The stars

The actual process of *star formation* remains shrouded in mystery because stars form in dense, cold molecular clouds whose dust obscures newly formed stars from our view. For reasons which are not fully understood, but which may have to do with collisions of molecular clouds, or shockwaves passing through molecular clouds as the clouds pass through spiral structure in galaxies, or magnetic-gravitational instabilities (or, perhaps all of the above) the dense core of a molecular cloud begins to condense under its self-gravity, fragmenting into stellar mass clouds which continue to condense forming *protostars*. As the cloud condenses, gravitational potential energy is released - half of this released gravitational energy goes into heating the cloud, half is radiated away as thermal radiation. Because gravity is stronger near the center of the cloud (remember $F_g \sim 1/\text{distance}^2$) the center condenses more quickly, more energy is released in the center of the cloud, and the center becomes hotter than the outer regions. As a means of tracking the stellar life-cycle we follow its path on the Hertzsprung-Russell Diagram.

1. Protostar

The initial collapse occurs quickly, over a period of a few years. As the star heats up, pressure builds up following the Perfect Gas Law:

$$PV = NRT$$

where, most importantly P=pressure and T=Temperature. The outward pressure nearly balances the inward gravitational pull, a condition called *hydrostatic equilibrium*.

- **Age: 1--3 yrs**
- **$R \sim 50\ R_{sun}$**
- **$T_{core} = 150{,}000K$**
- **$T_{surface} = 3500K$**
- **Energy Source: *Gravity***

The star is cool, so its color is red, but it is very large so it has a high luminosity and appears at the upper right in the H-R Diagram.

2. Pre-Main Sequence

Once near-equilibrium has been established, the contraction slows down, but the star continues to radiate energy (light) and thus must continue to contract to provide gravitational energy to supply the necessary luminosity. The star must continue to contract until the temperatures in the core reach high enough values that nuclear fusion reactions begin. Once nuclear reactions begin in the core, the star readjusts to account for this new energy source Gravity releases its potential energy throughout the star, but due to the very high temperature dependence of the nuclear fusion reactions, the proton-proton chain is highly centrally concentrated. During this phase the star lies above the main sequence; such pre-main sequence stars are observed as T-Tauri Stars, which are going through a phase of high activity. Material is still falling inward onto the star, but the star is also spewing material outward in strong winds or jets as shown in the HST Photo below.

- **Age: 10 million yrs**
- **$R \sim 1.33\ R_{sun}$**
- **$T_{core} = 10{,}000{,}000K$**

- $T_{surface}$ = 4500K
- **Energy Source:** ***P-P Chain*** **turns on.**

3. Zero Age Main Sequence

It takes another several million years for the star to settle down on the main sequence. The main sequence is not a line, but a band in the H-R Diagram. Stars start out at the lower boundary, called the *Zero-Age Main Sequence* referring to the fact that stars in this location have just begun their main sequence phases. Because the transmutation of Hydrogen into Helium is the most efficient of the nuclear burning stages, the main sequence phase is the longest phase of a star's life, about 10 billion yrs for a star with 1 solar mass.

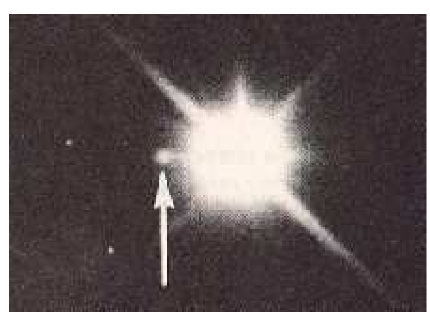
- **Age:** **27 million yrs**
- $R \sim R_{sun}$
- T_{core} = 15,000,000K
- $T_{surface}$ = 6000K
- **Energy Source:** ***P-P Chain*** **in core.**

During the main sequence phase there is a "feedback" process that regulates the energy production in the core and maintains the star's stability. The basic physical principles are:

- **The thermal radiation law, $L \sim R^2T^4$, determines the energy output, which fixes requirement for nuclear energy production.**
- **The nuclear reaction rates are very strong functions of the central temperature; Reaction Rate ~ T^4 for the P-P Chain.**
- **The inward pull of gravity is balanced by the gas pressure which is determined by the Ideal Gas Law: PV=NRT.**

A good way to see the stability of this equilibrium is to consider what happens if we depart in small ways from equilibrium: Suppose that the amount of energy produced by nuclear reactions in the core is not sufficient to match the energy radiated away at the surface. The star will then lose energy; this can only be replenished from the star's supply of gravitational energy, thus the star will contract a bit. As the core contracts it heats up a bit, the pressure increases, and the nuclear energy generation rate increases until it matches the energy required by the luminosity.
Similarly, if the star overproduces energy in the core the excess energy will heat the core, increasing the pressure and allowing the star to do work against gravity. The core will expand and cool a bit and the nuclear energy generation rate will decrease until it once again balances the luminosity requirement of the star.

4. End of Main Sequence



- **Age:** **10 billion yrs**
- **Energy Source:** ***P-P Chain*** **in shell around core.**

5. Post Main Sequence

- **Age:** **About 1 billion years from Point 4**
- $R \sim 2.6R_{sun}$
- $T_{surface}$ = 4500K

- **Energy Source:** ***P-P Chain*** **in shell,**
  Gravitational contraction of core.

