<div align="center">**Star Clusters (sec. 19.6)**</div>

[Leftover from Ch.19—WILL be covered on exam 5]

Groups of stars all located in the same volume of space, i.e. **all at the same distance**, and so presumably **all formed at the same time**; i.e. all stars in a given cluster have the same age. Best chance to test theories of stellar evolution!

Can easily get H-R diagram using only apparent brightnesses, because effect of distance would be to just shift all the L's by the same factor (vertically in H-R diagram).

2 main types of clusters

A. Open clusters

Most have ~100-10,000 stars, size ~ 1-10 pc. Some show main sequence (MS) populated al the way to spectral type O (massive) ⇒ must be very young (less than ~ few million years)

Some have MS only populated up to redder (cooler, less massive) spectral types ⇒ most massive stars have died.

Can see that you can get ages of clusters by extent of the MS. Find that open cluster ages vary from very young (~few million yr.) to very old (~10 billion yr.)   This shows that star formation has been an ongoing process in over the whole history of our galaxy. But notice that they are *all* found in the disk of the Milky Way (we'll come back to this).

B. Globular clusters

Very dense clusters, up to 10^6 stars within ~50 pc size. Most are very distant (~ 1,000 to 100,000 pc), and are *not* distributed in the disk of the Milky Way ⇒ they form a spherical "halo" around the Milky Way.

H-R diagrams: MS includes low mass stars, but NO stars with mass > about 0.8 solar masses ⇒ all are old! Ages ~ 12-17 billion years.

These were almost certainly the first objects to be formed in our Galaxy. Note: Abundances of all elements heavier than carbon are very small compared to the sun and most other stars (because they formed when the Galaxy was relatively "pollution free"—we'll return to this).
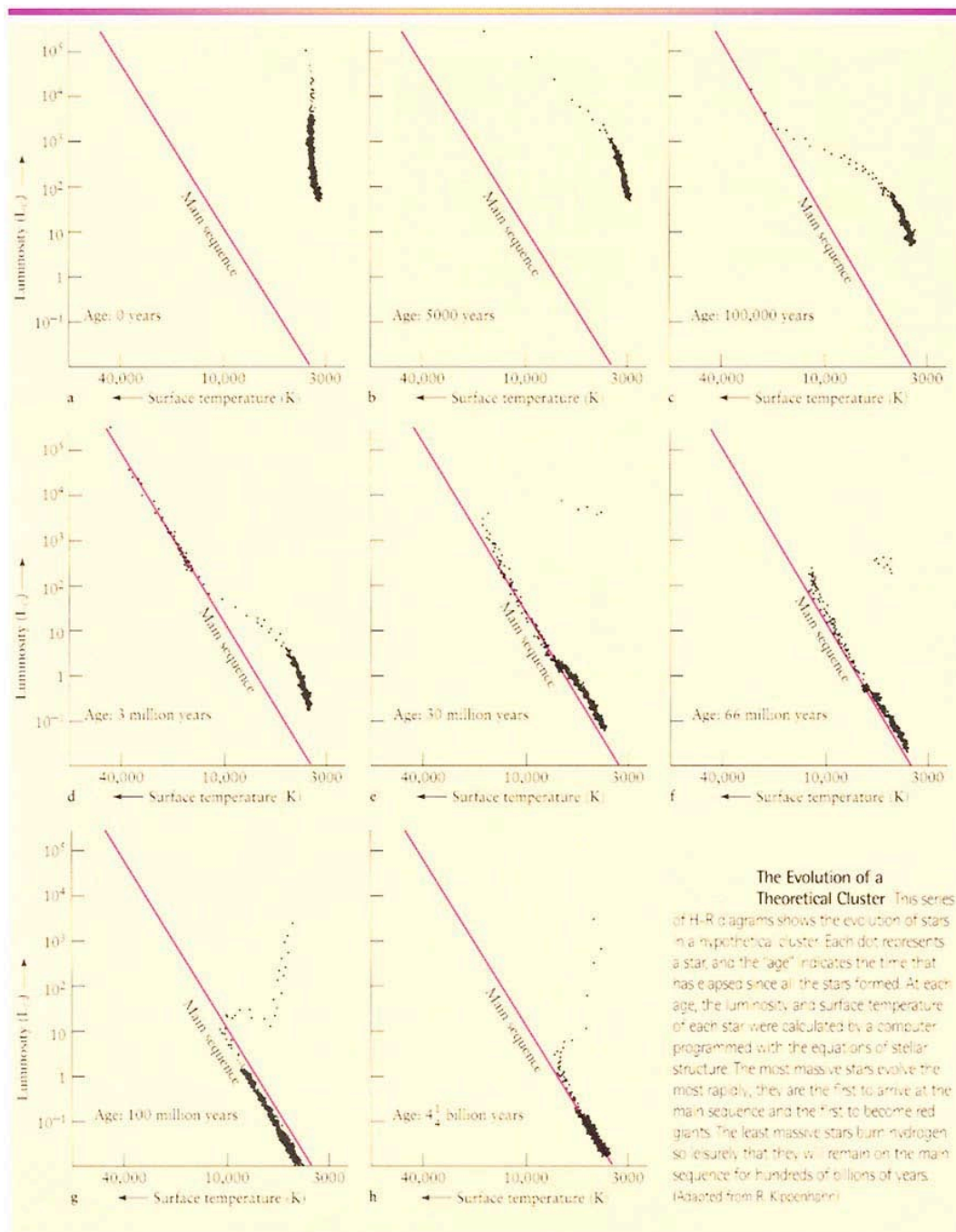
Make sure you understand the H-R diagrams in Figs. 19.18-19.19 (and see the HR diagrams shown below).

