Single star evolution continued…

Complications on the Asymptotic Giant Branch

A more detailed look at some of them.

**Mass Loss:**

The large amplitude of AGB pulsations changes the structure of the outer atmospheres. Momentum input from the pulsations drives strong stellar winds (e.g., > 10^{-8} M_{\text{sun}}/yr).

The low temperatures in the coolest pulsation phases allow the formation and growth of small dust grains. Radiation pressure on these grains drives them out like solar sails. Since they are still coupled to the gas, so an even stronger wind blows.

Molecules like H$_2$O with broad absorption bands can also contribute even more radiation pressure driving. Winds of steam!
Pulsationally driven winds.

Fig. 2—Radius vs. time for selected Lagrangian zones: standard model, fundamental period, piston velocity amplitude $= 3$ km s$^{-1}$. No dust is included, so the mass-loss rate is very small ($\dot{M} = 1.3 \times 10^{-7} M_\odot$ yr$^{-1}$) and motion is almost periodic. The innermost zone plotted is the photosphere.
**Dusty winds**

![Graph showing dusty winds](image)

**FIG. 3.—** Same as Fig. 2 except that radiation pressure on dust is included, so the mass-loss rate is substantial ($m = 1.6 \times 10^{-7} M_\odot \text{ yr}^{-1}$), with rapid expansion outside the shock-formation region and a wind developing in the outer atmosphere. (Model rezoned each cycle at phase 0.0 by subdivision of existing zones in rapidly expanding regions. Some of the newly created zone boundaries are shown here.)
Fig. 7.—Same as Fig. 6 except that the model was driven at the first overtone period with piston velocity amplitude = 1.5 km s$^{-1}$.
Mass Loss Runaway - the cliff

Figure 2. The direction of evolution of mass-losing AGB stars, computed with the Bowen dynamical atmosphere code for a grid of 90 fundamental-mode models having solar composition. The basic stellar parameters are consistent with the Ostlie & Cox (1986) period-mass-radius (PMR) relation and with the Iben (1984) radius-luminosity-mass (RLM) relationship, using (L/L⊙) = 0.90. (The pulsation period increases from left to right in a series of models at a given mass, in most cases ranging from 200 to 500 or 600 days.) The Paczynski (1970) core mass-luminosity relationship is shown by the lower curve.
**Planetary nebulae**

The runaway mass loss drives off the stellar envelope, and leaves behind the stellar core, which quickly evolves to become a white dwarf star. The process may produce a planetary nebula, like the classic Ring nebula (M57).
On the other hand, most planetary nebulae are not so symmetric, so something else may be going on.

The Eskimo

Cat’s Eye

NGC 2440 (all images from APOD).

It is believed that many of these morphologies result from the interaction of a binary companion with the late wind.
And then there’s the Helix!

**Dust and the Helix Nebula**

Credit: NASA, JPL-Caltech, Kate Su (Steward Obs, U. Arizona) et al.

**Explanation:** Dust makes this cosmic eye look red. The eerie Spitzer Space Telescope image shows infrared radiation from the well-studied Helix Nebula (NGC 7293) a mere 700 light-years away in the constellation Aquarius. The two light-year diameter shroud of dust and gas around a central white dwarf has long been considered an excellent example of a planetary nebula, representing the final stages in the evolution of a sun-like star. But the Spitzer data show the nebula's central star itself is immersed in a surprisingly bright infrared glow. Models suggest the glow is produced by a dust debris disk. Even though the nebular material was ejected from the star many thousands of years ago, the close-in dust could be generated by collisions in a reservoir of objects analogous to our own solar system's Kuiper Belt or cometary Oort cloud. Formed in the distant planetary system, the comet-like bodies have otherwise survived even the dramatic late stages of the star's evolution.
More AGB Complications

Thermal pulses and relaxation oscillations

In AGB large, impulsive mass loss events occur on a much longer timescale. These pulses are thought to result from thermal relaxation oscillations, see e.g., Iben (1987) in “Late Stages of Stellar Evolution.”

The oscillatory cycle has 4 stages:

1) **Quiescent H shell burning.**

   As $M_{\text{core}}/M_{\text{sun}}$ varies from 0.6 - 1.0
   
   the timescale of this phase varies from $10^3$ - $2 \times 10^5$ yrs
   
   $\Delta M_{\text{H}}/M_{\text{sun}}$ varies from $10^{-4}$ - $10^{-2}$

2) **He-shell flash**

   During phase 1) He ash builds up on the core until a critical value is reached.

   Then the flash begins.
Most of the flash energy goes to PdV work on the burning layer. H shell burning is turned off by the expansion. The whole region between the flash shell and the H-He discontinuity goes convective.

Essentially all C$^{12}$, O$^{16}$ passing through the H-shell is converted to N$^{14}$ during the convective phase, then,

\[
\text{N}^{14} \rightarrow \text{Ne}^{22} \rightarrow \text{Mg}^{25} + n, \quad \text{which results in crucial “S - processing.”}
\]

3) **Relaxation and dredge-up**

Convection briefly reaches into the He-burning zone and dredges up CNO, etc.

4) **Quiescent He shell burning**

A steady state is reached, with He burning until He used up in that zone, then H burning continues….
Brief Summary of Low-Mass Evolution

0) Pre-main sequence (discussed later).
   • Long main-sequence lifetime.
   • H-exhaustion & contraction.
   • H-shell burning &
   • Convective red giant envelope.
   • He flash.
   • Descent to HB.
   • He exhaustion & contraction.
   • He shell burning &
   • Ascent to AGB.
      ???….mass loss, thermal pulses runaway ML…???

10) Planetary nebula + white dwarf.

Schematics not to scale.