Chapter 14

Stellar Evolution I

I. Introduction

Stars evolve in the sense that they pass through different stages of a stellar life cycle that is measured in billions of years. The longer the amount of time a star spends in a particular stage of evolution, the greater the number of stars that one observes in that stage.

Stars evolve at different rates and they pass through different sequences of evolutionary stages, depending on their mass. **In general, the greater the mass of a star, the faster it evolves.** For example, red dwarf stars may spend more than a hundred billion years as a main sequence star, whereas the much more massive stars, which are at the top of the main sequence, spend only a few million years as a main sequence star. Stars with a mass similar to that of the Sun have a main sequence lifetime of about 10 billion years.

Objects with a mass less than about 0.06 solar mass units **(**the **Kumar Limit)** never initiate TNF of any significant amount, and never become true stars. These objects are called **Brown Dwarfs.** Since brown dwarfs are intrinsically faint objects it is difficult to detect them at great distances. However, several nearby ones have been detected recently, so there existence has been verified.

Brown dwarfs, like ordinary stars, are comprised mostly of hydrogen and helium, whereas terrestrial-like planets are comprised mostly of metals and silicates (rocks). Jupiter Saturn Uranus and Neptune are comprised mostly of hydrogen and helium just like stars and brown dwarfs. The IAU has established a lower limit of 17 Jupiter masses to qualify as a brown dwarf. Such an object could not even initiate deuterium fusion, whereas a brown dwarf could.

The exact sequence of evolutionary stages also depends on the mass of a star.

14-2. The Russell-Vogt Theorem

The structure of a star is uniquely determined by its mass and molecular weight *vis-à-vis* the law of gravity and the laws of thermodynamics. This is the Russell-Vogt Theorem. Therefore, stars with the same molecular weight but different mass will define a locus in a temperature-luminosity diagram, that is, the ZAMS. As the average molecular weight changes due to TNF, the evolution of the star proceeds, the rate being determined by the mass via gravity.

Gravity is a force of attraction on every little parcel of the star acting as if all the mass of the star were a point at the very center of the star. This force acts to contract and compress the star. The greater the mass of a star, the stronger gravity is and the greater the compression of the star. The greater the compression of the star, the higher the temperature becomes. The higher the temperature is, the greater the gas pressure. The gas pressure produces a force that is trying to expand the star and balance gravity. Also, he higher the temperature, the faster the TNF reactions take place. The faster the TNF reactions take place, the faster the star evolves.

Hence, stellar evolution is the result of the interplay between gravity and gas pressure.

