A Different Perspective on Stellar Evolution

Stellar Evolution

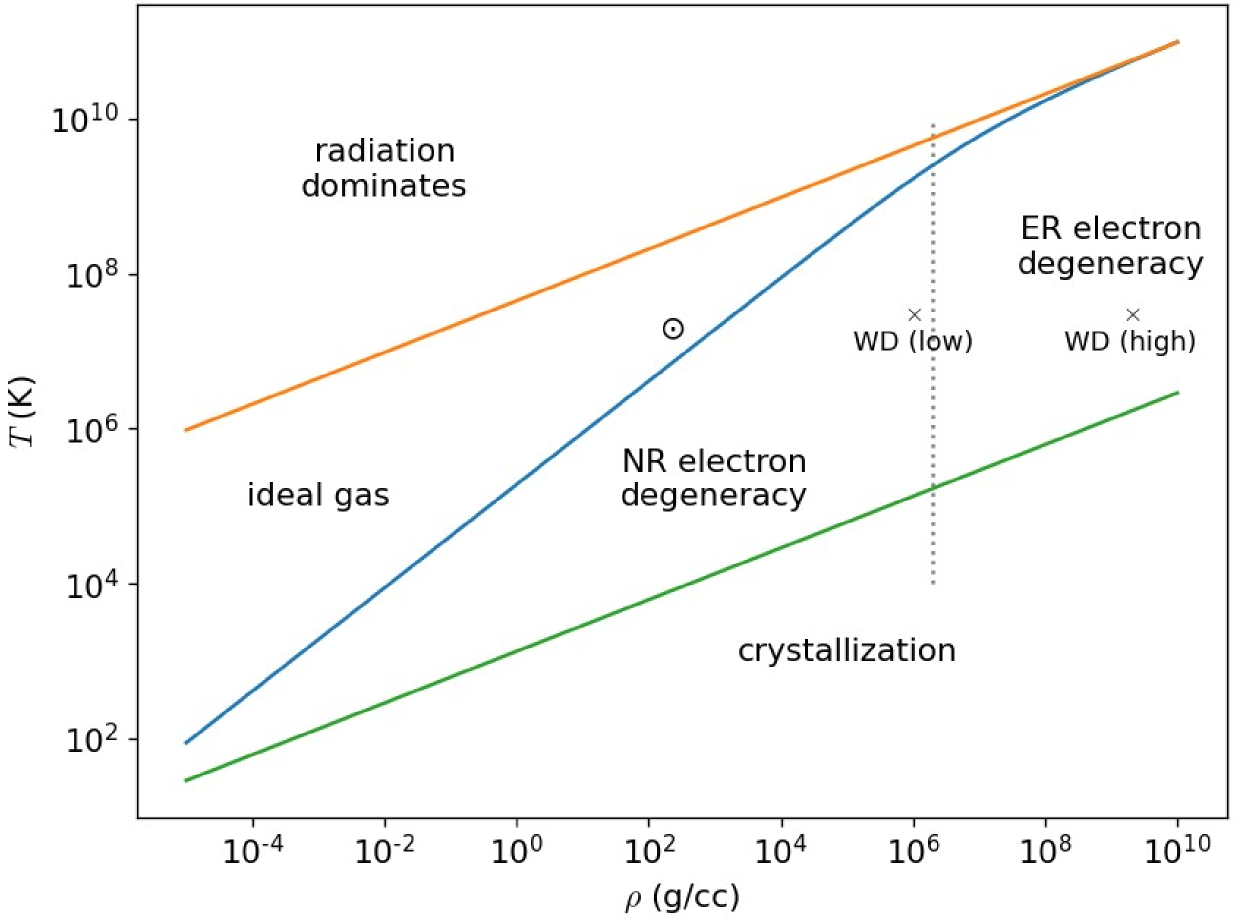
- We know how to compute the structure of a star given its mass and composition
- We also know how the composition changes due to nuclear reactions
- Together this means we can compute the evolution of stars

This discussion follows the excellent text by
Prialnik, Ch. 7

- T is highest at center
  - Reactions will be most energetic in center
  - Evolutionary changes are driven by exhaustion of fuel
- We can start to get a sense of stellar evolution by looking at the central conditions, ρ_c, T_c

Log T – Log ρ Plane

- In your homework, you explored the different EOS regimes



Nuclear Burning Ignition Curves

- We can also look at what fuel can burn as curves in the ρ-T plane
- For simplicity, we can take

$$q = q_{\min}$$

- Most sources will ask for the energy generation to be net positive, comparing to neutrino losses

$$q = |q_\nu|$$

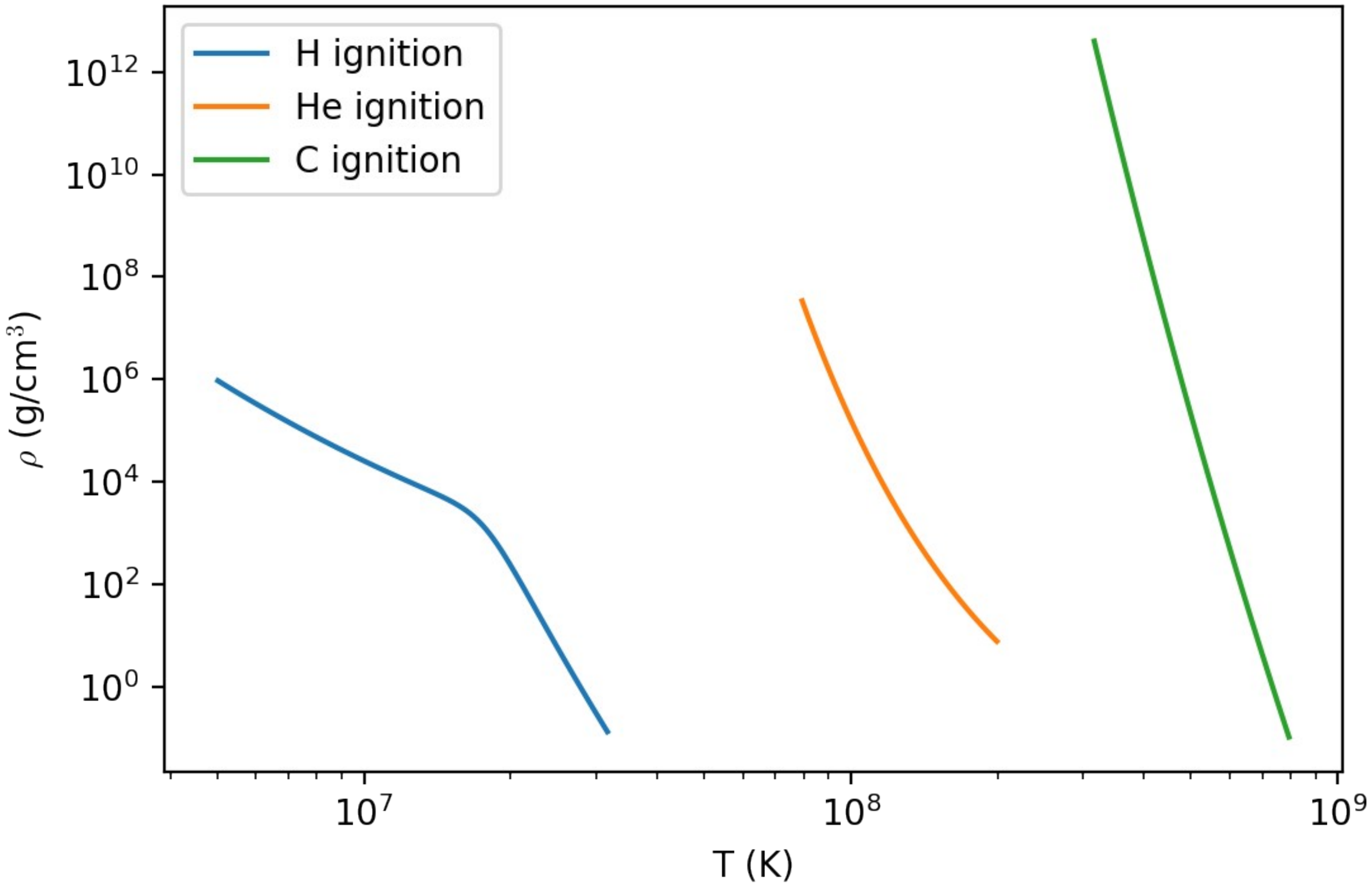
- Example:

