triple Alpha Process - fusing 3 helium atoms to form Carbon

$$\begin{aligned} {}^{4}_{2}He + {}^{4}_{2}He &\longrightarrow {}^{8}_{4}Be + \gamma \\ {}^{8}_{4}Be + {}^{4}_{2}He &\longrightarrow {}^{12}_{6}C + \gamma \end{aligned}$$

Helium fusion can take place either fast or gradually.

If gradual, no significant effects, only more energy generation so star expands even more.

Helium Flash - helium explosively fuses heliun in the core, does not happen to all stars

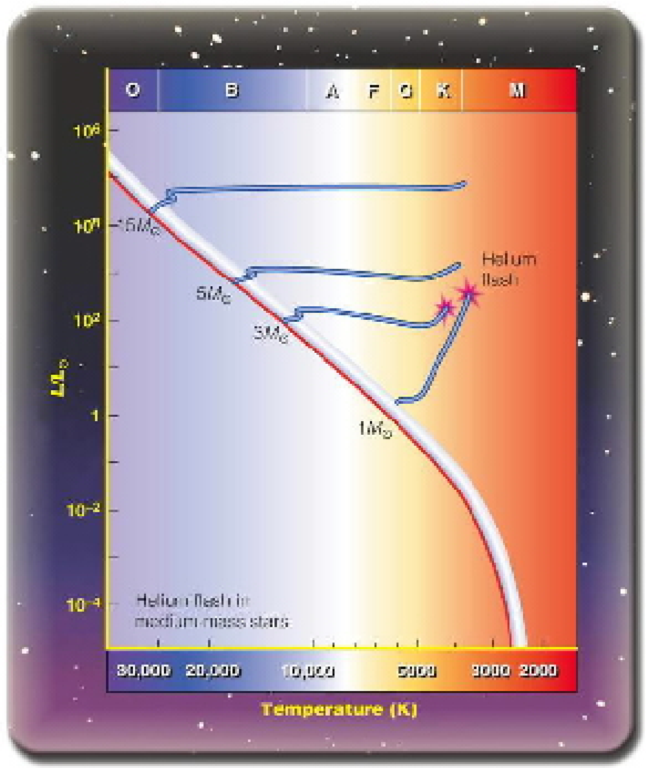
Star is not destroyed and explosion is unseen to the outside, outer layers absorb the energy of the explosion

Stars less than 0.4 solar masses are not massive enough to ignite helium fusion in their cores.

Stars more than about 3 solar masses ignite the helium gradually before the core becomes degenerate.

Medium mass stars experience the helium flash.

Medium mass stars can produce planetary nebula.



Medium mass stars end their lives as white dwarfs, wd.

Eventually, all of the helium will have fused into carbon and oxygen but the core can not collapse any further nor the temperature is not high enough to fuse carbon into oxygen and silicone.

Carbon fusion needs stars > 3 solar masses which can generate temperatures of $600,000,000\,\mathrm{K}$

Table 12-3 | Nuclear Reactions in Massive Stars

Nuclear Fuel	Nuclear Products	Minimum Ignition Temperature	Main-Sequence Mass Needed to Ignite Fusion	Duration of Fusion in a 25-$M_\odot$ Star
H	He	4×10^6 K	0.1 $M_\odot$	7×10^6 yr
He	C, O	120×10^6 K	0.4 $M_\odot$	0.5×10^6 yr
C	Ne, Na, Mg, O	0.6×10^9 K	4 $M_\odot$	600 yr
Ne	O, Mg	1.2×10^9 K	~8 $M_\odot$	1 yr
O	Si, S, P	1.5×10^9 K	~8 $M_\odot$	~ 0.5 yr
Si	Ni to Fe	2.7×10^9 K	~8 $M_\odot$	~ 1 day

Star Clusters Allows astronomers to learn about stellar evolution.