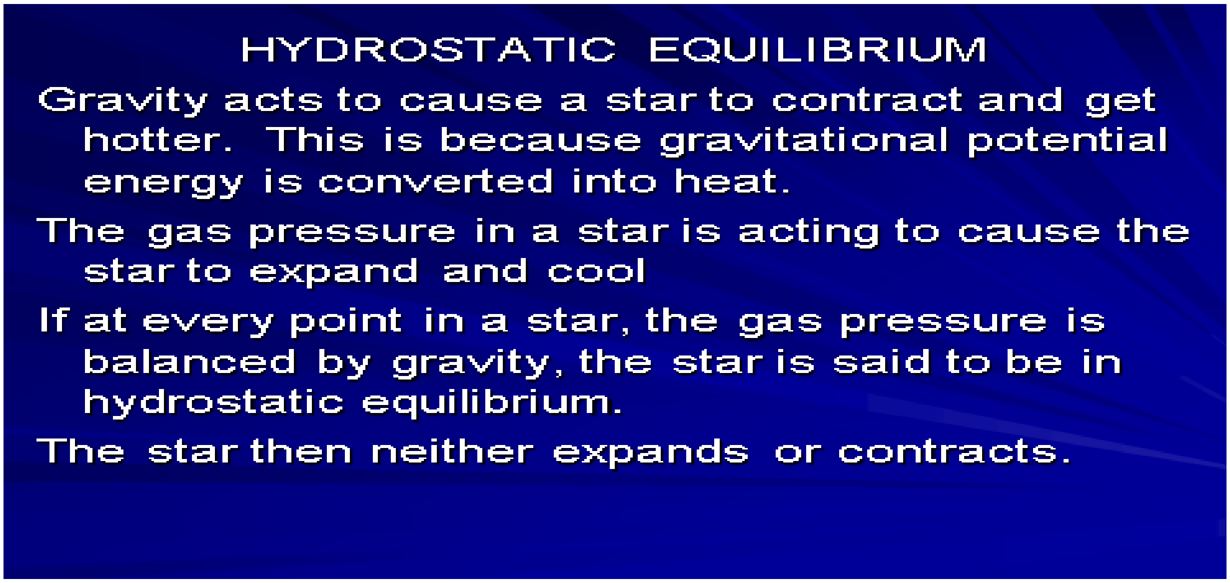
14-3. Stellar Evolution in General

Gravitational contraction is what begins the formation of a star and its evolution. As a star contracts, the virial theorem says, that for a gravitationally bound system, half the change in potential energy goes into kinetic energy of motion of the particles (atoms, molecules, and dust). As the particles collide, this kinetic energy is randomized and becomes thermal energy, E_T, which may be associated with a kinetic temperature.

Conservation of energy demands that the other half of the potential energy becomes electromagnetic energy or radiation, E_R.

$$\Delta GPE \rightarrow ½E_T + ½E_R$$

Since energy is being lost through radiation, the gas pressure can never keep up with gravity to bring about hydrostatic equilibrium. At best, the star is in a state of quasi-hydrostatic equilibrium. So the star can not stop contracting if it depends totally on its gravitational potential energy to produce its gas pressure. This assumes that the gas is infinitely compressible, such as an ideal gas, and that there is no change in phase. However, ionization and nuclear forces eventually come into play to change matters.



HYDROSTATIC EQUILIBRIUM

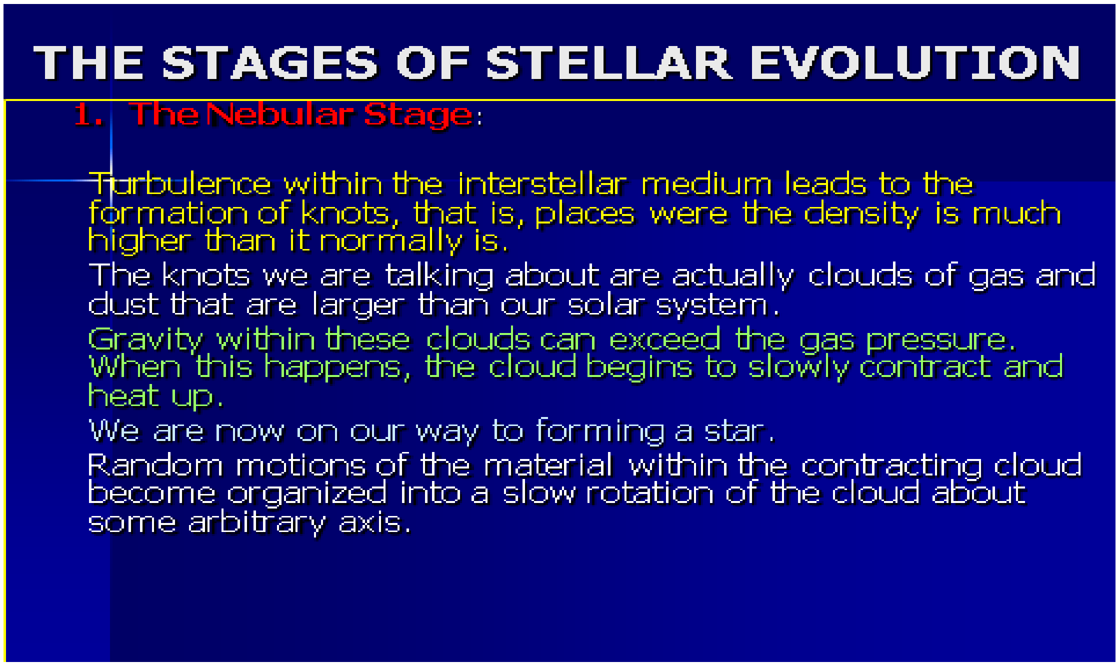
Gravity acts to cause a star to contract and get hotter. This is because gravitational potential energy is converted into heat.