$$q_0 \rho^m T^n = q_{\min}$$

$$\log \rho = -\frac{n}{m} \log T + \frac{1}{m} \log \left(\frac{q_{\min}}{q_0} \right)$$

  - Typically m = 1, n ≫1

Nuclear Burning Ignition Curves



Instability Zones

- We can have regions where $\gamma_a \leq 4/3$
  - Extremes in radiation dominated and relativistic degenerate regions
  - Iron photodisintegration (high T)
  - Pair production ($\gamma + \gamma \rightarrow e^+ + e^-$)
- Furthermore, nuclear burning is unstable in degenerate regions

Evolution of Central Conditions

- How does the stellar center evolve in log ρ – log T?
- From polytropes:

$$P_c = (4\pi)^{1/3} B_n G M^{2/3} \rho_c^{4/3}$$

  - B_n varies slowly with n (and not much at all between n = 1.5 and 3
  - B_n does not depend on K
- For star in ideal gas region:

$$\rho_c = \frac{K_0^3}{4\pi B_n^3 G^3} \frac{T_c^3}{M^2}$$

  - These are parallel lines for different masses
  - For same ρ_c, higher mass stars have higher T_c

Evolution of Central Conditions

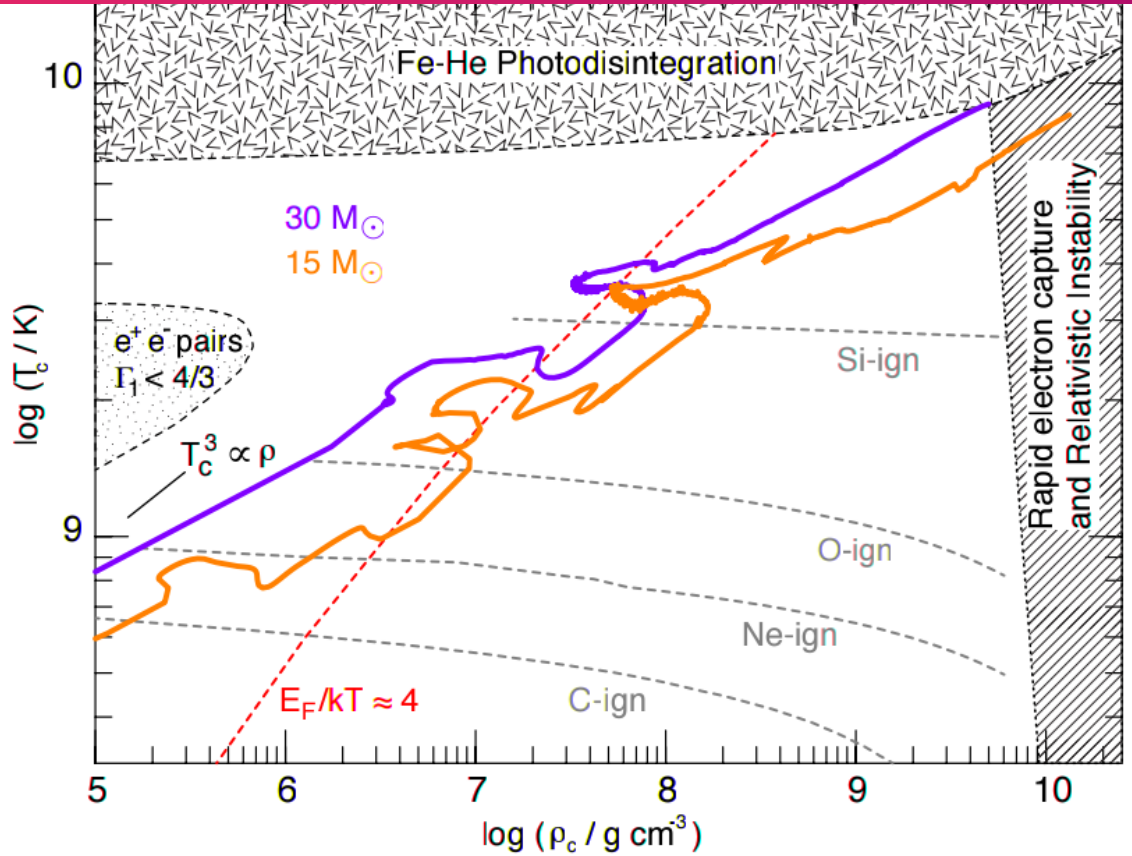


Figure 24. Evolution of T_c and ρ_c in solar metallicity, non-rotating $M_i = 15$ and 30 $M_\odot$ pre-supernova models. The curves are calculated using an in-situ 204 isotope reaction network. Locations of the core carbon, neon, oxygen, and silicon ignition are labeled, as is the scaling relation $T_c^3 \propto \rho_c$, and the $E_F/k_BT \approx 4$ electron degeneracy curve. Regions dominated by electron-positron pairs, photodisintegration, and rapid electron capture are shaded and labeled.

(Paxton et al. MESA III paper)

