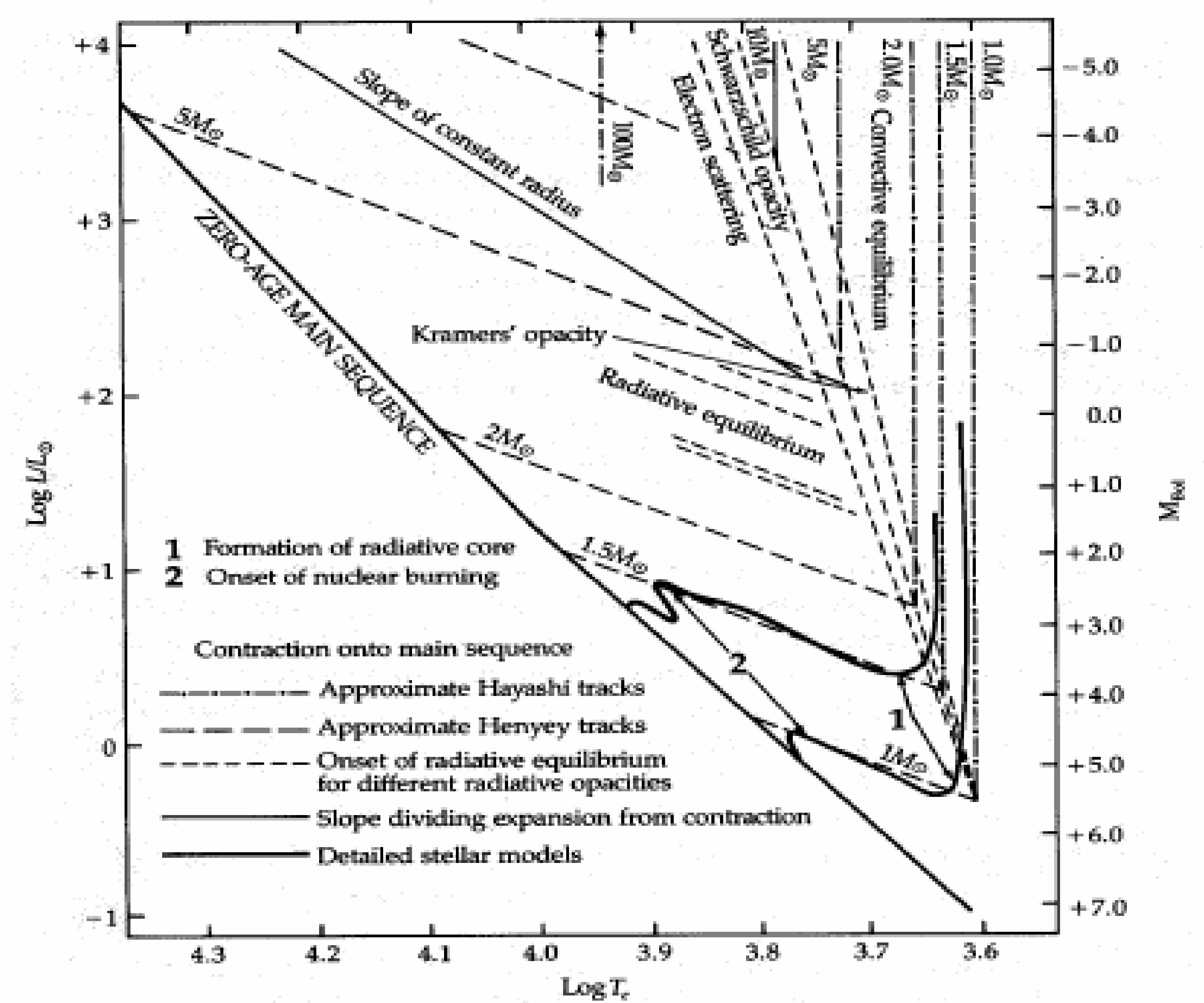
Relativistic Universe

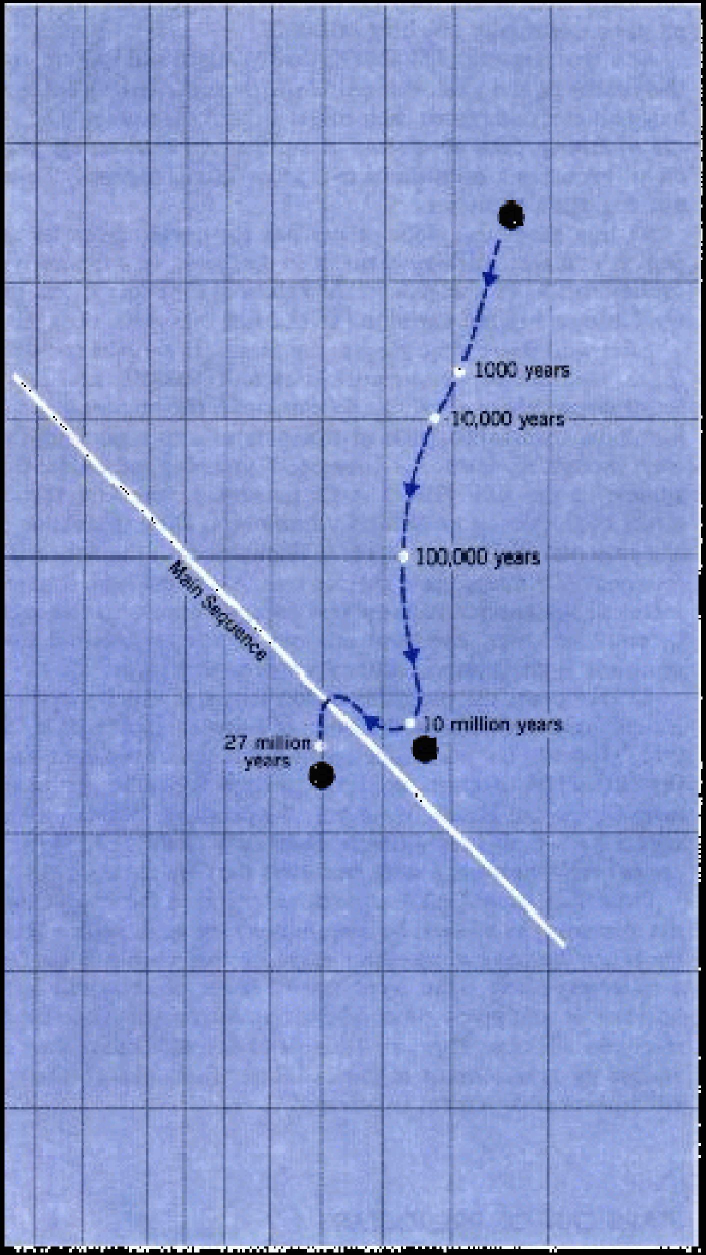
Mature and old stars