Can you explain what determines the lifetime of a star cluster (not the current age, but how long it will remain as a cluster)?

What is suggested by the fact that *all* globular clusters are much older than any open cluster?

Below are two important HR diagrams:
1. The evolution of a number of stars all formed at the same time in a cluster. Note that both during the approach to the main sequence and evolution away from the main sequence the most massive stars evolve most rapidly. This is what gives us a way to obtain ages of clusters from the extent of the main sequence.

The Evolution of a Theoretical Cluster This series of H-R diagrams shows the evolution of stars in a hypothetical cluster. Each dot represents a star, and the "age" indicates the time that has elapsed since all the stars formed. At each age, the luminosity and surface temperature of each star were calculated by a computer programmed with the equations of stellar structure. The most massive stars evolve the most rapidly; they are the first to arrive at the main sequence and the first to become red giants. The least massive stars burn hydrogen so leisurely that they will remain on the main sequence for hundreds of billions of years. (Adapted from R. Kippenhahn)

2. This illustration shows some real clusters' HR diagrams, illustrating directly how ages of clusters can be estimated. The oldest cluster known, M67, is only about 4-5 billion years because almost all clusters dissolve or "evaporate" long before this. M67 is just a "lucky survivor."
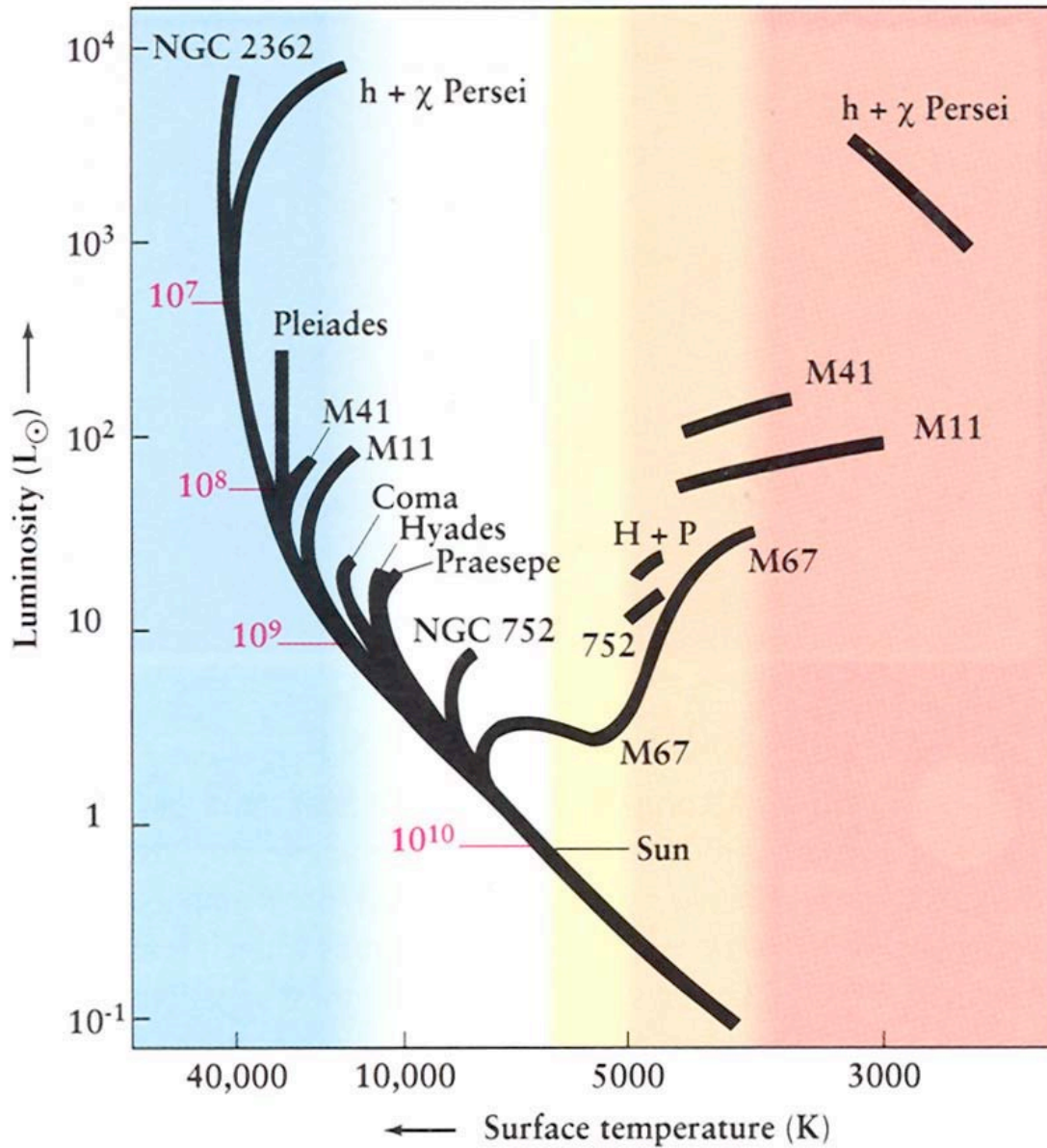
Stellar Evolution (ch.20)

Main Phases for stars ~1Mo to ~8Mo (Notation from here on: Mo means
M$_{sun}$ = mass in units of the Sun's mass)

Main sequence equilibrium: pressure balances gravity at every
depth, so hottest in center ⟹ nuclear reactions H → He "core H-burning".

Two nuclear reaction procceses: proton-proton (dominates in stars ~
sun's mass and lower), and CNO cycle (dominates in stars more massive
than sun; see More Precisely 20-1).