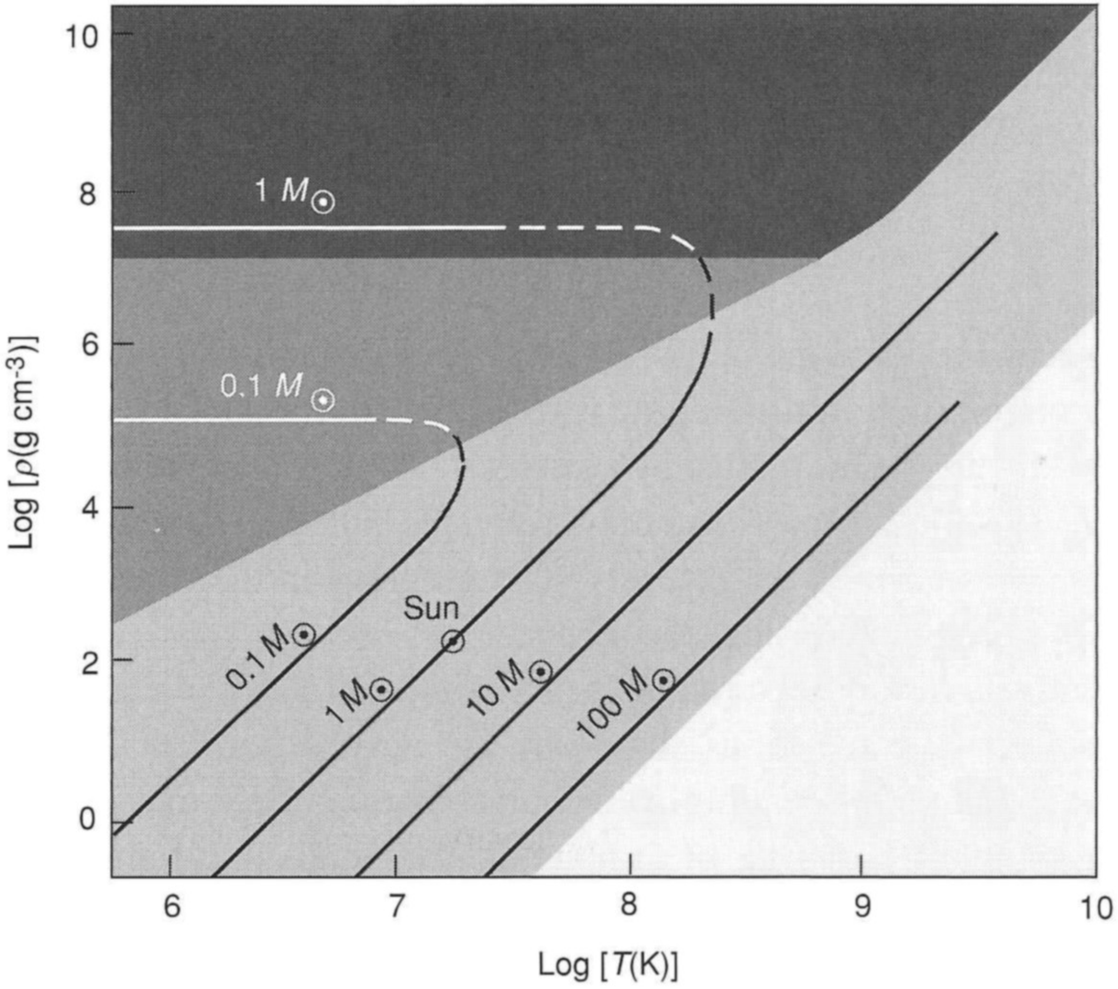
Evolution of Central Conditions

- For star in degenerate region:

$$\rho_c = 4\pi \left(\frac{B_n G}{K_1} \right)^3 M^2$$

  - No T dependence, only depends on M
  - Maximum mass support by electrons is Chandrasekhar mass
    - Stars with M > M_{ch} will not enter this region

Evolution of Central Conditions



(Prialnik)

Figure 7.4 Relation of central density to central temperature for stars of different masses within the stable ideal gas and degenerate gas zones.

Overview of Evolution

- Star forms at low ρ-T (gas cloud)
  - Start at lower left corner
  - No burning: star radiates gravitational potential energy and contracts / heats
  - Star follows $\rho_c \propto T_c^3$
- Star crosses H ignition line
  - Core H burning begins
  - Thermal equilibrium established
  - We stay here a long time: main sequence
  - Where we cross H line determines pp or CNO

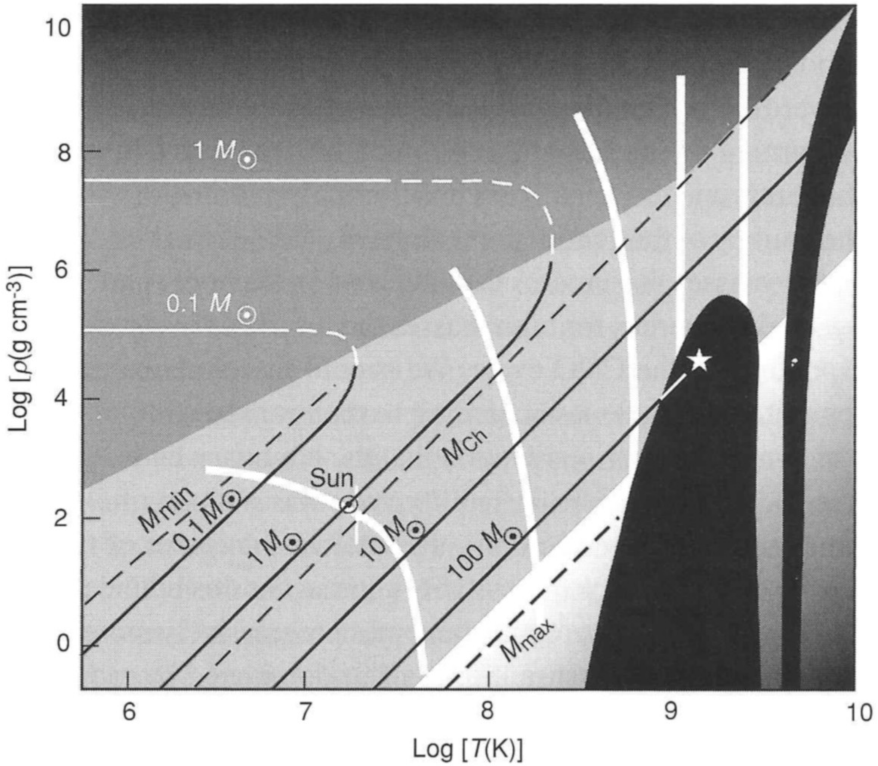


Figure 7.5 Schematic illustration of the evolution of stars according to their central temperature-density tracks.

Overview of Evolution

- If we are in the radiation zone, then we are unstable
  - Most massive stars will be here and not form
  - Upper limit to stellar masses
- Lower limit to stellar masses is where H curve stops (T ~ 10^6 K)
  - Somewhere near M ~ 0.1 $M_\odot$

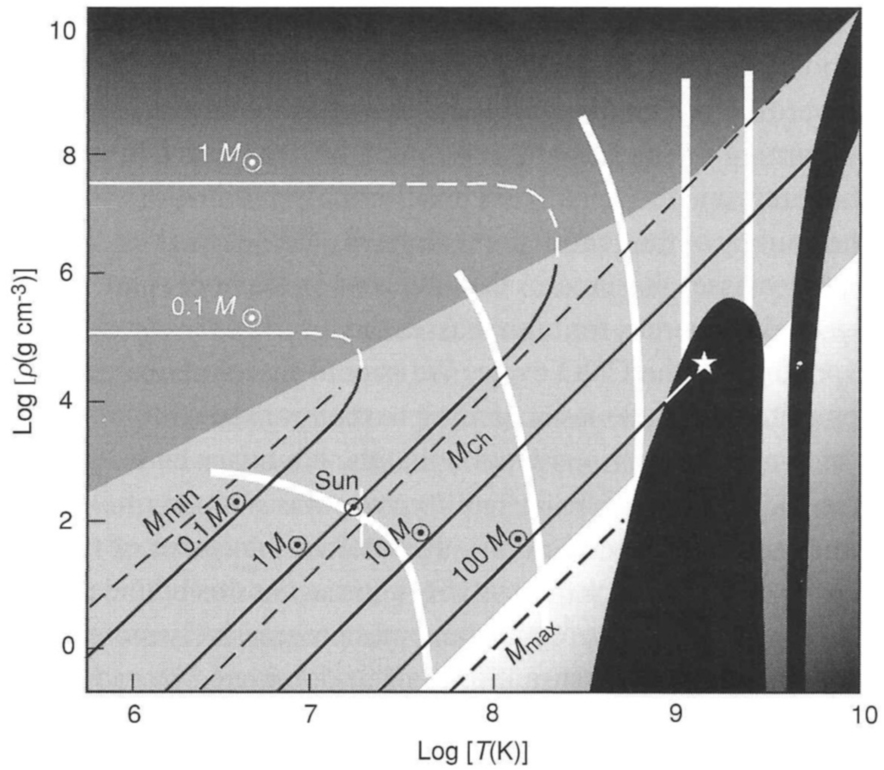


Figure 7.5 Schematic illustration of the evolution of stars according to their central temperature-density tracks.

