ASTR 498N   Lecture 18   The Big Picture Redux

(online at www.astro.umd.edu/~drabin/)

Stellar evolution at a glance

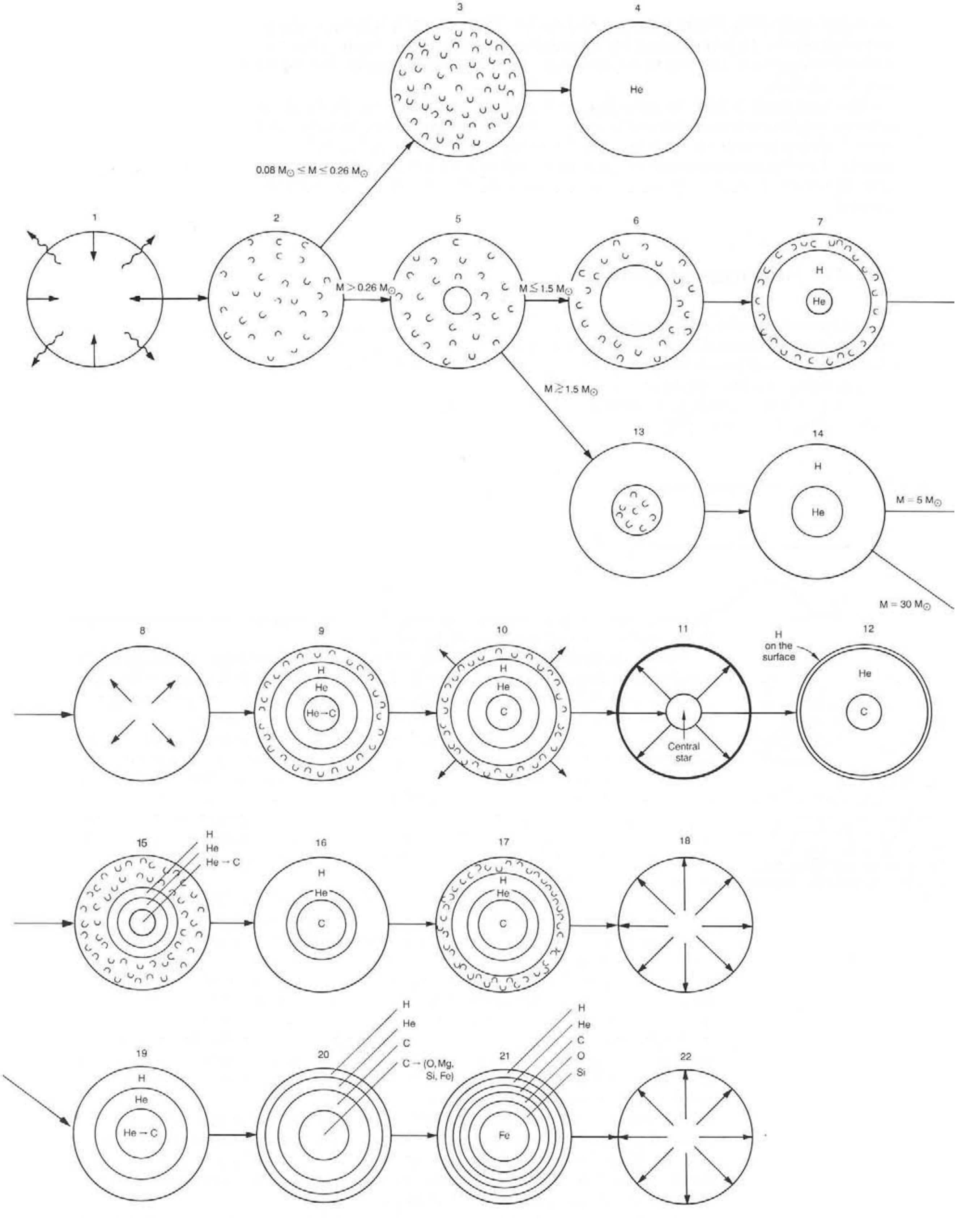
In *Fundamental Astronomy* by Karttunen et al. (3rd ed. 1996, Springer), there is a nice cartoon view of stellar evolution, shown below. Perhaps we should call it a graphic novel version, as it has enough content to spend some time with.