The gas pressure in a star is acting to cause the star to expand and cool

If at every point in a star, the gas pressure is balanced by gravity, the star is said to be in hydrostatic equilibrium.

The star then neither expands or contracts.

14-3



THE STAGES OF STELLAR EVOLUTION

1. The Nebular Stage:

Turbulence within the interstellar medium leads to the formation of knots, that is, places were the density is much higher than it normally is.

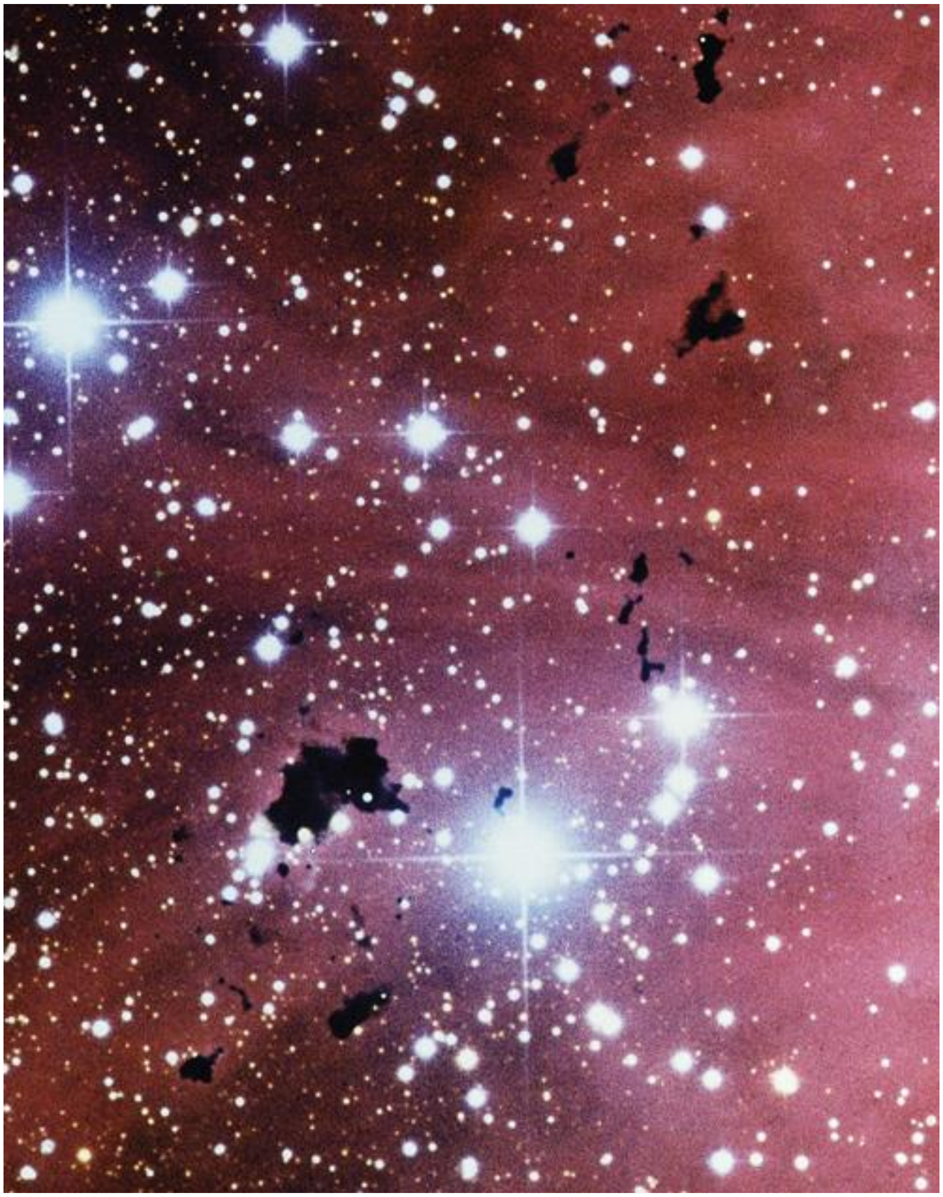
The knots we are talking about are actually clouds of gas and dust that are larger than our solar system.

