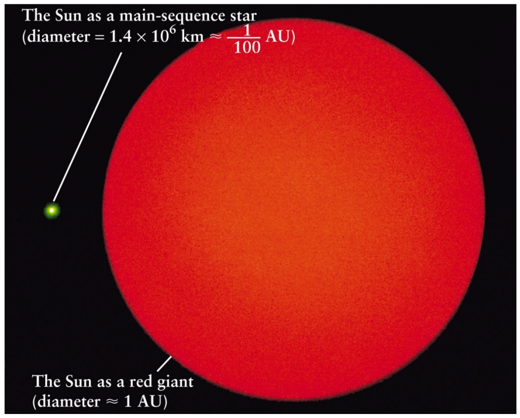
Evolution Beyond the Red Giants



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Pressure vs Gravity

The evolution of a star is shaped by the balance of **pressure** and **gravity**. When these two forces are in balance, a star is stable.

As a star consumes its supply of hydrogen and evolves away from the Main Sequence, these two forces get out of balance. The star changes the way it generates energy, and related changes in its size and internal structure are required to achieve a new equilibrium.

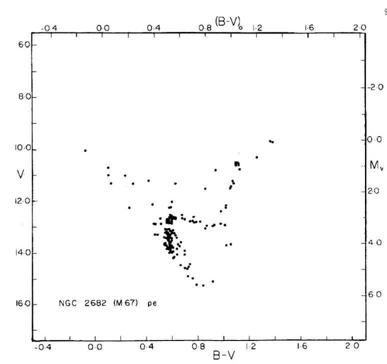
Its ultimate fate depends on its initial mass.

Red Giant Phase

After the He flash, the core contains an ordinary, nondegenerate He plasma, which is stably fusing He into C.

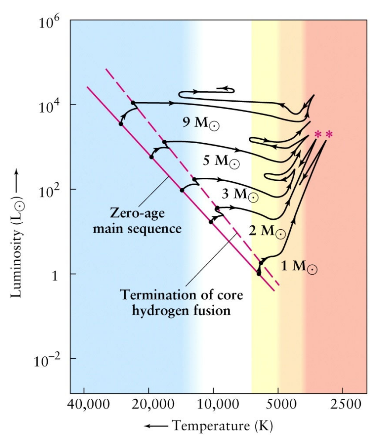
Surrounding this core is a H-burning shell, whose strength depends on the mass of the overlying envelope.

This is the **Red Giant Phase.**



Atlas of Open Cluster CM Diagrams, Hagen

Evolutionary Tracks



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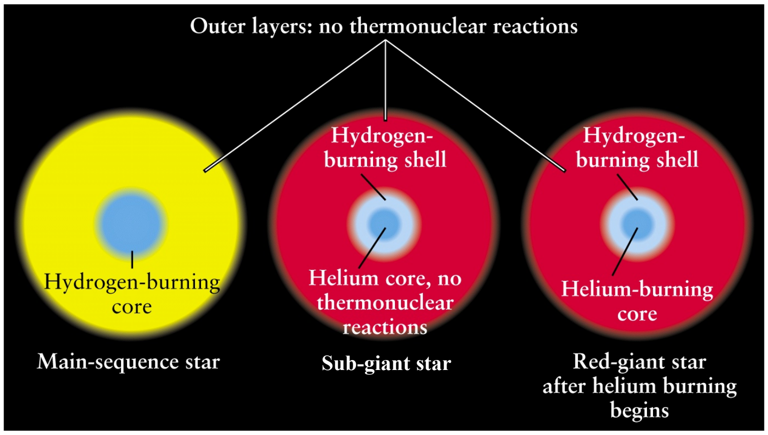
Interior Changes