Some preliminary caveats:

1. This depicts the evolution of isolated stars. Most stars are in binary or multiple systems. Usually the stars are sufficiently separated that the main features of their evolution follow the scheme below. However, in close binary systems, where the separation is not much greater than the largest stellar radius that occurs during evolution, the joint evolution is definitely and often drastically affected. The statistical distribution of stellar remnants cannot be understood without considering the effects of mass transfer in binary systems.
2. Even single stars lose mass through winds. The effect on main-sequence evolution is negligible for the Sun but important for massive stars. Mass loss is important on the giant branch, even more so on the asymptotic giant branch.
3. Many low-mass stars eject a planetary nebula. This dynamic phenomenon is by no means as well understood as earlier evolutionary phases (even those that are quite rapid by main-sequence standards), and it is not handled by conventional evolutionary codes. Ditto squared for supernovae.
4. Although mass is the dominant factor controlling evolution, evolutionary tracks and timescales also depend on the initial chemical composition.

On to the tour, by numbered phases. The radius is scaled to be the same in every phase; the actual radii vary greatly, as you know.

1. Gas cloud collapsing in free fall. Initially it is optically thin.
2. Protostar in quasistatic equilibrium, fully convective.


3
4
He
0.08 M⊙ ≤ M ≤ 0.26 M⊙
1
2
5
6
7
M > 0.26 M⊙
M ≲ 1.5 M⊙
H
He
M ≳ 1.5 M⊙
13
14
H
He
M = 5 M⊙
M = 30 M⊙
8
9
10
11
12
H
He
He→C
H
He
C
Central star
H on the surface
He
C
15
H
He
He → C
16
H
He
C
17
H
He
C
18
19
H
He
He → C
20
H
He
C
C → (O, Mg, Si, Fe)
21
H
He
C
O
Si
Fe
22

3. Parting of the ways. For $M \lesssim 0.08\,M_\odot$, the central temperature never gets high enough to burn hydrogen and stardom is denied (brown dwarf, not shown). For $\mathbf{0.08}\,\boldsymbol{M_\odot \lesssim M} < \mathbf{0.26}\,\boldsymbol{M_\odot}$, the star remains fully convective as it burns hydrogen on the main sequence. Its luminosity is very low and its evolution very slow (particularly since the whole star is available for fuel because of convective mixing).
4. Its central temperature is never high enough to ignite helium so, when the hydrogen is exhausted, it contracts to a helium white dwarf.
5. Stars with $\boldsymbol{M} > \mathbf{0.26}\,\boldsymbol{M_\odot}$ develop a radiative core. Why? Recall the structure equation for radiative transport,

   $$\frac{dT}{dr} = -\frac{3\bar{\kappa}\rho}{4acT^3}\frac{L}{4\pi r^2}$$

   and the temperature-density dependence of the Kramers free-free opacity, $\bar{\kappa}_{\text{ff}} \propto \rho T^{-3.5}$, which is still a significant part of the total opacity at this point. The radiative temperature gradient thus decreases strongly with increasing temperature, outweighing the more gradual influences of central density and the energy generation rate. As the core temperature rises, convection ceases when the radiative temperature gradient falls below the adiabatic gradient.
6. Another parting of the ways. Stars with $\mathbf{0.26}\,\boldsymbol{M_\odot} < \boldsymbol{M} \lesssim \mathbf{2}\,\boldsymbol{M_\odot}$ remain radiative in the center during the main sequence phase as they burn hydrogen through the p-p chain.
7. When hydrogen in the core is exhausted, hydrogen burning continues in a shell around the helium core as the star leaves the main sequence and evolves gradually ($>10^9$ y) redward toward and then up the red giant branch. Although the mass of the isothermal helium core exceeds the Schönberg-Chandrasekhar limit, that limit (derived under the assumption of ideal gas pressure) does not apply because the core is partially supported by the pressure of degenerate electrons. The core contracts gradually and heats up.
8. The core is strongly degenerate when the temperature becomes high enough to ignite the triple-alpha process. As we saw in Lecture 7, this leads to a thermal runaway: the increased deposition of energy causes the core to expand but not to cool, since the degenerate electron pressure does not depend on temperature. This is the *helium flash* (a somewhat misleading name, you'll recall, because

essentially all the energy is absorbed within the star, lifting the degeneracy in the core.

