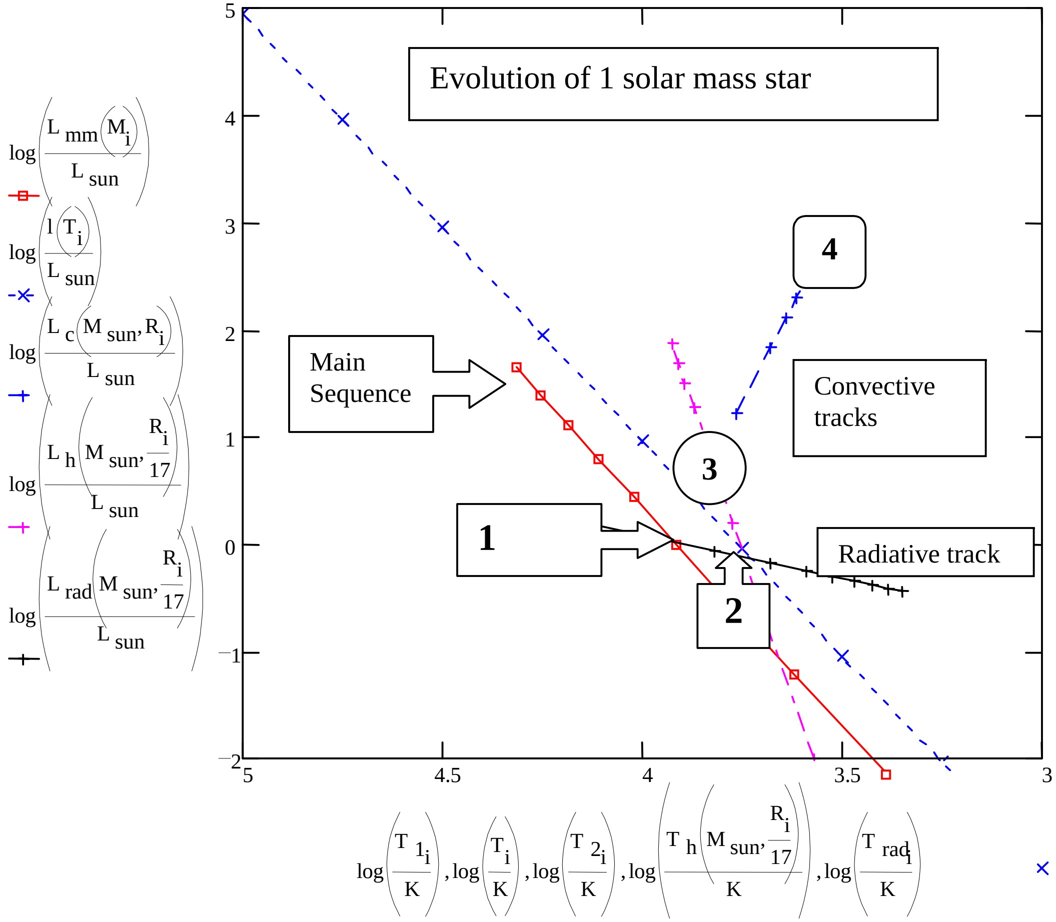
Handout 25
Evolution off the Main Sequence

- The details of this process are quite complex and there is no simple explanation.
  - I quote Hansen and Kawaler (1993, "Stellar Interiors", p. 55)
    - "The enormous increase in radius that accompanies hydrogen exhaustion moves the star into the red giant region of the H-R diagram. While the transition to red giant dimensions is a fundamental result of all evolutionary calculations, a convincing yet intuitively satisfactory explanation of this dramatic transformation has not been formulated."
  - However, the main external feature, that the star back-tracks along its pre-Main Sequence track, can be understood using simplified stellar models using the *Ansatz* that: the **nuclear luminosity increases**. .
    - This increase is caused by the depletion of H fuel, leading to
      - a He rich, inert, isothermal core
      - a H-burning shell surrounding the core
    - which we return to later

Equilibrium Stellar Configurations

- Refer to the stages of contraction to the zero-age Main Sequence



Stellar evolution to main sequence

- From Lecture 16:

R/Rsun	<T>	timescale	comment
10	10^6 K	$t_{K\text{-}H} \sim 10^4$ y	
5	$2\ 10^6$ K	$t_{K\text{-}H} \sim 10^5$ y	Nuclear reactions start
2	$5\ 10^6$ K	$t_{K\text{-}H} \sim 10^6$ y	Vigorous Nuclear reactions
1	10^7 K	$t_{nucl} \sim 10^{10}$ y	Nuclear = Luminosity

  – Here we identify the 4 marked positions on the H-R diagram's evolutionary track with the 4 radii above

- Recall the definition of Thermal Equilibrium
  – $L_{nuc} = L_{H\text{-}R}$.
    - i.e. the nuclear energy generation rate integrated over the whole star equals the Luminosity on the H-R diagram

Thought experiment

- Imagine the cross sections for nuclear capture in the p-p chain are all doubled
  - For a given configuration (i.e. T and density), the nuclear energy generation rate will be doubled.
    - The Main Sequence (i.e. thermal equilibrium) will be reached sooner
  - The new Main Sequence point will be position 2 on my H-R diagram
- Double them again
  - Now the Main Sequence will be position 3
- Double them again
  - Thermal equilibrium achieved at position 4
- Thermal Equilibrium depends on the rate of nuclear energy generation in the central regions of the star

Ascent into Red Giant branch

- So, if a new, potent, energy source is created in the center of star
  - It will travel from 1 to 3
- If even more energy is created
  - It will go from 3 to 4
- It has become a Red Giant
  - Temperatures around 3000 K
  - Luminosity greater than 1000 times solar
  - Lifetime
    - $< 10^{11}/1000 = 100$ million years
      - burning the 90% of the total H remaining after the Main Sequence
- The puzzle is: what is this energy source?

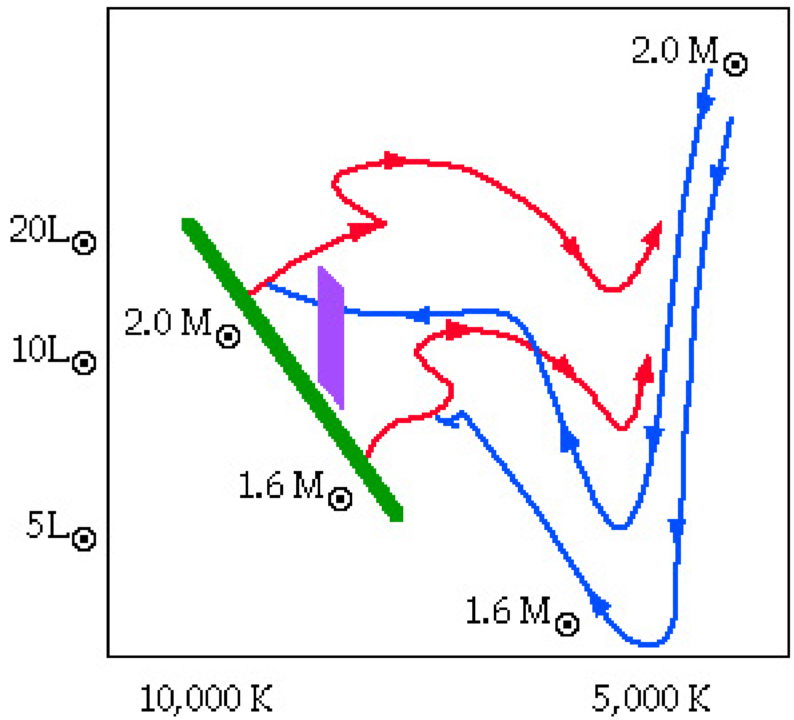
Evolutionary tracks on H-R diagram

The blue lines show the evolutionary path to the **Main Sequence**.

The vertical portion happens when the star is **fully Convective**. **Hayashi** figured this out.

The star's take a right turn when they develop a Radiative core – this track is nearly horizontal.

The time from the right turn to the main sequence
Is about 10 million years for a 1 solar mass star – the Kelvin-Helmholtz timescale.