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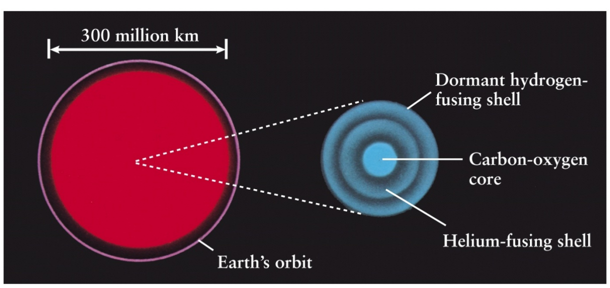
Post-Helium Burning



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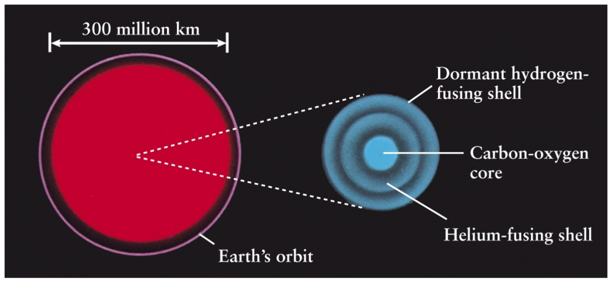
What happens when there is a new core of non-burning C and O?

1. The core must contract, which increases the pressure and temperature of the overlying layers.

Post-Helium Burning



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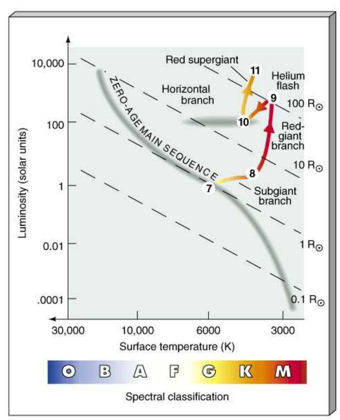
2. Thus, He fuses in a shell just outside the core, and H burns in a shell just outside of that. The star is now in a double-shell-burning stage. The mass of the inert CO core continues to increase, and it continues to contract just as the He core did when the star first left the main sequence.

Asymptotic Giant Branch

3. The energy generation in the two shell sources must proceed at an ever-increasing pace just as before, and the rapidly increasing luminosity must distend the overlying envelope just as before.

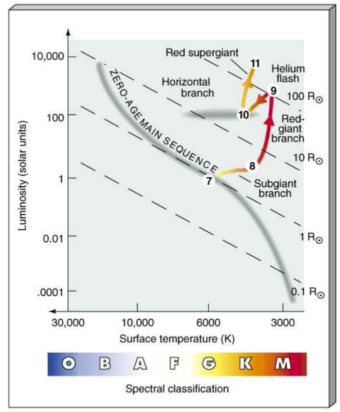
4. Thus, the star must ascend the Red Giant Branch again, and the double-shell source phase is known as the **Asymptotic Giant Branch (AGB)**.



Astronomy Today, Chaisson and McMillan

Asymptotic Giant Branch

5. Eventually, the shrinkage of the core again causes the free electrons to become degenerate. Now the mass of the degenerate CO core is larger than before because of the additional "ash", and the radius is smaller than its He counterpart at the tip of the red giant branch. Thus, the gravity of any overlying shell sources would be correspondingly larger, forcing them to generate higher luminosities. Stars at the end of the AGB phase may become **Red Supergiants**.



Astronomy Today, Chaisson and McMillan

Asymptotic Giant Branch

6. What happens to stars at these very late stages of stellar evolution is theoretically quite uncertain. One model indicates the onset of

"Thermal Relaxation Oscillations"

when the He-shell source becomes spatially very thin.

The origin of this instability is very different from the "He flash". Here, an initial over-production of nuclear energy also leads to a thermal run-away, but for an entirely different reason. The nuclear burning region is nondegenerate, but it is a spatially thin shell.

Asymptotic Giant Branch

With the input of excess nuclear energy, the **thin He shell** can and will expand. But the expansion of a thin shell does little to push up the weight of the overlying material; this material is lifted only a little.