Stable, lasts most of star's lifetime. (Will explain why this is so stable
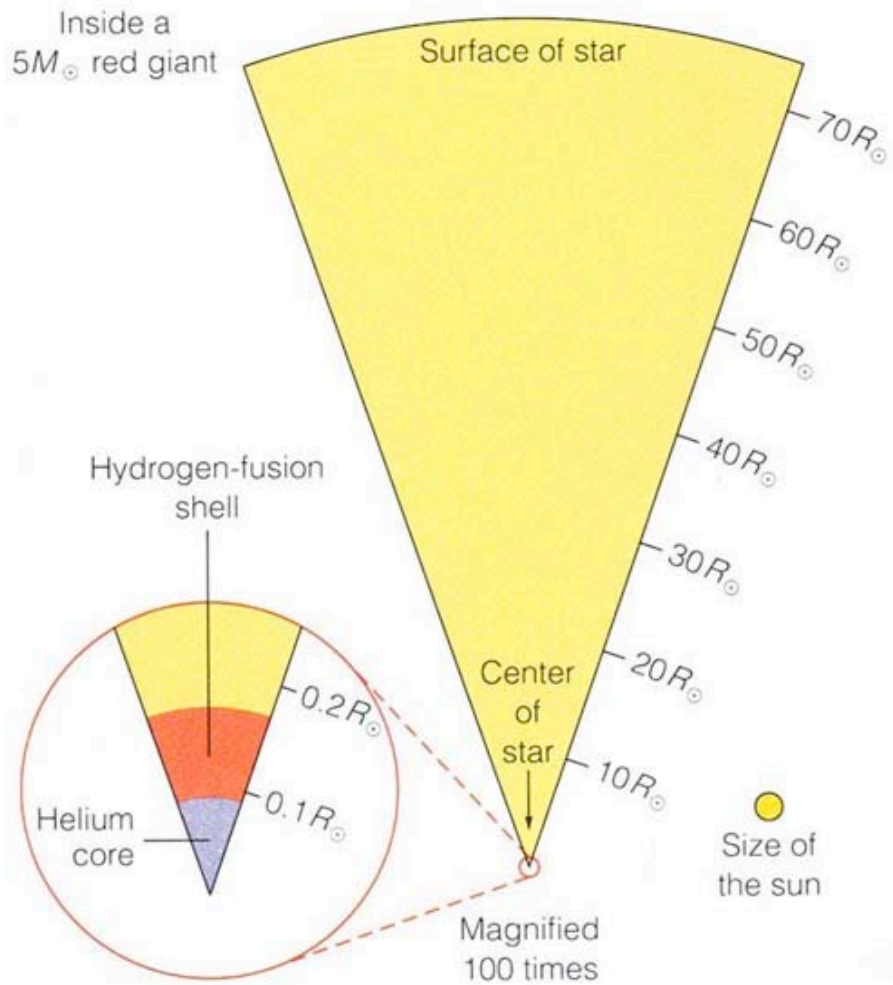in lecture.) [You already know how lifetime varies with mass.]

Depletion of H in core [see Fig. 20.2].
Starting in center (hottest), and moving out, the He (the "ashes")
accumulates in core (can't burn the He as fuel—would require higher
temperatures), H-burning only occurs in outer core.

Contraction of He core. He nuclei can't fuse, so there is a pressure
deficit compared to gravity, so core contracts, heating up (just like for a
protostar). But the overlying layers heat as well, causing H-burning just
outside the core to become very rapid ⟹ H shell-burning. See Fig. 20-3. So
star gets brighter (L rises) even though it has lost its fuel at the center.
The layers *above* the H-burning shell expand (not really understood,
although models are undoubtedly correct—explained in class), so surface
temperature cools ⟹ subgiant branch, then star ascends the red giant branch.
(See Fig. 20-4)
Red giants: surface is large, luminous (partly because of large surface
area), cool, but the core has shrunk to ~ 1/1000 size of entire star (~ size of
earth). The density in core is *huge*, around 10,000 x MS central density (~
10^6 gm/cm^3 vs. 10^2 for MS phase). This core will later become a white
dwarf when exposed by the loss of the envelope.