Gravity within these clouds can exceed the gas pressure. When this happens, the cloud begins to slowly contract and heat up.

We are now on our way to forming a star.

Random motions of the material within the contracting cloud become organized into a slow rotation of the cloud about some arbitrary axis.

In the photograph below, there are several small, dark, nearly spherically shaped clouds that are called “Dark Globules” or “Bok Globules.” These globules are believed to be insipient protostars.



2. ProtoStar Stage

Our cloud continues to contract, spin faster, and become more dense.

The highest density occurs in the central region of the cloud. The high density results in the central parts of the cloud to become opaque.

The higher opacity there causes radiation to be absorbed, which, in turn, causes the center to heat more rapidly than the outer parts of the cloud.

This central region is now a protostar with a photosphere and core.

Protostar Evolution

It has taken about a million years for our cloud to form a protostar.

Surrounding the protostar is a disk of gas and dust some of which continue to fall onto the surface of protostar. See the artist's sketch in panel (a) in the adjacent diagram, which goes with the actual photo in panel (d)

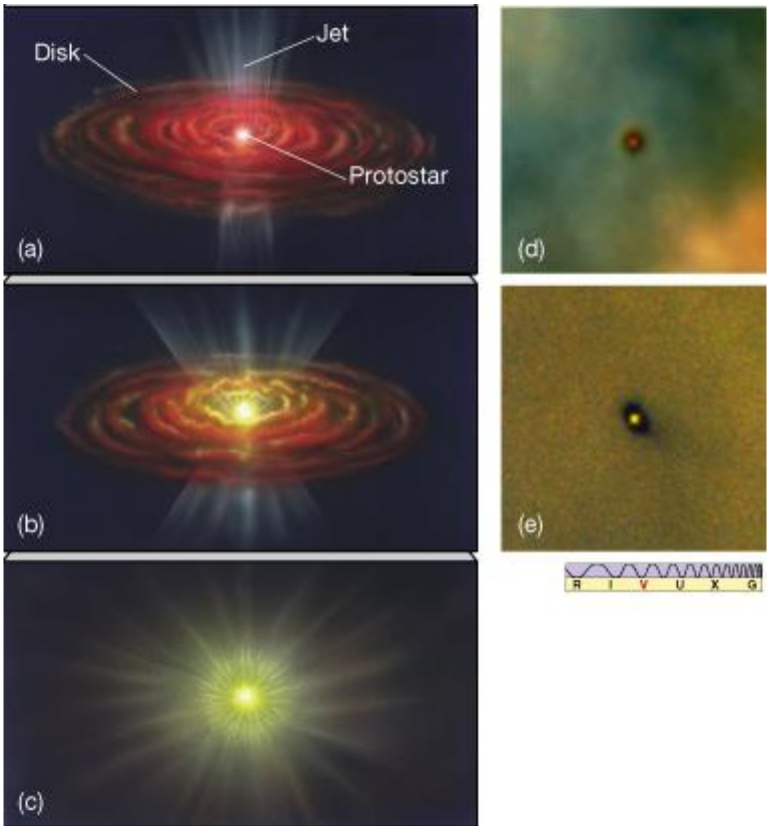
Hence, the mass of the protostar continues to grow.

Eventually planets may form from the left over material in the rapidly rotating disk.

Protostars continue to contract and get hotter

They convert gravitational potential energy into thermal energy (heat).

Some of the thermal energy is converted into EM radiation in accordance with the laws of radiation.



Most of the radiation is absorbed in the dust and gas surrounding the protostar.