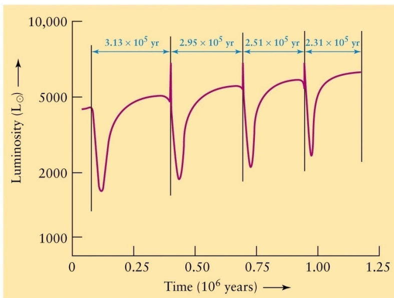
Thus, the weight hardly changes, and therefore the pressure that the thin shell has to maintain to offset this weight also hardly changes.

Asymptotic Giant Branch

Meanwhile, the **temperature** has increased, so the triple-alpha reaction rate increases further before the excess heat has a chance to diffuse away.

Thus, a **thermal runaway** ensues. The runaway is checked only after the thin shell has expanded by a great amount and after convection begins and manages to carry away the excess heat.

Asymptotic Giant Branch



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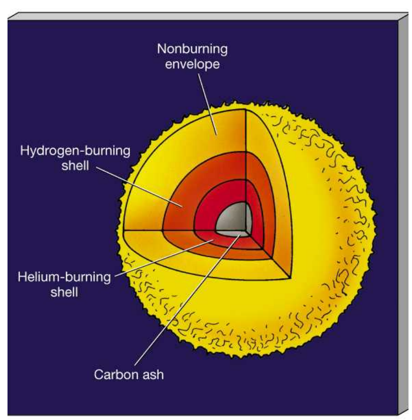
But the basic problem remains. After the runaway is checked, and when the star tries to adopt the "natural" double-shell-burning configuration appropriate for this stage of its evolution (i.e., when it tries to "relax" back to the "natural" stage of equilibrium), it finds itself in the same difficulty.

Thus, the star undergoes a series of "**thermal relaxation oscillations**," which consist of one or more sharp pulses of extra energy generation followed by relatively long periods of quiet evolution.

Post-Helium Burning

7. In stars with masses similar to that of the Sun, the formation of a Carbon-Oxygen core signals the end of the generation of nuclear energy at the star's center. **These stars cannot make the CO core hot enough to fuse.**

[*However, higher mass stars can build up many layers of heavy elements that are fusing to form still heavier nuclei.*]



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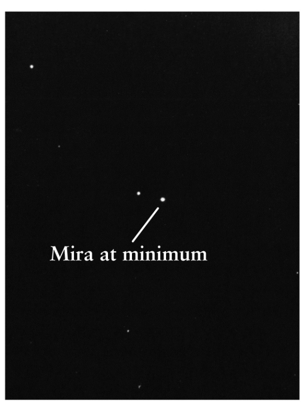
Final Phases

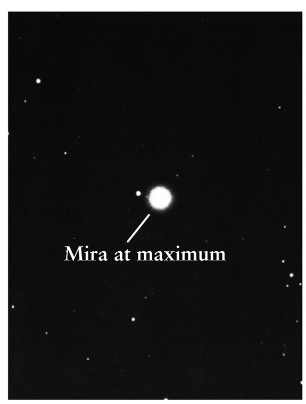
The death of the star is close at hand.

But first, most stars will experience at least one phase of pulsational instability accompanied by a change in luminosity.

These are Variable Stars.

Pulsating (Variable) Stars





Observations of Pulsating Stars

The light curves of pulsating stars exhibit continual changes in brightness. The temperature range can cover an entire spectral class.

In the spectra it is seen that the lines cyclically change back and forth in wavelength; hence, the radial velocity indicates the surface is moving.

This is how we observe that a star is pulsating: that is, expanding and contracting.

A Pulsation Mechanism

A star pulsates because *a layer* **in the Envelope** is not in **hydrostatic equilibrium**. Gravity on the outer mass of the star is not balanced by the interior pressure. **Pulsation mechanisms occur in the outer envelope – not in the core and shells.**

If a star expands as a result of increased pressure, the density (and pressure) decreases until the point of hydrostatic equilibrium is reached. But because of the momentum of the layers, an **overshot** occurs.