Inside a
$5M_\odot$ red giant

Surface of star

$70R_\odot$

$60R_\odot$

$50R_\odot$

$40R_\odot$

Hydrogen-fusion
shell

$30R_\odot$

$0.2R_\odot$

$20R_\odot$

Center
of
star

$0.1R_\odot$

$10R_\odot$

Helium
core

Size of
the sun

Magnified
100 times

When a star runs out of hydrogen at its center, the core contracts to a small size, becomes very hot, and begins nuclear fusion in a shell (red). The outer layers of the star expand and cool. The red giant star shown here has an average density much lower than the air at Earth's surface. Here $M_\odot$ stands for the mass of the sun, and $R_\odot$ stands for the radius of the sun. (*Illustration design by author*)

Helium nuclear fusion. Occurs by <u>triple alpha process</u> whereby three He-4 nuclei combine in a two-step process to form carbon-12 plus some energy. [The lucky placement of a "resonance" without which there would be no carbon or anything heavier is discussed in class.]   This reaction requires T~100 million degrees K, which the core has attained by its contraction and heating. But for low mass stars (less than about 2 Mo), when the He gets hot enough to ignite, the core is so dense that the gas is *degenerate*. (Recall discussion of brown dwarfs—same effect).

<u>Electron degeneracy pressure</u>—due to quantum effect called "Pauli exclusion principle." Result is that pressure does NOT depend on T, so He ignition increases T, which increases reaction rate, which increases T, … ⇒ runaway "<u>helium core flash</u>" (see p. 521): energy gets soaked up by the huge "buffer" of the envelope, so virtually unobservable from the outside—but very well established theoretically—note how almost all of this is stellar evolution *theory*).
Eventually (after only a few hours or less), the huge energy input does cause the pressure to increase and the core expands, making itself non-degenerate; it settles into a new equilibrium between pressure and gravity converting He into C ⇒ called "horizontal branch" phase, or just "core He burning." In effect, the star is given a new chance to resist gravity but for a shorter time than when it used H (He isn't as efficient a fuel).

Depletion of He in core. He ⇒ C ashes. T too cool to burn C (requires 600 million degrees K!), so core contracts (like after H depletion), heats, ignites He-burning shell. So in this phase have double shell burning (H and He—se Fig. 20.7). Actually get repeating "shell flashes" (again, all theoretical). The outer layers expand continuously during He shell burning, just as for the 1st red giant phase, so the star becomes even bigger and more luminous.
This 2nd ascent of the red giant branch ⇒ "<u>asymptotic giant branch (AGB)</u>". Now the carbon (He ashes) core becomes degenerate before C can ignite (if original mass of star is less than about 8 Mo), and the temperature stops increasing ⇒ *no more nuclear burning possible*. (Remember this is only for low-mass stars.)