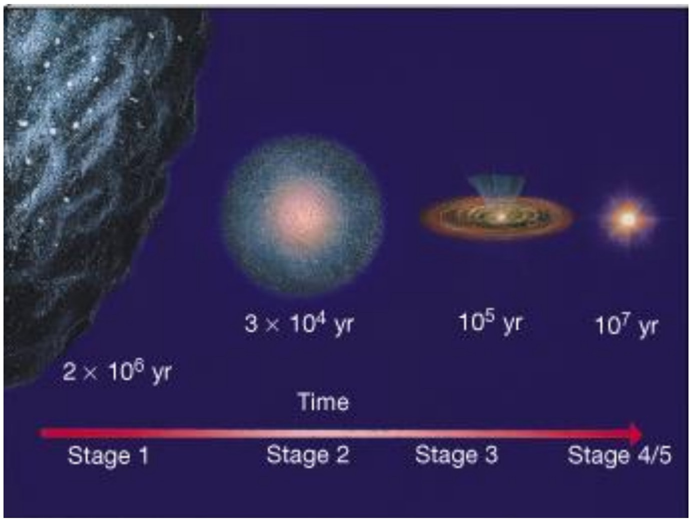
Eventually, the star gets so hot that its radiation ionizes the surround gases and vaporizes the dust. When this happens, surrounding material becomes transparent. The protostar then begins to shine much brighter than before. However it does so erratically, since clouds of gas and dust are still moving in orbit around the star. See panel (b) which goes with the photograph in panel (e). Panel (c) shows the protostar after much of the dust and gas has been used up to form planets or blown away.

It now a T Tauri star.

Such stars are said to be in a state of quasi-hydrostatic equilibrium, because they now contract very much slower. However, they cannot completely stop contracting. This is because they lose heat by radiation faster than they can generate by contracting.

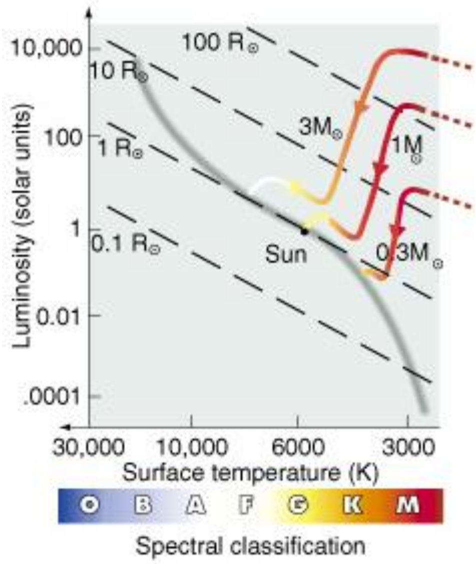
The star is now in a predicament. It seems to be destined to go on contracting and getting smaller and hotter forever!

However, something fantastic happens, when the central temperature of the star approaches 5 million K.



At this temperature, the atomic nuclei collide with one another with such high speeds that they get sufficiently close for the nuclear force to dominate over the repulsive electric force. Hence, thermonuclear fusion of hydrogen (protons) into helium nuclei begins.

The next diagram shows the protostar evolutionary tracks for several different initial masses.



3. Main Sequence Stage

A star enters this stage when it initiates TNF of hydrogen nuclei into helium nuclei in its core. This happens when the core of the star reaches about 5 million Kelvins. Main sequence stars are characterized by:

(1). TNF of H into He in the core of the star.
(2). Hydrostatic equilibrium: At every point in the star, gravity is balanced by gas pressure.

Hydrostatic equilibrium is achieved because the star does not radiate away its heat at the surface faster than it generates it by TNF.

Stars that are beginning the main sequence stage define in the H-R diagram what is called the Zero Age Main Sequence or ZAMS.