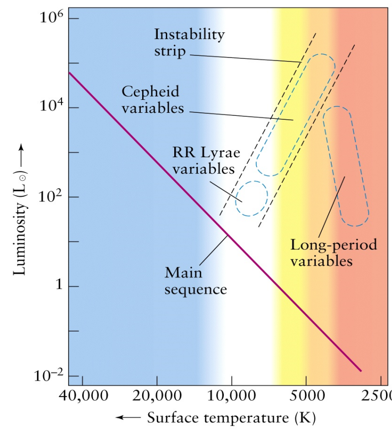
Now gravity dominates, and the star begins to contract. Again, the momentum of the in-falling material causes the contraction to go beyond the equilibrium point. Now the pressure is too high, and the cycle starts over.

Instability Strips

Why do some stars pulsate?

The structure of any star is determined in large part by how easily radiation can travel from the core to the photosphere.

That is, by the opacity – the degree to which the gas hinders the passage of light through it.



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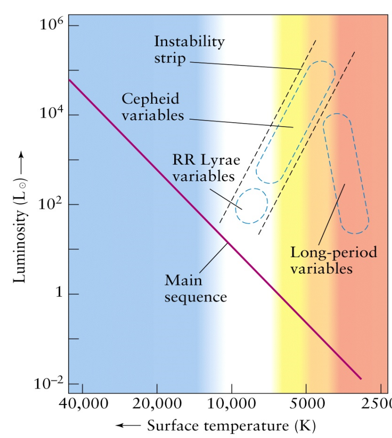
Instability Strips

If the stellar atmosphere is transparent, radiation flows freely and the star is bright. If the opacity is **high**, then the radiation is prevented from escaping and the star is faint.

If the star is compressed at the time of greatest opacity, the excess radiation is bottled up and exerts pressure on the outer layers.



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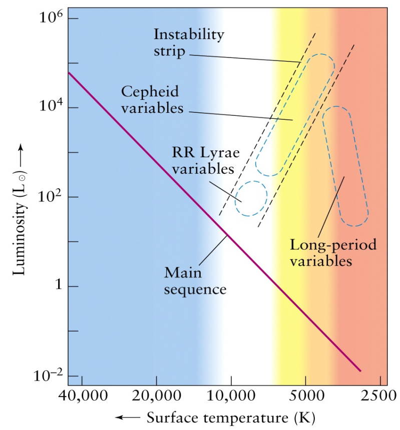
Instability Strips

When the opacity rises, the radiation becomes trapped, the internal pressure increases, and this causes the star's envelope to expand.

When the opacity falls, radiation can escape more easily, and then the star shrinks.

Under certain circumstances a star can become unbalanced.



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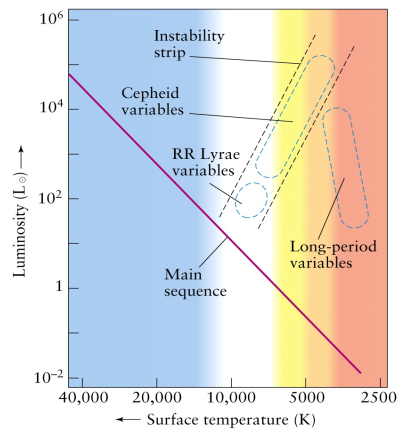
Instability Strips

The atmospheres of pulsating stars have a zone in which the opacity increases: **singly-ionized Helium** absorbs UV light to become doubly ionized.

The He^+ ionization region is cooler than the surrounding layers because energy normally used to heat the gas is used to ionize it.

The He ionization zone contributes to the instability of the stellar atmosphere and so perpetuates the pulsations.