The HR diagram below shows theoretical evolutionary tracks for low-mass stars of different masses, from 1 to 9 Mo. (9Mo is already just outside of our adopted range for "low-mass" stars.)
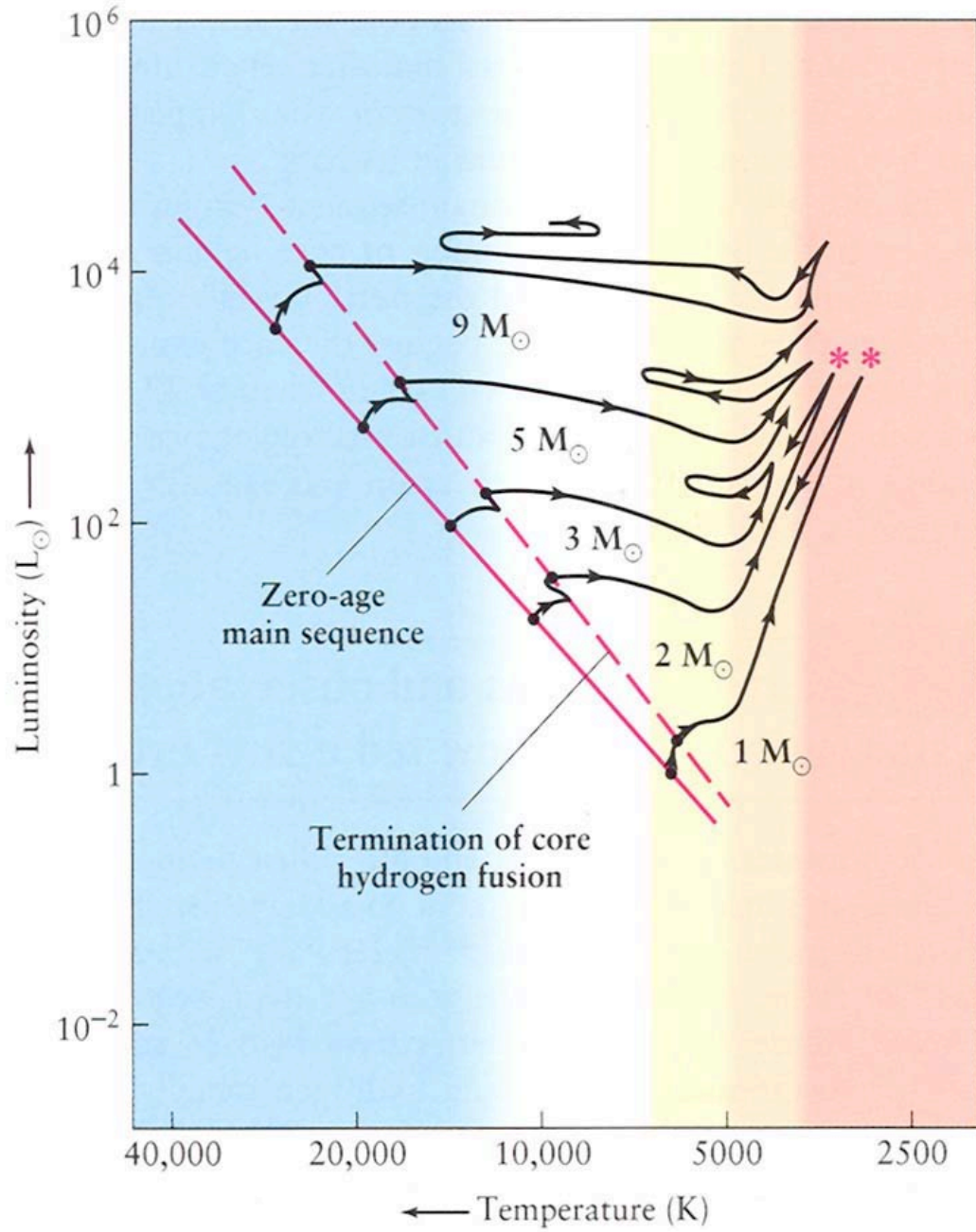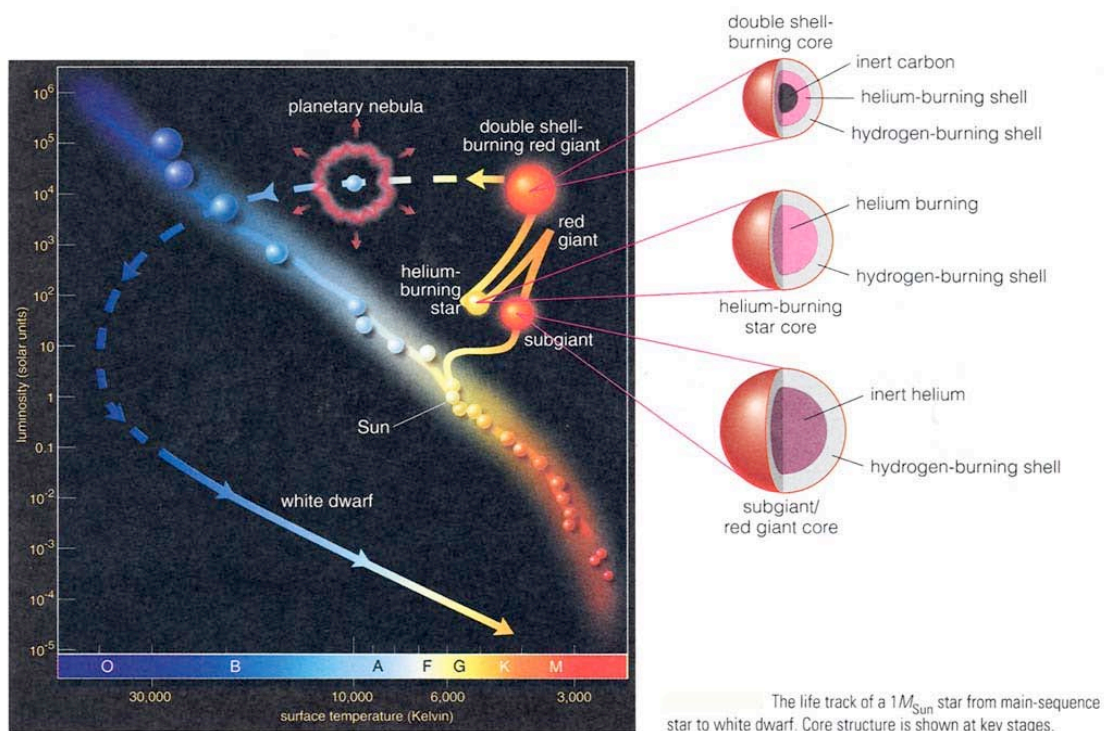
Further evolution of low-mass stars: Planetary nebulae, white dwarfs