Overview of Evolution

- H core exhaustion: core contracts and heats up
  - Climb up the curve
  - Low mass stars cross into degeneracy
  - Higher masses cross He ignition line
    - Lowest masses here cross close to degeneracy: He flash

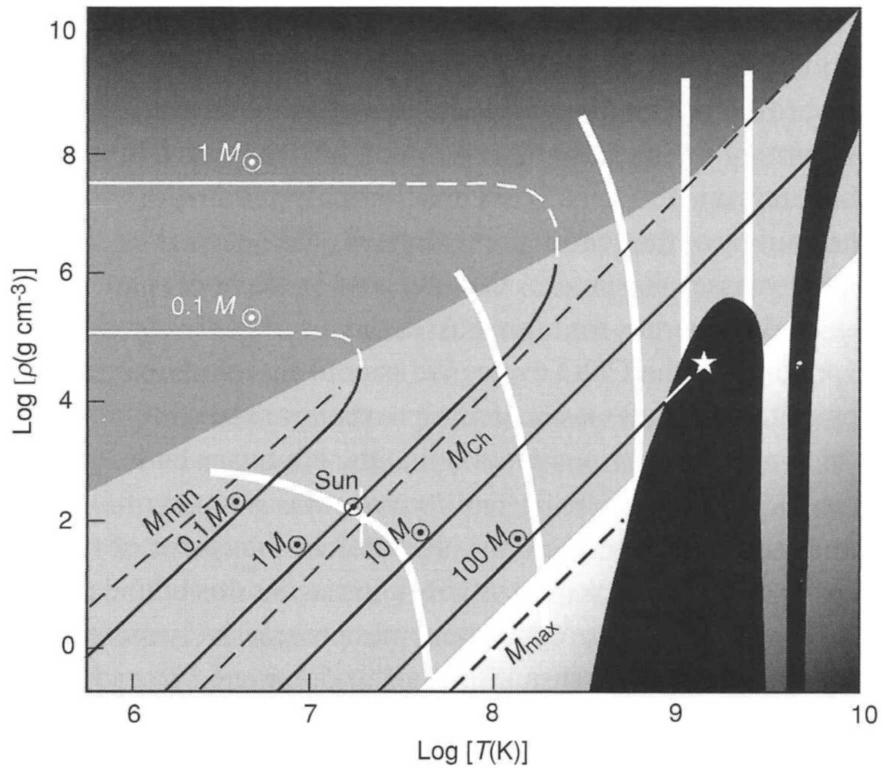


Figure 7.5 Schematic illustration of the evolution of stars according to their central temperature-density tracks.

Overview of Evolution

- Process continues
  - Higher masses (core mass > Chandra masss) continue to reach other burning zones
  - Evolution passes shortly at each new fuel
- When we reach Fe, photodisintegration kicks in: instability
- Highest masses have path enter pair-instability region—instability before Fe burning

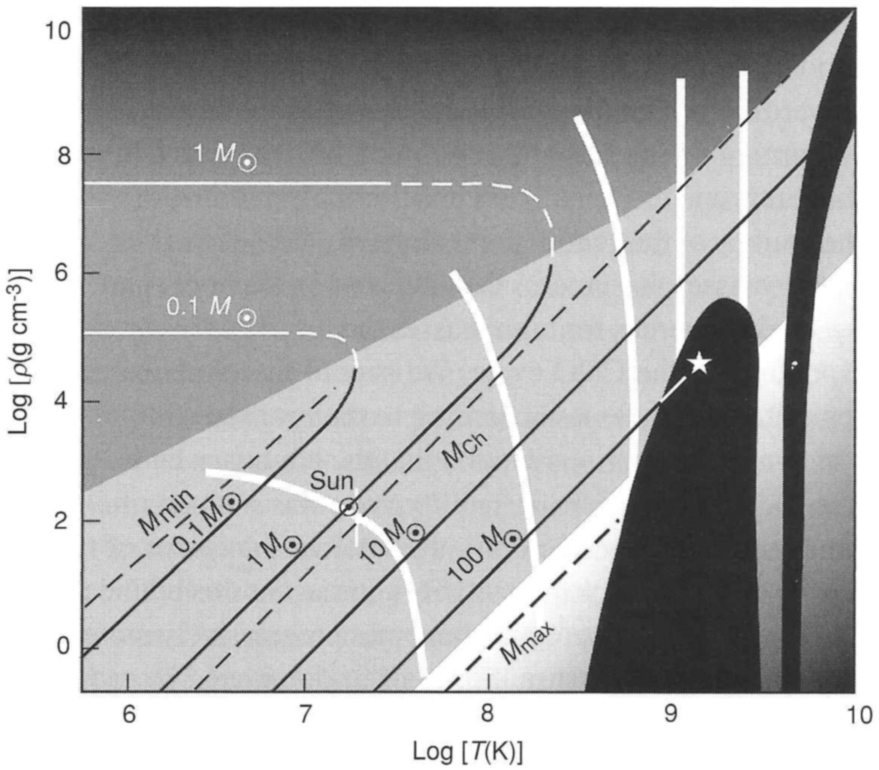
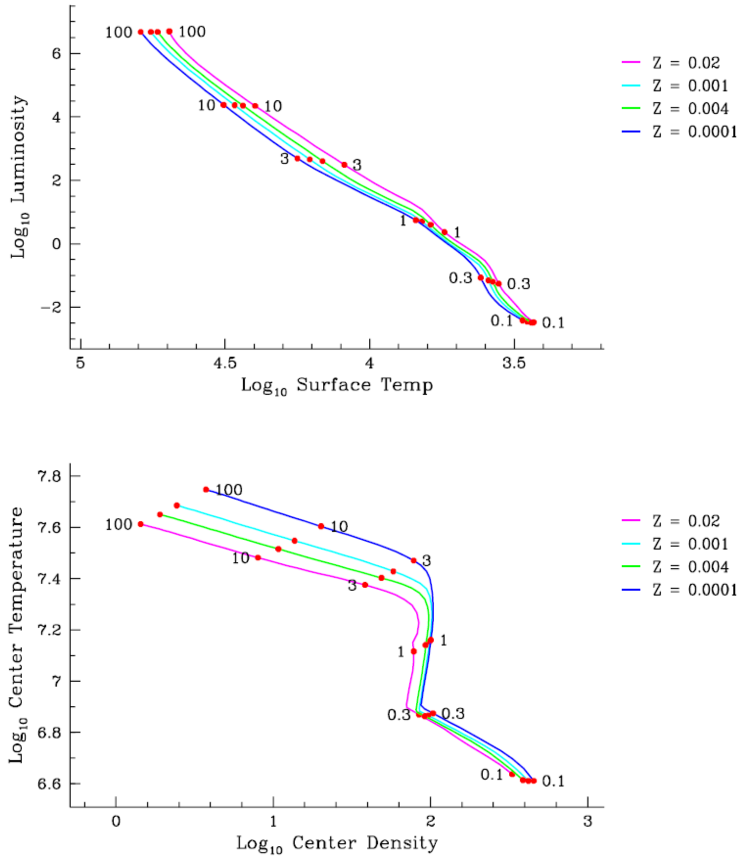


Figure 7.5 Schematic illustration of the evolution of stars according to their central temperature-density tracks.