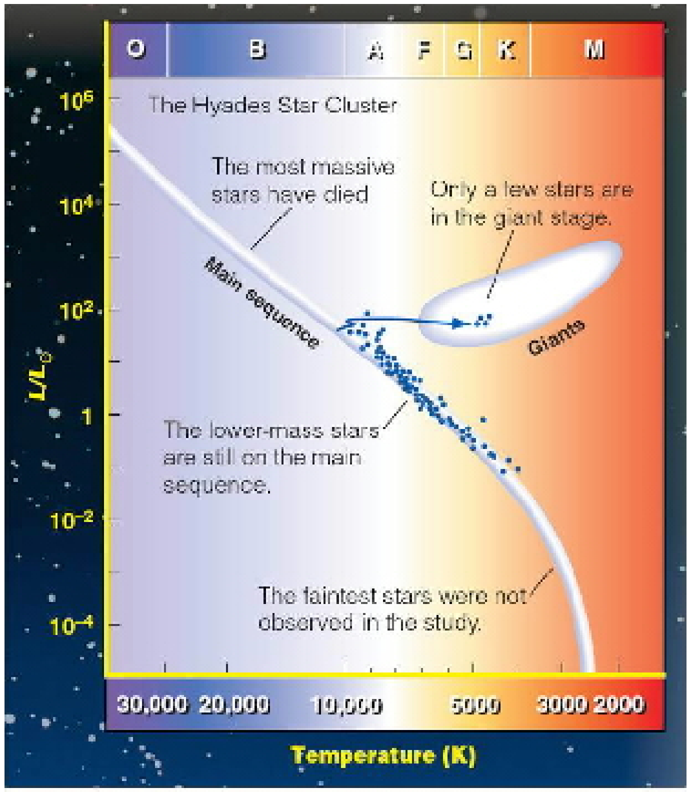
Properties of star clusters

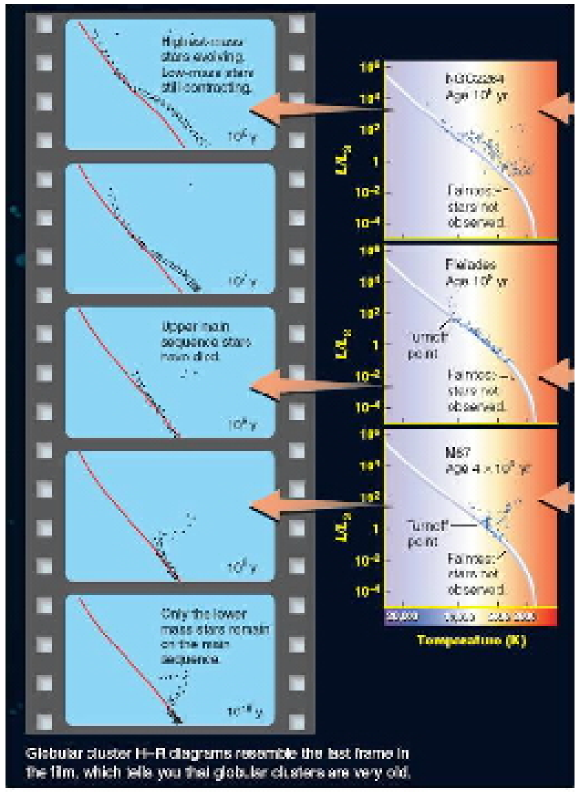
The following is a list of the relationships between the stars in a cluster

1. All stars are of the same distance (approx.) - need only plot apparent visual magnitude, m_v, vs. temperature
2. All formed from the same nebula
3. All have the same chemical composition
4. All formed at about the same time

Turnoff point The masses of the stars at the turnoff point gives the age of the cluster.

The life expectancy of the stars at the turnoff point equals the age of the cluster.


O
B
A
F
G
K
M
The Hyades Star Cluster
The most massive stars have died
Only a few stars are in the giant stage.
Main sequence
Giants
The lower-mass stars are still on the main sequence.
The faintest stars were not observed in the study.
10^6
10^4
10^2
1
10^{-2}
10^{-4}
$L/L_{\odot}$
30,000 20,000
10,000
5000
3000 2000
Temperature (K)



Globular cluster H–R diagrams resemble the last frame in the film, which tells you that globular clusters are very old.

Two types of clusters

1. Open clusters - found mainly in the disk of the galaxy

2. Globular clusters - found in the halo of the galaxy

Variable Stars When stars reach the giant stage their interiors can be highly unstable.

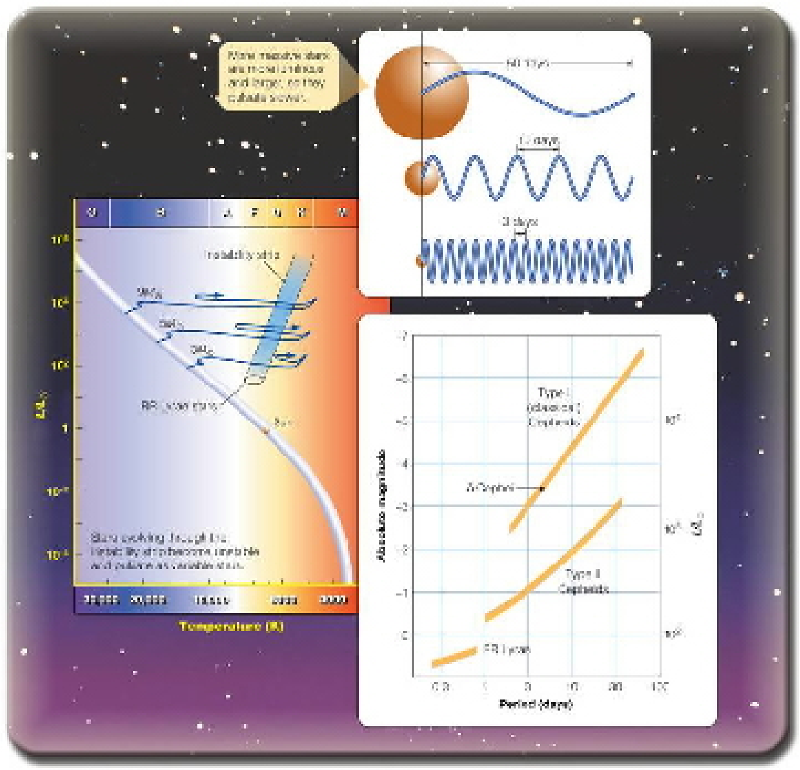
They enter the instability strip on the $H - R$ diagram.

