37 — The End of Low-Mass Stars [$Revision : 1.2$]

- Burning to a degenerate core
  - Stars with masses $M \gtrsim 9\,M_{\odot}$ do not burn as far as iron (although some may burn further than helium)
  - Recall: after helium flash, star settles onto horizontal branch (HB), with (convective) core helium burning and shell hydrogen burning
  - As helium burns to carbon and also oxygen, molecular weight increases, core contracts
  - Contraction accompanied by envelope expansion; star moves redward in HRD, toward Hayashi line
  - Eventually, core runs out of helium, burning stops; contraction continues until electron degeneracy pressure halts it
  - Helium burning resumes in shell
- The Asymptotic Giant Branch
  - When star reaches Hayashi line, turns upwards with luminosity increase; this **asymptotic giant branch** is similar to red giant branch, but star now has He-burning shell, and is more luminous
  - Initially, star is on lower part of AGB — the **early AGB** (E-AGB)
  - On E-AGB, helium shell source is dominant source of energy; hydrogen shell is almost dormant
  - Because on Hayashi line, deep convection zone
  - When convection zone dips through hydrogen shell, mixes helium and nitrogen (produced by incomplete CNO-cycle burning) up to surface — **second dredge-up** (first dredge up occured on RGB)
  - As star moves to upper AGB, hydrogen shell reignites and becomes dormant
  - Helium burning shell become unstable, switching on and off periodically — thermal pulses. This part of AGB known as **thermal pulse AGB** (TP-AGB)
  - When helium shell switched off, helium accumulates from above due to outer hydrogen burning shell (which is producing helium)
  - Eventually, enough helium accumulates for (slightly degenerate) ignition in a mini-flash; sudden temperature increase causes envelope to expand
  - Expansion cools hydrogen shell and switches it off
  - Eventually, helium burning dies down, hydrogen shell reignites and becomes dominant again
  - During a helium burning episode, large flux in inter-shell region causes convection zone to develop
  - If this convection zone merges with envelope convection zone, products of helium burning (esp. carbon) can be brought to surface — *third dredge-up*
  - Dredge up also can bring to surface heavy elements produced by s-process neutron capture — esp. the radioactive isotope ${}^{99}_{43}\mathrm{Tc}$
- AGB Mass Loss
  - Stars on AGB show strong mass loss
  - Winds are low temperature, typically form dust (composition depends on whether third dredge up has occurred)

  - Mechanism for wind outflow not yet clear; may be linked to thermal pulses or long-period pulsations observed in some AGB stars
  - As star continues to expand up Hayashi line, radius increases and mass decreases; surface gravity drops and envelope becomes less and less tightly bound
  - Final stages show superwind, with $\dot{M} \sim 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$; star has huge, optically thick, dusty envelope, which shows OH (hydroxyl) **maser emission**
  - Eventually, envelope expands so much it becomes optically thin; star moves blueward on HRD
  - During this movement, envelope is finally ejected, leaving behind degenerate CO core with thin surface layer of H/He; star now appears very hot ($\log T_{\mathrm{eff}} \approx 5$)
  - Shell burning stops, and luminosity begins to drop; star starts to cool toward becoming **white dwarf**

- Planetary Nebulae
  - Ejected envelope material is illuminated from within by very hot central star, with strong UV radiation field
  - UV radiation ioinizes ejecta; as ions recombine, produce emission lines at specific frequencies