ZAMS



ZAMS Hertzsprung-Russell and Temperature-Density Plots. Numbers show mass in solar units.

- Notice that at the low end, stars with the same mass, but lower Z are more luminous (dimensional analysis told us that)
- But… it you look at the main sequence, lower Z have the main sequence beneath that of higher Z

(Bill Paxton)

Late Stellar Evolution

- We can use the same log ρ – log T plane to look at the structure of a star at some instant in time
  - Now the curves show (ρ(m), T(m))
- Ex: 10 solar mass star
- A is main sequence: core H burning
  - Core is on the H ignition curve

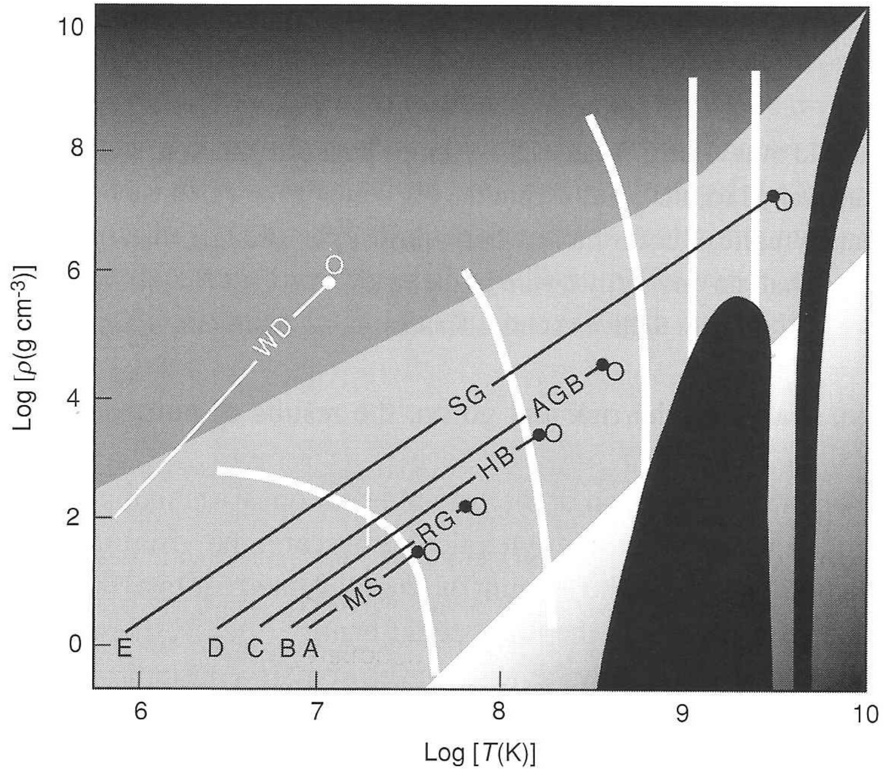
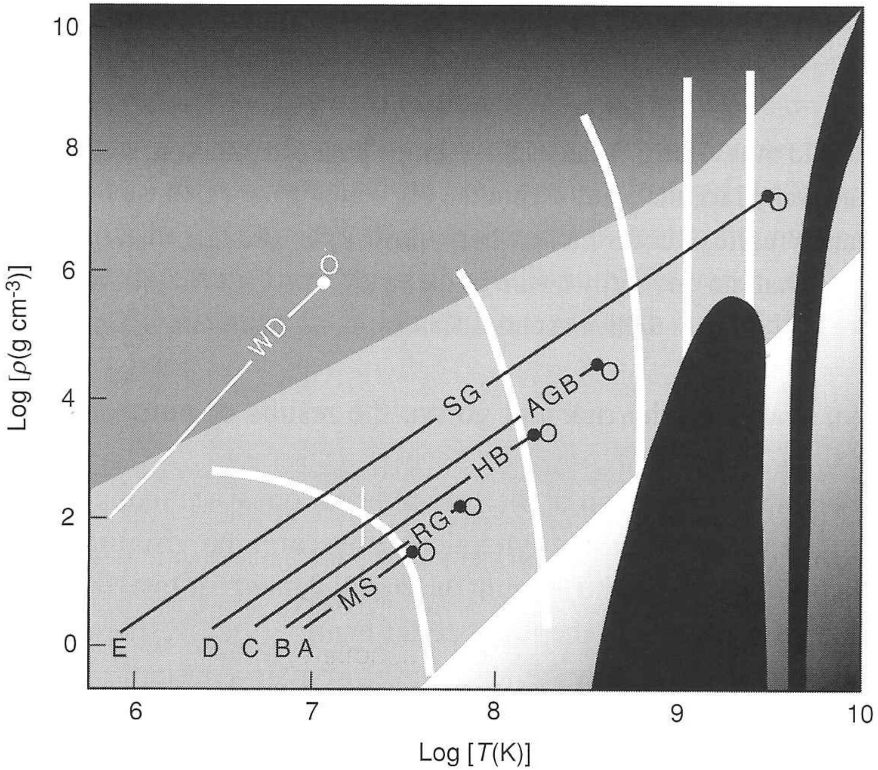


Figure 7.6 Schematic illustration of the stellar configuration in different evolutionary phases for a $10M_\odot$ star (A, B, C, D, E) and a white dwarf (WD).