9. After the helium flash, the star ends up on the *horizontal branch*, burning helium to carbon and oxygen in the inner core and hydrogen in a shell. The core mass is close to 0.5 $M_\odot$ irrespective of the total mass. The helium burning region is convective.
10. When helium is exhausted at the center of the star, the C-O core contracts and heats while the envelope expands and cools, in analogy to evolution away from the (hydrogen) main sequence. The redward evolution stops near the Hayashi line, as for red giants—this is the asymptotic giant branch. Hydrogen and helium burn in shells, but not simultaneously. Most of the time, the hydrogen is burning and adding to a quiescent helium layer. This layer contracts and heats, eventually igniting helium under degenerate conditions. The result is a *helium shell* flash at the base of the helium layer, analogous to the earlier helium core flash. The flash energy expands and cools the outer layers, briefly quenching the hydrogen shell. Helium burning advances outward, adding to the C-O core, until it meets the hydrogen layer and reignites it. The resulting series of thermal pulses is characteristic of the AGB.
11. The star is losing mass at a prodigious rate on the AGB, up to 10^{-4} $M_\odot$ yr^{-1} (probably more than one mechanism contributes to the mass loss). When, for whatever reason, the mass loss ceases, the star contracts and heats up until it can ionize the ejecta around it, which is coasting outward at 10–30 km s^{-1}. This is seen as a *planetary nebula*. I depart from my usual dry-as-dust style to show you a few of these beautiful objects:

12. The shell sources are exhausted, but the central temperature of the carbon-oxygen core is not high enough to ignite carbon. The star cools and becomes a white dwarf with a mass of about 0.6 $M_\odot$.

13. For $\boldsymbol{M \gtrsim 2\, M_\odot}$ (the other branch originating from Phase 5), the CNO cycle dominates the main sequence phase. The core is convective (because of the high temperature-sensitivity of the CNO cycle) while the envelope is radiative, the opposite of the configuration for $0.26\, M_\odot < M \lesssim 2\, M_\odot$.

14. When the main sequence phase ends with the exhaustion of central hydrogen, the helium core is nondegenerate. Therefore, the Schönberg-Chandrasekhar limit applies: when the isothermal helium core grows past the limit, the core collapses while the envelope expands and the star moves swiftly redward toward the Hayashi line.

15. Because the core is nondegenerate, helium ignites quietly when the central temperature reaches about 10^8 K. Hydrogen continues to burn in a shell. The outer envelope is convective.

16. When central helium is exhausted, helium and hydrogen burn in shells.

17. Stars with $\boldsymbol{M \lesssim 4\, M_\odot}$ never achieve a central temperature high enough to ignite carbon. Stars with $\boldsymbol{4\, M_\odot < M \lesssim 8\, M_\odot}$ can in principle undergo a core collapse because not even degeneracy pressure can support a core more massive than about 1.4 $M_\odot$ (this is the Chandrasekhar limit, derived below) (and note, the Chandrasekhar limit is different from the Schönberg-Chandrasekhar limit).

18. If carbon ignites under degenerate conditions, the resulting carbon flash would probably be so powerful as to disrupt the star entirely: a supernova. It is not clear, however, that this type of supernova occurs in nature; mass loss might instead bring the core under the Chandrasekhar limit.

19. For stars more massive than **8–10** $\boldsymbol{M_\odot}$, electrons remain everywhere nondegenerate and nuclear burning can proceed through all the gaudy stages discussed in Lecture 14, culminating in highly endothermic photodisintegration of the iron core and fearsome neutrino losses. The result: core collapse, a Type II supernova (Phase 22), and a neutron star or black hole remnant.