During the entire RG and AGB phases, significant <u>mass loss</u> is occurring (observed) by a wind. (Probably the radiation pressure and shock waves from pulsations driving matter away—see Fig. 20.9 and Discovery 20-2.) The star is also <u>pulsating</u> (period ~years). Eventually so much of the envelope is lost that the last bit of envelope gets ejected as a more or less spherical shell of gas called a <u>planetary nebula</u>. (see pretty images, pp. 526-527) (Note: "planetary" has nothing to do with planets; just a historical term.)

What remains, the degenerate hot core, now unveiled, is a young **white dwarf**, which will just cool and fade forever (*unless* it receives some new mass from a binary companion…) Since these objects just contain the products of helium-burning, white dwarfs should be composed mainly of carbon (and some oxygen, depending on how far He-burning proceeded).

This is what happens to all low mass stars, by which we mean initial total masses less than about 8Mo.

Shown below is an illustration to help remember the phases of evolution and the internal structure of a low-mass star (like the sun).

The life track of a $1 M_{Sun}$ star from main-sequence star to white dwarf. Core structure is shown at key stages.

The following HR diagram shows theoretical evolutionary tracks and points representing observed stars, showing how the theory described so far can account for the observations.
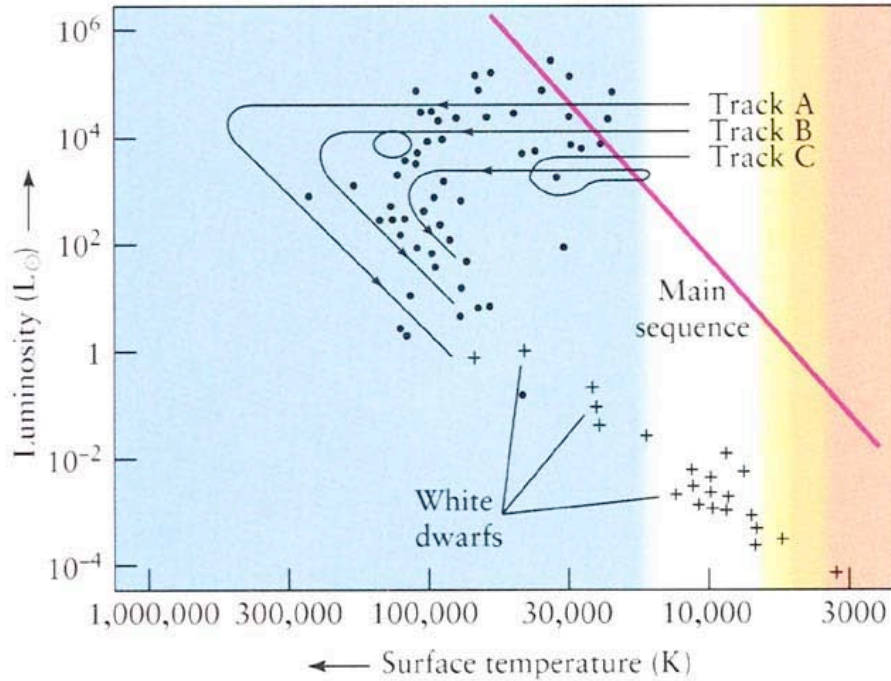
Evolutionary track	Giant star	Ejected nebula	White dwarf
	Mass (M$_\odot$)		
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