Late Stellar Evolution

- B: core H depleted
  - Core contracts
  - Other mass elements cross the H ignition curve: shell burning
  - Contraction is quasi-static
    - Virial theorem applies
    - Assume thermal equilibrium: both U and Ω conserved independently
- Core contraction: Ω increases in magnitude at core → outer layers expand
- Core heating means U increases at core, so U must decrease in envelope: red giant



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Late Stellar Evolution

- C: He ignition reached
  - Now 2 ignition curves are crossed: He core burning and H shell burning
- D: He core exhaustion, so core contracts again
  - Two shell burning phases
- E: multiple burning shells, no more core fuel… lead up to core collapse

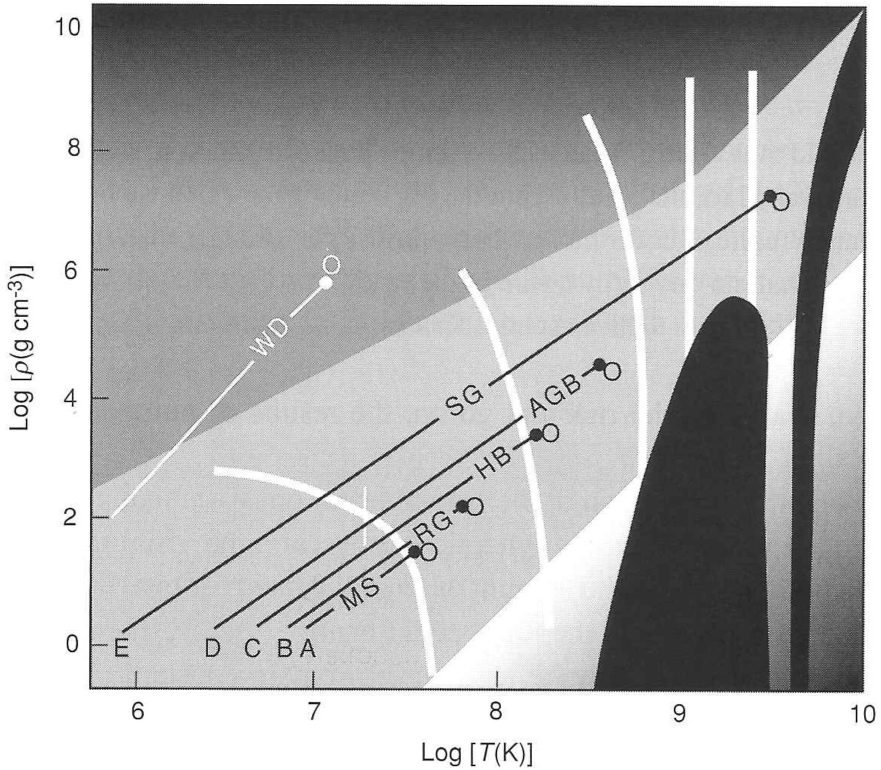


Figure 7.6 Schematic illustration of the stellar configuration in different evolutionary phases for a $10M_\odot$ star (A, B, C, D, E) and a white dwarf (WD).

Massive Star Evolution

- Massive stars ($M > 8\ M_\odot$) ignite He and C under non-degenerate conditions
  - Stars above $11\ M_\odot$ also ignite heavier fuels beyond carbon non-degenerately
  - Some uncertainty due to mass loss
- Note: this simple picture did not include mass loss by winds

Mass Cuts

- Mass plays a big role in the outcome of stellar evolution

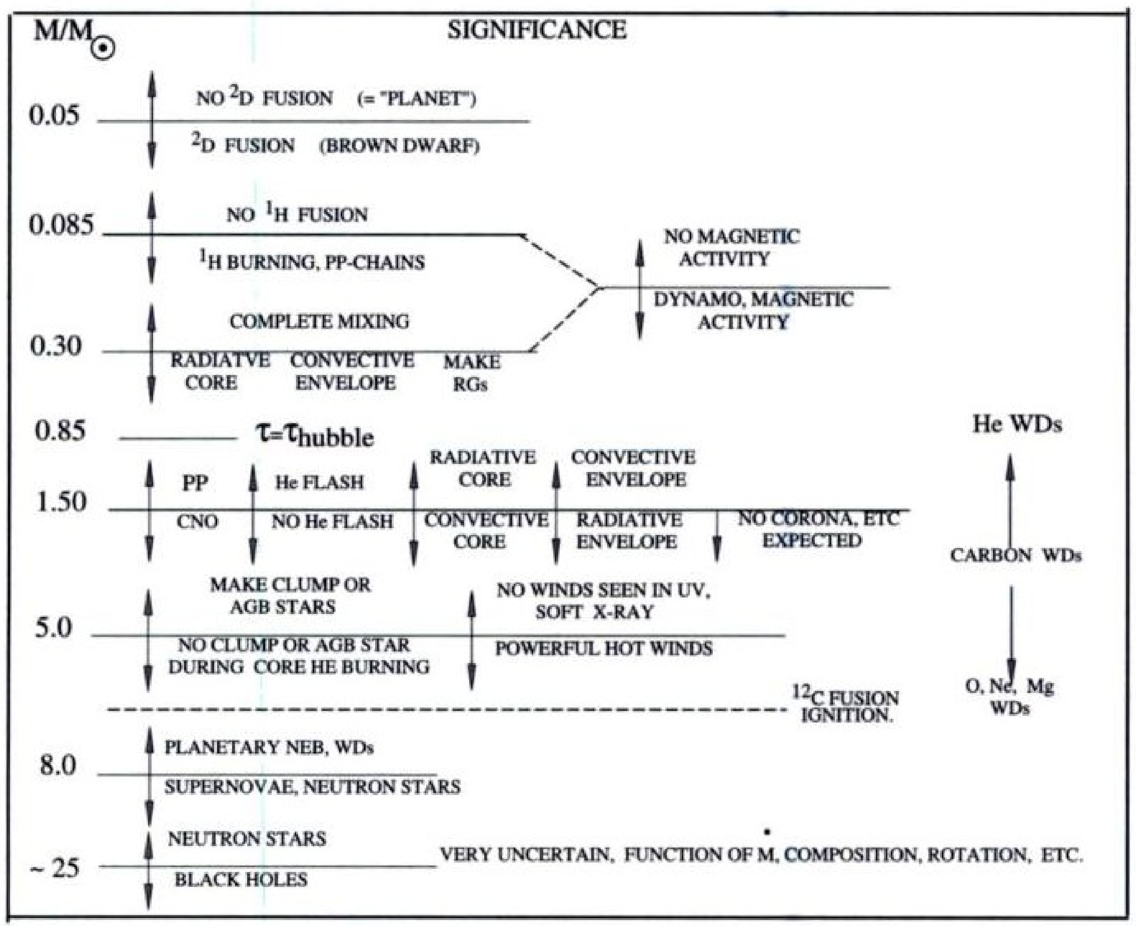


Fig. 2.4. Our "Mass Cut" diagram showing the fate of single stars in various mass classes. See text.

(Hansen, Kawaler, Trimble)