Evolved star

- Unfortunately, a simple linear stellar model won’t work for this phase of evolution
  - All the action near a small central region
    - High density
    - High temperature
    - Mostly He
  - Incompatible with a simple linear stellar model
    - It’s possible (Stein) to add a linear-stellar-model core to a diffuse envelope
      - simplicity lost
      - physics made no clearer
    - permits more realistic tracks
      - i.e. path from 1 to 3 doesn’t go via 2 in real stars

For a touch of reality
H-R diagram of Globular Cluster

- Globular cluster group of 100,000 to a million stars
  - Size, of order parsec
  - Held together by gravity
    - Satisfies virial theorem
    - Isothermal sphere
    - Heavier stars sink to center
      - lower velocity since $(1/2)mv^2 = (3/2)kT$
  - All formed at same time
    - free- fall and sound-crossing times short compared to age
  - Age about 10 billion years
    - Stars more massive than sun have left main sequence
      - higher masses have evolved further than lower masses
      - positions on H-R diagram gives locus of tracks for 1-2 solar masses
        - » Vu-graph, Fig. 2.10, M3
        - » >2 solar masses have become white dwarfs

H-R diagram of Globular Cluster

- The Globular clusters stars are Population II
  - formed with low metal abundance
    - 1/10 to 1/1000 solar
  - Opacities less
    - Both interior (Kramers) and photosphere (H-)
  - Main sequence different
    - opacity less
    - radiation luminosity greater
      - effective T and L greater for a given R
    - must contract further to achieve Thermal Equilibrium
  - Evolutionary tracks also will be different than Pop I stars like the sun
- Check out Globular Cluster H-R diagram

Formation of He core

- Concentrate on stars near 1 solar mass
  - p-p chain converts 4 H atoms to He + energy
  - Strong temperature dependence (~ T^4) means reactions primarily in central hot, dense, central regions
  - Lack of convection throughout H-burning regions and beyond means H will be depleted and He enriched
  - p-p reactions stop when all H converted to He
    - Happens first at the very center
    - Moves outward with time
    - Star leaves Main Sequence when about 10% of the star's H has been converted to He
      - i.e. creating a He core with about 10% of star's mass
        - » sun has He core with about 5% of its mass
  - He is inert
    - triple alpha burning to C requires 100 million degrees