Main sequence lifetimes:
$15.0M_{\odot}$: 10 million years
$5.00M_{\odot}$: 65 million years
$2.25M_{\odot}$: 480 million years
$1.00\ M_{\odot}$: 7 - 9 billion years
$0.10\ M_{\odot}$: 100 billion year

Hydrogen fusion by the p-p chain (Chp. P5-7 in Z&G) occurs in main sequence stars with core temperatures less than 20 million K. For higher core temperatures, the carbon cycle dominates.

Carbon Cycle of H Fusion   Dominates for $T > 20 \times 10^6 K$

$${}_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13} + \gamma$$

$${}_7N^{13} \longrightarrow {}_6C^{13} + e^+ + \nu_0$$

$${}_6C^{13} + {}_1H^1 \longrightarrow {}_7N^{14} + \gamma$$

$${}_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15} + \gamma$$

$${}_8O^{15} \longrightarrow {}_7N^{15} + e^+ + \nu_0$$

$${}_7N^{15} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4$$

Triple α Reaction at $100 \times 10^6 K$

$${}_2He^4 + {}_2He^4 \rightleftarrows {}_4Be^8 + \gamma \quad \text{(unstable)} \ (1.59\ \text{Mev})$$

Before a Be^8 can decay it may be hit by an α-particle (a helium nucleus). Then

$$Be^8 + {}_2He^4 \longrightarrow {}_6C^{12} + \gamma \quad \text{(stable)}$$

Hence, 3 He nuclei fuse to form a carbon nucleus. This is the triple alpha fusion reaction.

Other possible reactions involving He nuclei are:

$${}_6C^{12} + {}_2He^4 \longrightarrow {}_8O^{16} + \gamma$$

$${}_8O^{16} + {}_2He^4 \longrightarrow {}_{10}Ne^{20}$$

$${}_{10}Ne^{20} + \alpha \longrightarrow {}_{12}Mg^{24}$$

$${}_{12}Mg^{24} + \alpha \longrightarrow {}_{14}Si^{28}$$

4. Shell-hydrogen “Burning” stage

Upon exhaustion of H in the core, the star begins to contract and get hotter. The star has now left the main sequence. Eventually TNF of H into He begins in a shell around the core. The energy released from this shell heats the outer layers of the star thereby causing these layers to greatly expand. The star then tracks to the right in the H-R Diagram, getting cooler and larger. Meanwhile, the He core continues to contract and get hotter.

5. Red Giant or Supergiant

The star now begins to expand enormously as the temperature in the core increases and provides more radiation to be absorbed by the envelope. Which it becomes depends on the mass of the star.

6. He Flash.

At 100 million Kelvins, He nuclei in the core collide an fuse to form C by what is known as the triple-alpha reaction. The onset of He fusion happens almost explosively, and the star undergoes a rapid change in its structure to enter a stage of hydrostatic equilibrium again as it undergoes helium fusion. The star then descends in the H-R Diagram to become a horizontal branch star.

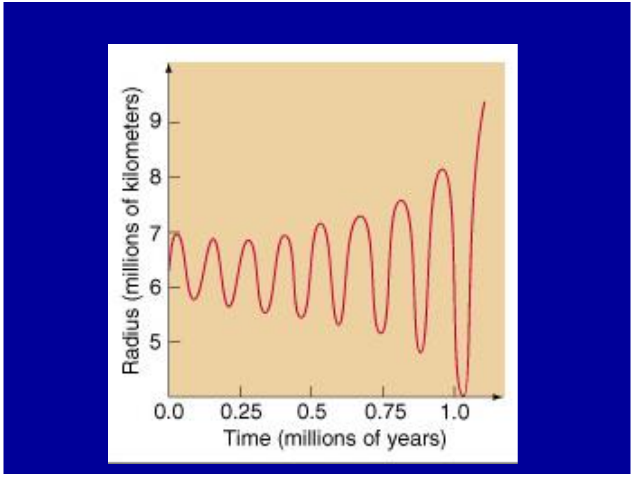
7. Horizontal Branch Stage

Which is also the stage of He fusion in the core with hydrostatic equilibrium again, similar to the main sequence stage. This is sometimes referred to as the helium main sequence stage. In addition to the production of C, the elements O, Ne, Mg, and Si are produced. See the previous page for a list of these reactions.