Evolution from Giants to White Dwarfs This H-R diagram shows the evolutionary tracks of three low-mass giant stars as they eject planetary nebulae. The table gives the extent of mass loss in each case. The dots represent the central stars of planetary nebulae whose surface temperatures and luminosities have been determined. The crosses are white dwarfs for which similar data exist. (Adapted from B. Paczynski)

Evolution of high-mass stars
Evolution is similar to low-mass stars, *except*:

1. They evolve more rapidly through all phases (because they have huge luminosities to support, and are hotter in their cores).

2. Their central densities are lower, so never get degenerate. This means they can keep burning the ashes as new fuels:

H → He → C → O → Ne → …

The star will have an "onion skin" interior, with the heavier "ashes" closer to the center. During this burning the stars cross the H-R diagram horizontally, sometimes with loops (see Fig. 20.16).

Another illustration of this structure is shown below.

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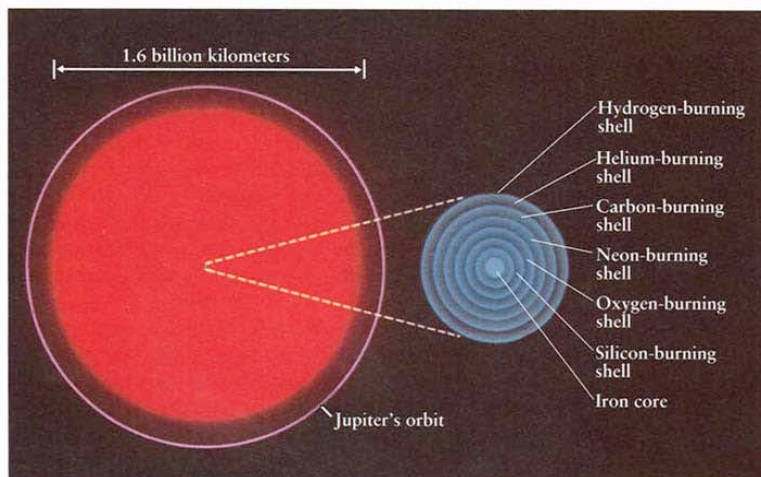
The Structure of an Old High-Mass Star
Near the end of its life, a high-mass star becomes a supergiant whose overall size can be as large as Jupiter's orbit around the Sun. The star's energy comes from six concentric burning shells, all contained within a volume roughly the same size as the Earth. Thermonuclear reactions cannot occur within the iron core, because fusion reactions that involve iron absorb energy rather than releasing energy.

High-mass stars do lose mass, and if they lose enough, their mass at the time the carbon core forms could be small enough to result in a white dwarf.   But it is believed that most stars more massive than 8-12 Mo cannot be "saved" as white dwarfs, and instead find themselves with a very different fate… (supernovae, neutron stars, black holes). This is covered in detail in subsequent chapters.

Observing Stellar Evolution in Star Clusters (sec. 20.5)

An intro. to this is sec. 19.6 which you should read again now. Read sec. 20.5 carefully and understand the H-R diagrams of open and globular clusters and their significance. We covered this in class in connection with sec. 19.6.

Extremely important question for you to think about: Why do open cluster HR diagrams have a variety of turnoff masses, while globular clusters all have a turnoff mass around 1 Mo? How is this related to the low metal abundances in globular clusters? The answer to this is the first hint for how our Galaxy formed. [Already discussed in class.]