High Mass Evolution

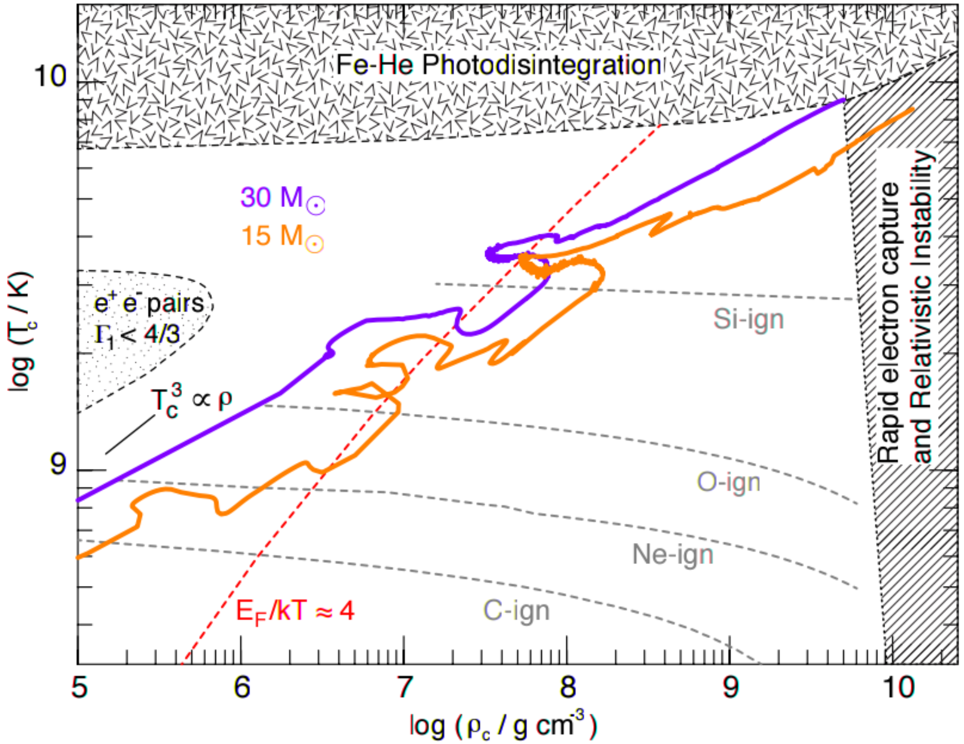


Figure 24. Evolution of T_c and ρ_c in solar metallicity, non-rotating $M_i = 15$ and 30 $M_\odot$ pre-supernova models. The curves are calculated using an in-situ 204 isotope reaction network. Locations of the core carbon, neon, oxygen, and silicon ignition are labeled, as is the scaling relation $T_c^3 \propto \rho_c$, and the $E_F/k_BT \approx 4$ electron degeneracy curve. Regions dominated by electron-positron pairs, photodisintegration, and rapid electron capture are shaded and labeled.

- Core evolution follows (roughly), $T^3 \sim \rho$
  - This is also what Eddington standard model shows
- Neutrino losses become important
  - At T > 5×10^8 K, this dominates energy losses
  - Burning ignites where $\varepsilon_\nu \sim \varepsilon_{nuc}$
- Burning from C to Fe core is so fast that the outer layers don't really have time to adjust
  - We'll be mostly stationary on the HR diagram

(Paxton et al. MESA III paper)

Burning Lifetimes

- Lifetimes can be estimated using the energy generate rate where $\varepsilon_\nu \sim \varepsilon_{nuc}$

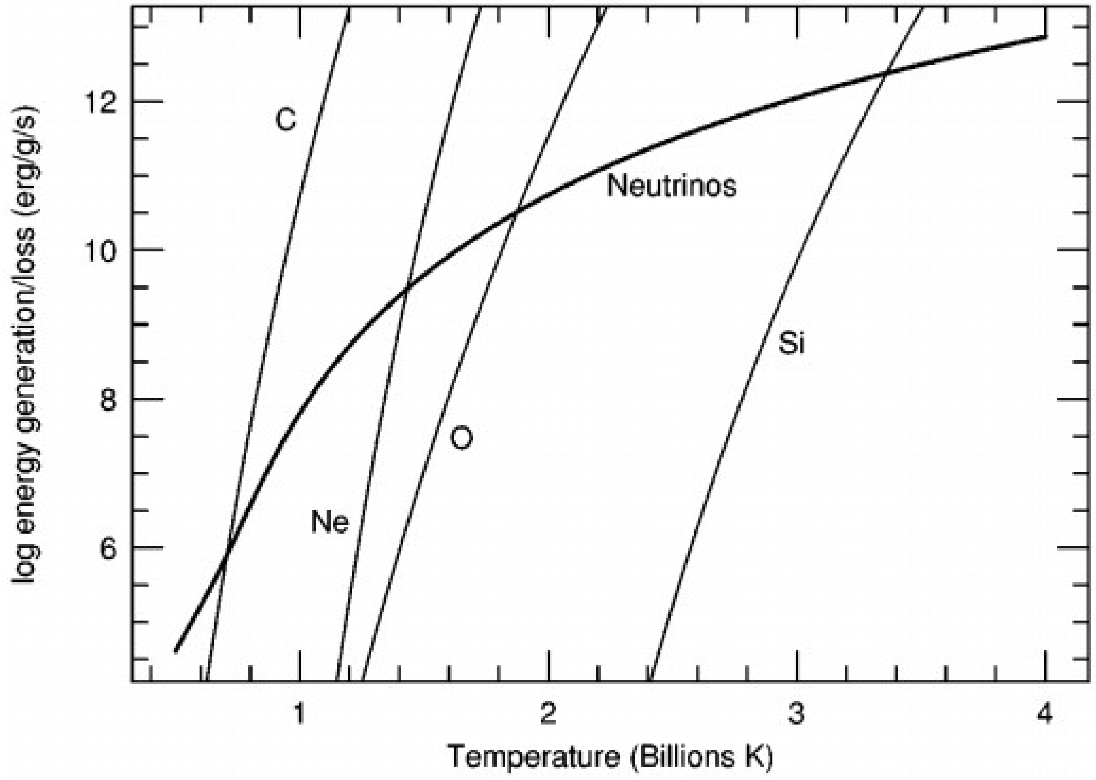


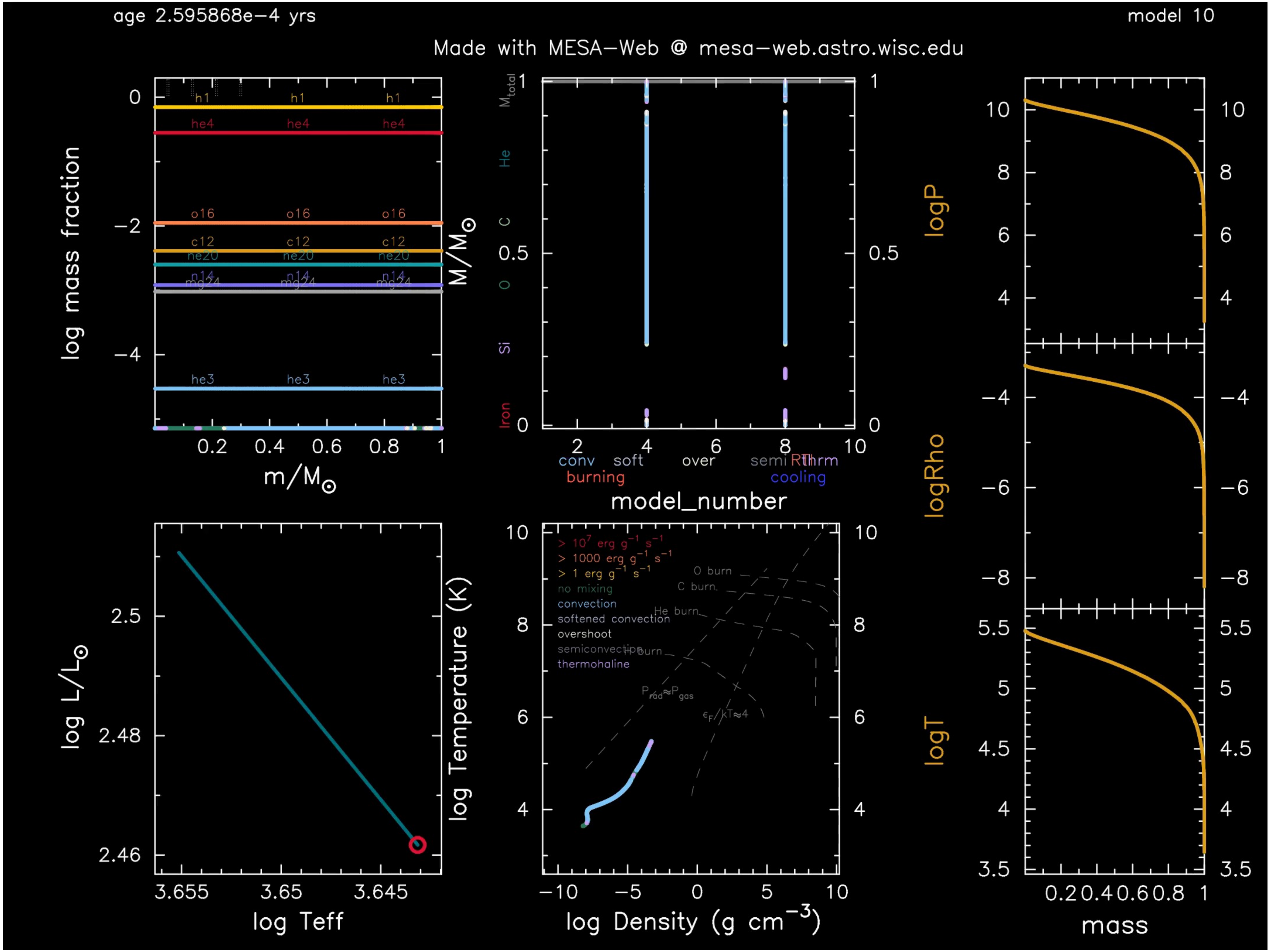
Figure 12.6. Energy generation rate and neutrino loss rate during the advanced evolution of a massive star. The stellar center is assumed to follow a track approximating that shown in Fig. 12.5. The intersections of the nuclear burning lines with the neutrino loss line define the burning temperature of the corresponding fuel. Figure from Woosley, Heger & Weaver (2002).