The star can change its brightness over a period of a few days to a few months.

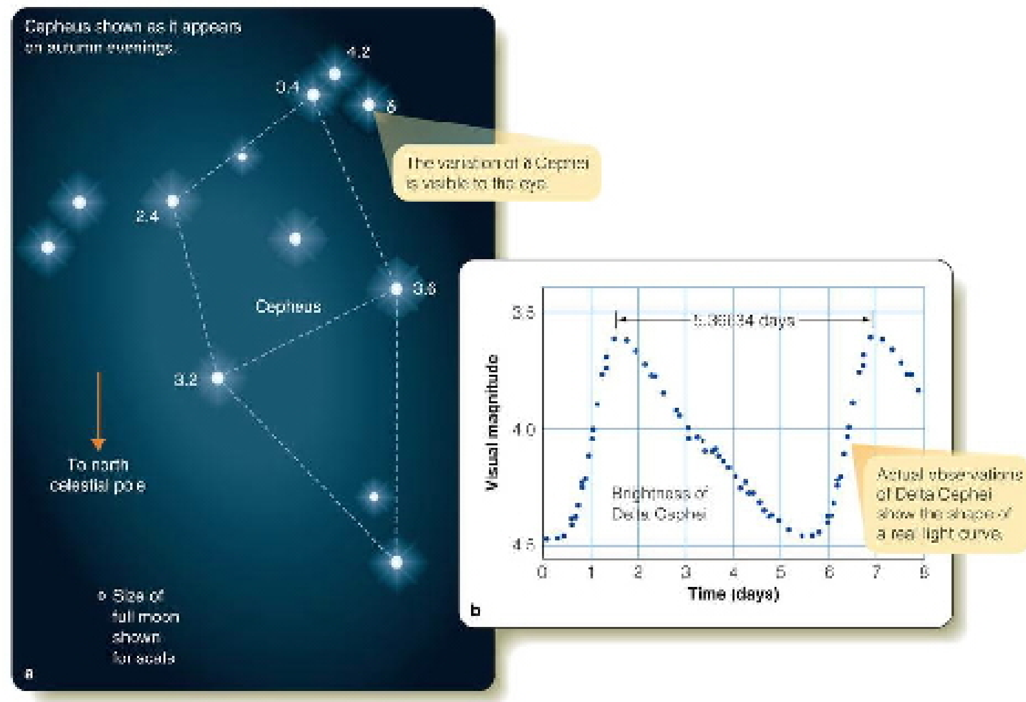
These stars change their brightness by pulsating - i.e., expanding and contracting over time.

A layer of helium cycles between transparent and opaque over time.

The star acts like a mass on a spring which has been disturbed from its equilibrium position.



Types of Variable Stars



1. Cepheid Variables - named after δ Cephei, Period of 5.37 days

   They are supergiant and bright giant stars of spectral type F or G.

   Periods range from 2 days up to about 60 days.

   Polaris is a Cepheid variable.

   Two types of Cepheids -

   (a) Type I Cepheids - have chemical composition similar to Sun, contains elements heavier than helium

   (b) Type II Cepheids - have chemical composition of only hydrogen and helium.

2. RR Lyrae Variables - Periods of less than a day.

   Fainter than Cepheids

Variable Stars are important distance indicators

There exists a Period - Luminosity relation - connects the period of the variation to the luminosity (absolute magnitude, M) of the star.

For a classic Population I type Cepheid variable star

$$M_v = -2.81 \log_{10}(P) - (1.43 \pm 0.1)$$

where P is measuree in days.

1.2.1 Variable stars can be used to find distance

Luckily, variable stars are supergiant stars so we can see them from great distances. Distances to galaxies can be determined.

Classical Cepheids are yellow supergiants of spectral class F6 – K2 and their radii change by (~25% for the longer-period Cepheid variables) which is millions of kilometers during a pulsation cycle