6. Red Giant - Helium Flash

As the Helium core of the star contracts, nuclear reactions continue in a shell surrounding the core. Initially the temperature in the core is too low for fusion of helium, but the core-contraction liberates gravitational energy causing the helium core and surrounding hydrogen-burning shell to increase in temperature, which, in turn, causes an increase in the rate of nuclear reactions in the shell. In this instance, the nuclear reactions are producing more than enough energy to satisfy the luminous energy output. This extra energy output pushes the stellar envelope outward, against the pull of gravity, causing the outer atmosphere to grow by as much as a factor of 200. The star is now cool, but very luminous - a *Red Giant.*

(You do the arithmetic: 200 x 700,000km = ?; where will the outer radius of the sun be?)

- **Age: 100 million yrs from Point 5**
- **$R \sim 200R_{sun}$**
- **$T_{core} = 200{,}000{,}000K$**
- **$T_{surface} = 3500K$**
- **Energy Source:** ***P-P Chain*** **in shell around core;**
  Ignition of Triple-Alpha Process.

The contraction of the core causes the temperature and density to increase such that, by the time the temperature is high enough for Helium nuclei to overcome the repulsive electrical barrier and fuse to form Carbon, the core of the star has reached a state of *electron degeneracy*. Degeneracy comes about due to the *Pauli Exclusion Principle*, which prohibits electrons from occupying identical energy states. The core of the Red Giant is so dense that all available lower energy states are filled up. Because only high-energy states are available, the core resists further compression -- there is a pressure due to the electron degeneracy. This pressure has a significant difference from pressure produced by the Ideal Gas Law -- it is independent of temperature. This removes a key element in the feedback-stability mechanism that regulates hydrogen burning on the main sequence.

H-R Diagram from Helium Burning to White Dwarf.

7. Helium Burning Main Sequence

Once again the core of the star readjusts to allow for a new source of energy, in this case fusion of Helium to form Carbon via the Triple-Alpha Process. The Triple alpha process releases only about 20% as much energy as hydrogen burning, so the lifetime on the Helium Burning Main Sequence is only about 2 billion years.

- **Age: About 10,000 yrs from point 6.**
- **$T_{surface} = 9000K$**
- **$T_{core} = 200{,}000{,}000K$**
- **Energy Source:** ***Triple-alpha process*** **in core;**
  P-P Chain **in shell**

During this phase some Carbon and Helium will fuse

$$^{12}C + {}^{4}He \rightarrow {}^{16}O$$

resulting in the formation of a Carbon-Oxygen core. When the Helium is exhausted in the core of a star like the sun, no further reactions are possible. Helium burning may occur in a shell surrounding thecore for a brief period, but the lifetime of the star is essentially over.

8. Planetary Nebula

When the helium is exhausted in the core of a star like the sun, the C-O core will begin to contract again. Central temperatures will never reach high enough values for Carbon or Oxygen burning, but the Helium and Hydrogen burning shells will conyinue burning for a while. Throughout the star's lifetime it is losing mass via a stellar wind, like the solar wind. This mass loss increases when the star swells up to the size and low gravity of a Red Giant. During Helium Burning, thermal pulses, caused by the extreme temperature sensitivity of the 3-alpha Process, can cause large increases in luminosity with accompanying mass ejection. During Helium Shell Burning, a final thermal pulse produces a giant "hiccough" causing the star to eject as much of 10% of its mass, the entire outer envelope, revealing the hot inner regions with temperatures in excess 100,000K, shown in this animation of the Helix**, below. The resulting** Planetary Nebuala **is the interaction of the newly ejected shell of gas with the more slowly moving ejecta from previous events and the ultraviolet light from the hot stellar remnant, which heats the gas and causes it to fluoresce. The Ring Nebula in Lyra (**Messier Database**,** Web Nebulae**) shown below is**

HST images of Planetary Nebulae: The Ring Nebula and the young Planetary Nebula known as MyCn18, the Hourglass Nebula.

- **More about Planetary Nebulare from George Jacoby's (b& w) Planetary Nebula Gallery.**
- **Planetary Nebulae at the SED's Messier Gallery.**
- **The Planetary Nebula Observer's HomePage includes more links to Planetary Nebula Resources.**
- **Univ. of Calgary Planetray Nebula Homepage with theoretical models of PN emission structure.**
- **Bruce Balick's HST Images of Planetary Nebulae.**

9. White Dwarf

As the nebula disperses, the shell nuclear reactions die out leaving the stellar remnant, supported by electron degeneracy, to fade away as it cools down. The white dwarf is small, about the size of the earth, with a density of order 1 million g/cm^3, about equivalent to crushing a volkswagen down to a cubic centimeter or a "ton per teaspoonful."

- **$R \sim R_{earth}$ (a few thousand km)**
- **$T_{surface}$ = 30000K - 5000K**
- **Energy Source: *"Cooling Off".***

A white dwarf star will take billions of years to radiate away its store of thermal energy because of its small surface area. The white dwarf will slowly move down and to the right in the H-R Diagram as it cools until it fades from view as a "black dwarf". To the right is the white dwarf companion to the nearby star Sirius.

- **Astronomy Picures of the Day of White Dwarfs and Planetary Nebulae**

Report

on the theme:

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