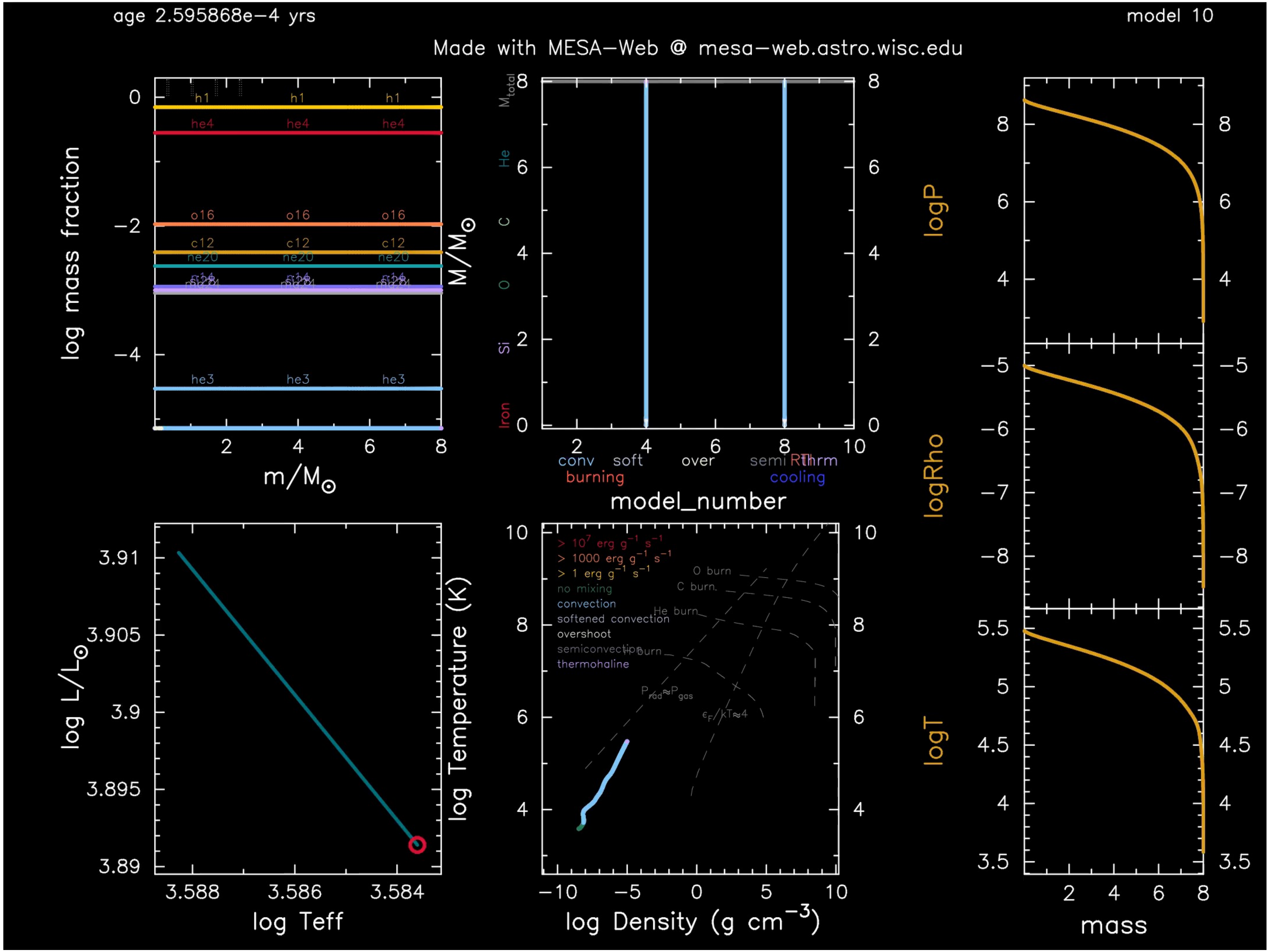
(via Onno Pols notes)

Looking Again At Stellar Evolution

- Let’s look at results of stellar evolution calculations again, now that we’ve learned about the physics that goes into the models

Zingale


age 2.595868e−4 yrs
model 10
Made with MESA−Web @ mesa−web.astro.wisc.edu
log mass fraction
h1
he4
o16
c12
ne20
n14
mg24
he3
0
−2
−4
0.2
0.4
0.6
0.8
1
m/M⊙
M/M⊙
Mtotal
He
C
O
Si
Iron
1
0.5
0
2
4
6
8
10
conv
soft
over
semi
RTI
thrm
burning
cooling
model_number
logP
logRho
logT
10
8
6
4
−4
−6
−8
5.5
5
4.5
4
3.5
0.2
0.4
0.6
0.8
1
mass
log L/L⊙
2.5
2.48
2.46
3.655
3.65
3.645
log Teff
log Temperature (K)
> 10^7 erg g^−1 s^−1
> 1000 erg g^−1 s^−1
> 1 erg g^−1 s^−1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
Prad≈Pgas
εF/kT≈4
10
8
6
4
−10
−5
0
5
10
log Density (g cm^−3)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log mass fraction
h1
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ne20
n14
si28
mg24
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C
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Si
Iron
model_number
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soft
over
semi
Rti
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