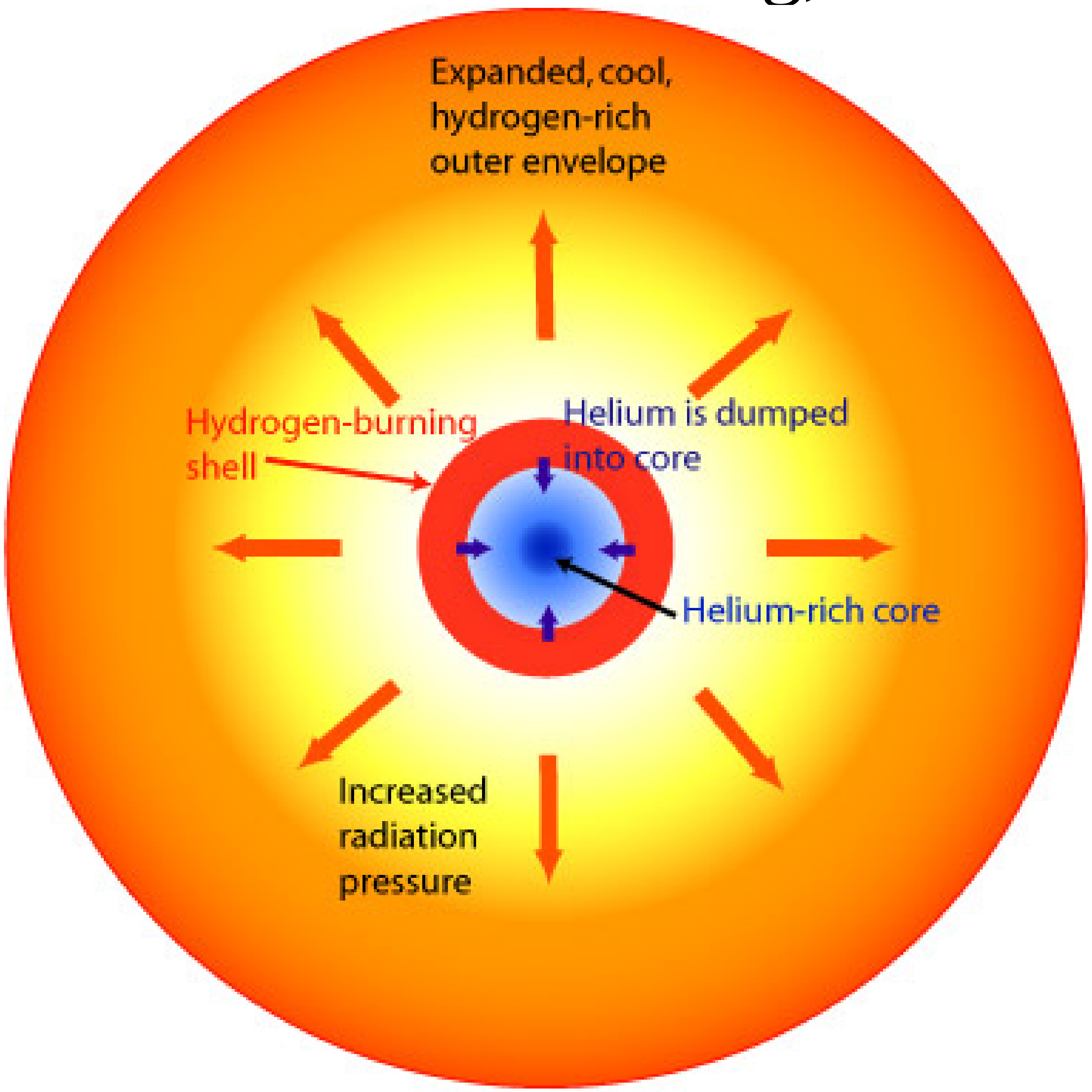
Nature of He core

- He core is nearly isothermal
  - No nuclear reactions
  - Only very slow contraction
  - L(r) essentially **zero** for $r < r_{core}$.
  - therefore dT/dr is close to zero, i.e. **isothermal**
- He core hot and dense
  - Hydrostatic equilibrium
  - pressure at r_{core} must support the 90% of the star mass above it
  - mean molecular weight about twice as big (calculate)
    - product of ρT has to be twice that of the H-burning shell just above
      - P and T continuous across r_{core} boundary
        - » no infinite acceleration or luminosity
    - Actually, e-degeneracy pressure is quite significant in core
      - i.e. pressure without temperature!

Ascent to Red Giant status

- He core kept hot by H-burning shell surrounding it
  - As shown by Stein and others, the nuclear luminosity from the shell will be
    - ~ ρ_{shell}^2
      - i.e. 2-body reaction
    - ~ $T_{shell}^{\mathbf{n}}$
      - where **n** = **4** for **p-p chain** but more like **14-18** for **CNO bi-cycle**
  - Models for the He core show the shell temperature is quite high
    - about **60 million** degrees for a 1 solar mass star
  - Therefore, the **CNO bi-cycle** will dominate
    - energy generation concentrated in thin, hottest region
    - Energy generation quite high
  - High luminosity forces star onto convective track
    - see vg Fig. 17 from Stein
      - compare to accurate, Iben tracks
        - » compare Iben pre (Fig.12.8)- and post (13.1)- Main Sequence tracks