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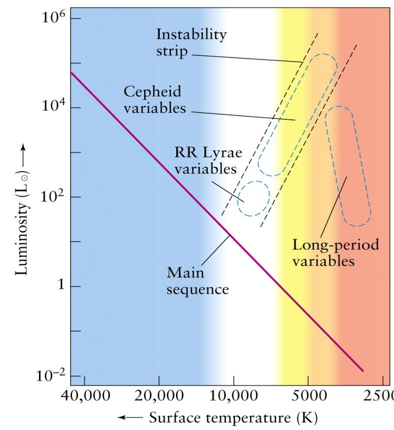
Instability Strips

Pulsating stars occupy well-defined areas of the HR Diagram. This is explained by the depth of the He^+ ionization zone. This depth depends on the structure of the star, which in turn is a function of the star's stage of development.

When the He^+ ionization zone lies too deep in the star, the valve action is insufficient to overcome damping. When the zone is shallow, the damming action is inefficient and pulsations do not start.



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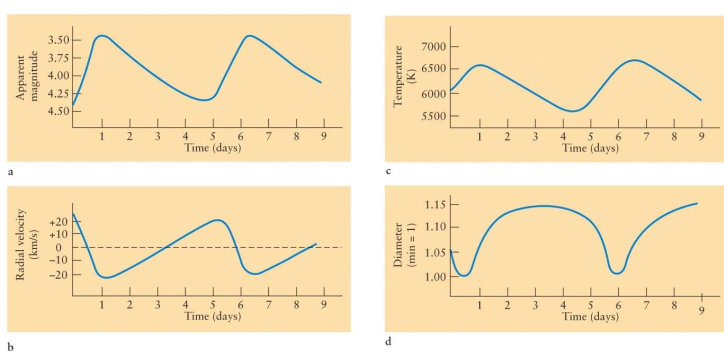
The Cepheid Variable Stars

These yellow supergiants have periods in the range of 3 to 50 days and absolute magnitudes (at median light) from -1.5 to -5.0 magnitudes. The amplitudes range from 0.1 to 2 mags. More than 700 are known.



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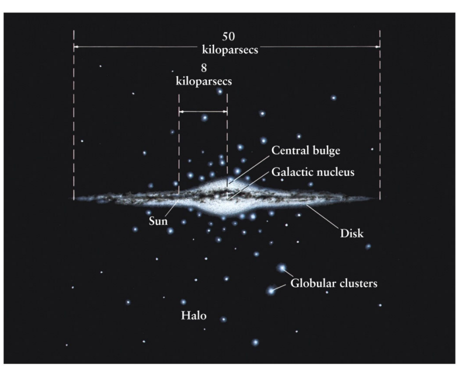
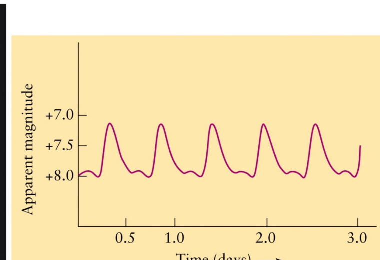
Period-Luminosity Relation

Henrietta Leavitt analyzed 25 stars in the Magellanic Clouds, so these stars are the same distance from us. When we find new Cepheids in clusters or galaxies, after determining the period and amplitude, we can get a distance.

The RR Lyrae Variable Stars

These giants are found in globular clusters and in the Milky Way's halo. Observed periods range from about 0.5 to 1.0 days.





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Final Phases

After the post-AGB phase, the death of the star is close at hand.

Function of Mass
(For stars < ~ 4 solar masses)

1. Lowest mass stars will never have sufficient pressure and temperature for the electron-degenerate He core to begin fusion.

2. Intermediate mass stars will never have sufficient pressure and temperature for the electron-degenerate CO core to begin fusion.

3. **Highest mass** stars might ignite the electron-degenerate **CO** core, but the current models have difficulties.

Final Phases

Low- and Intermediate-mass stars experience a phase of stellar winds and excess **mass loss**, which culminates with the production of a

"Planetary Nebula".

The non-burning, electron-degenerate CO (or He) core is now exposed. This object is a **White Dwarf**.

But first, Planetary Nebulae …