8. Asymptotic Giant Branch Stage

When all the He is exhausted in the core, the core begins to contract again until He fusion occurs in a shell around the core, while hydrogen fusion occurs in a layer above that. The star then expands to become even larger, while the core is contracting. The star is then said to ascend the asymptotic giant branch

In stars like the Sun, electron pressure will eventually halt further contraction of the star and it eventually enters the "Planetary Nebula Stage." This is a stage of instability due to He fusion in a shell around the carbon core. This instability causes the outer envelope to undergo pulsations of ever increasing amplitude until the outer layer is lost to the star’s gravity. The outwardly expanding envelope then forms a “planetary nebula." This term is an accident of history and has nothing to do with planets, but merely the telescopic appearance of the expand shell around the star.



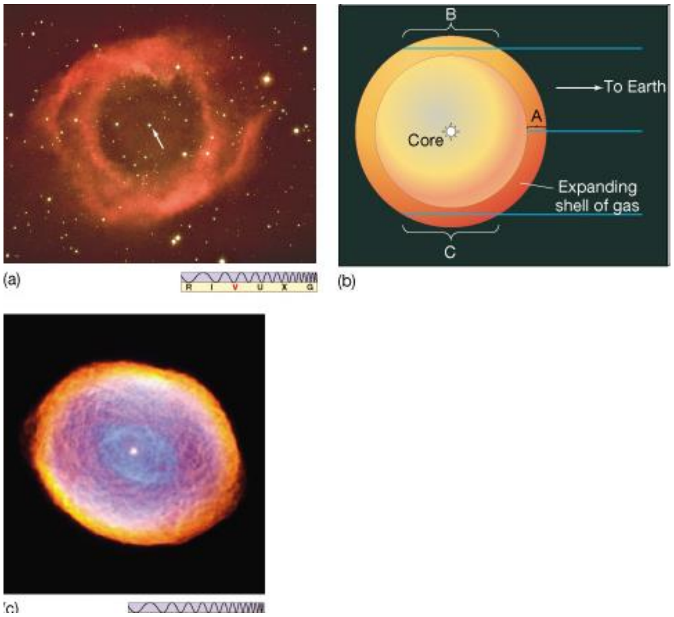
9. Core carbon “burning” Stage

When the core temperature reaches 600 million Kelvins, carbon nuclei begin to undergo fusion into Mg. The star then readjusts itself and hydrostatic equilibrium is established again but this does not last very long.

10. Other stages of TNF

The above scenarios repeat as the elements in the core are exhausted and the core contracts to a higher temperature and a new TNF reaction begins. This is the end though, since Fe will not undergo TNF. What happens to a star after developing and iron core will be taken up later.

The Planetary Nebula Stage



Other Reactions

At 600×10^6 K, TNF of C^{12} occurs

$$_6C^{12} + {}_6C^{12} \longrightarrow Mg^{24}$$

At 1×10^9 K, TNF of $_{12}Mg^{24}$ occurs

$$_{12}Mg^{24} + {}_{12}Mg^{24} \longrightarrow {}_{24}Cr^{48} \longrightarrow {}_{22}Ti^{48} + 2\beta^+$$

At $\sim 2 \times 10^9$ K TNF of $_8O^{16}$

$$_{32}O^{16} + O^{16} \longrightarrow S^{32},\ Si^{28} + \alpha,\ P^{31} + p^+,\ S^{31} + n^0, \text{ or } Mg^{24} + 2\alpha$$

At $3 - 5 \times 10^9$ K

$$_{14}Si^{28} + {}_{14}Si^{28} \longrightarrow {}_{28}Ni^{56} \longrightarrow {}_{26}Fe^{56} + 2\beta^+$$

14-5. Post Main Sequence Evolutionary Tracks

We now turn to looking at the post main sequence evolutionary tracks that have been computed by I. Iben. These are shown in the adjoining figure for several different masses. The figure and Table 1 are taken from The Annual Reviews of Astronomy and Astrophysics, **5**, 570 ff.