H-shell burning, inert He core



Hydrogen Shell Burning on the Red Giant Branch

He core and H shell are tiny
very high T and density

H envelope is huge
100 Rsun, 1 AU

Large size implies low T
T ~ M/R

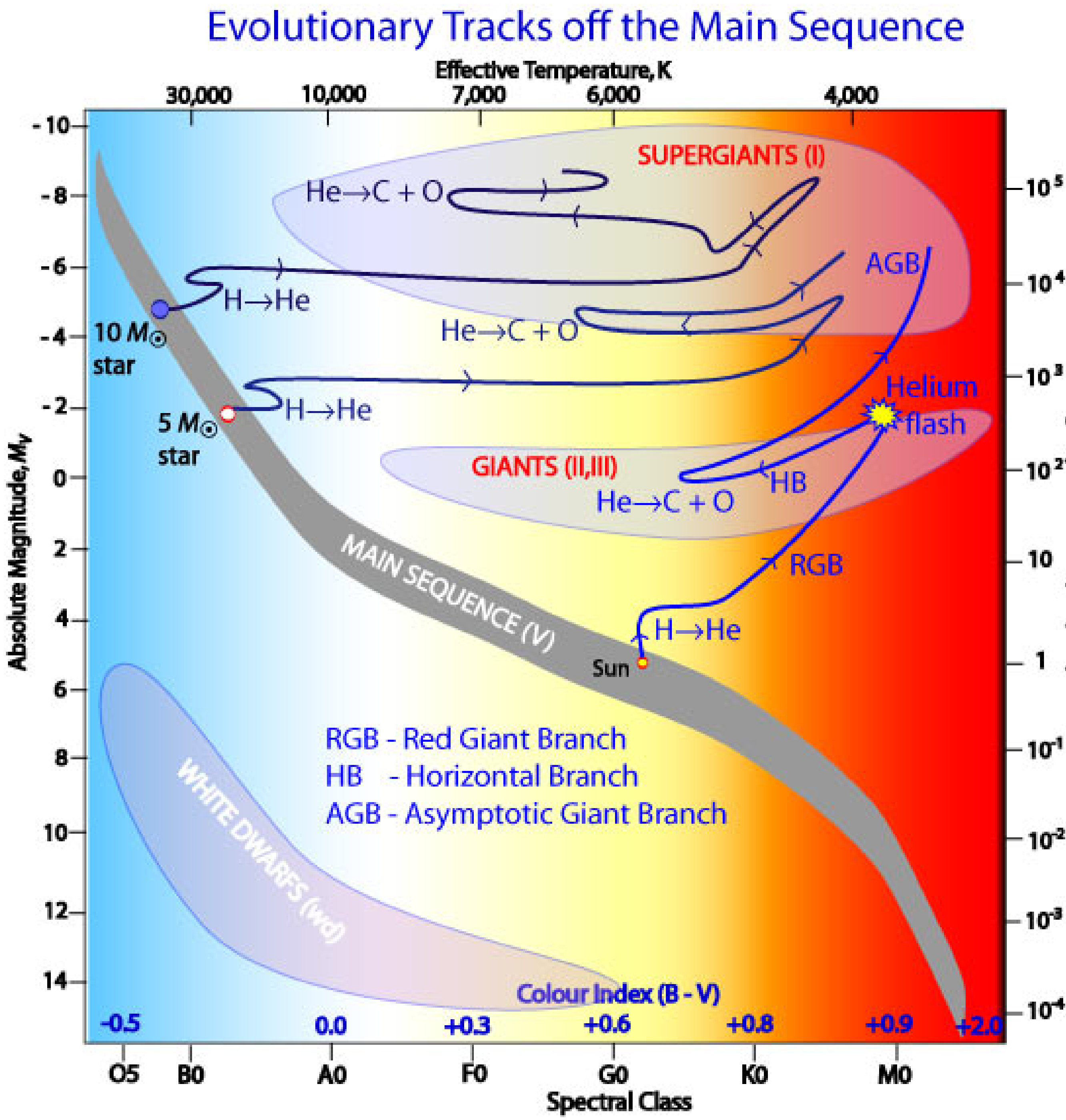
Low T means high opacity
Kramers b-f and f-f

High opacity forces large T gradient
$|dT/dr| \sim \kappa$

Large T-gradient causes convection

Core contracts

Envelope expands



Notice, tracks are basically the reverse
of pre-main-sequence tracks

Stars return to where they were born
High luminosity and low effective T

Basically what would happen if a light
Bulb were turned on at the center of
The star.
the equilibrium state for a given L

In pre-main-sequence, power is gravity
here it's nuclear burning

Details of tracks from non-homogeneous
structure

i.e. inert He core eventually ignites,
causing "He flash", burning He to
C and O

"Horizontal branch", see Glob Cluster
HR diagram