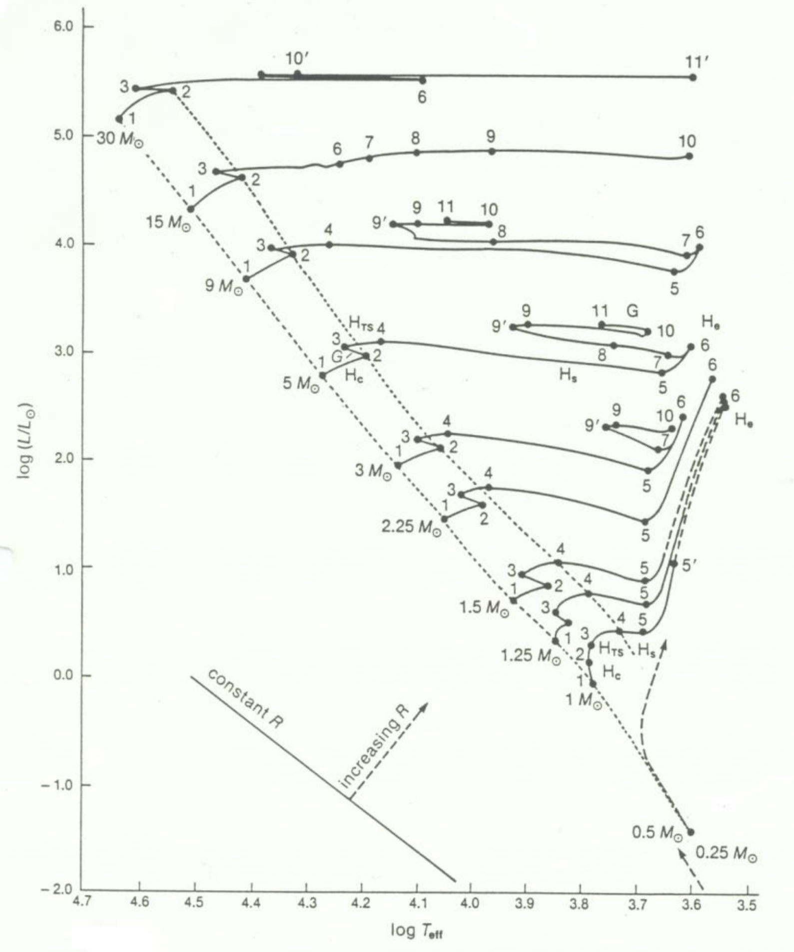


Figure 6-7. Evolutionary tracks for models of stars after the main sequence. Model mass is shown next to the initial point on zero age main sequence. Dotted lines indicate boundaries of the main sequence. Lines of constant radius and increasing radius as shown in lower left. Elapse times between points are shown in Table **3**. The stages are labeled as: H_c, hydrogen core burning; H_{TS}, thick hydrogen shell burning; H_s, shell hydrogen burning; He, helium core burning; and *G*, gravitational energy release. The 15 $M_☉$ track does not reverse in the giant region, because the semiconvective region was treated as fully convective in this model.

Table 1

Stages of evolution corresponding to the numbers on the evolutionary tracks in Fig. 6-7.

Point	Stage of Evolution
1	Zero Age Main Sequence
2 – 4	Evolution on the main sequence
4	End of main sequence stage
5	Shell hydrogen burning
5 – 6	Ascent of the giant branch
6	Helium flash
7 - 9’	Core He burning stage and hydrostatic equilibrium.
9	End of core He burning stage
9 – 10	Asymptotic giant branch stage, shell-helium burning.

The following table lists the various amounts of time that it takes a 20M$_☉$ star to go from one numbered point on the track to the next for the different masses.

Table 2

TNF time scales for the core of a $20M_\odot$ star:

Fuel	**Exhaustion Time (years)**
H	**7×10^6**
He	**0.5×10^6**
C	**600**
Ne	**1**
O	**0.5**
Si	**1 day**