The route to main sequence



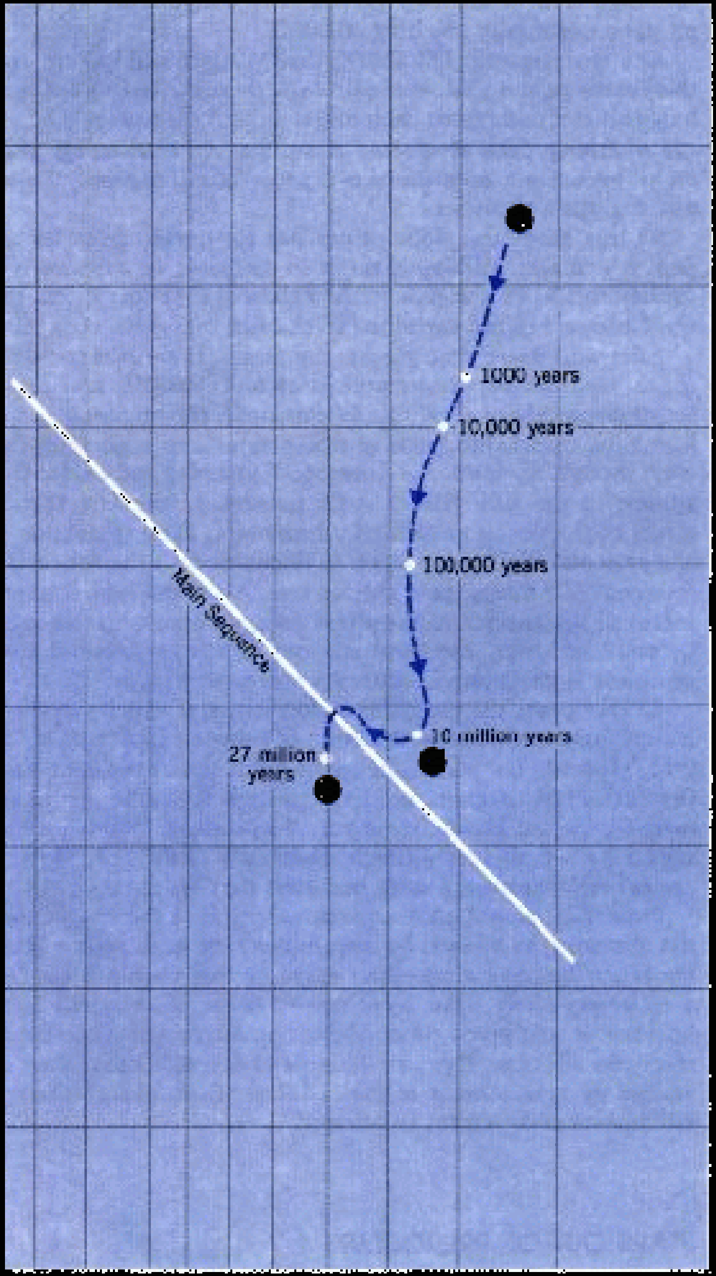
Protostar

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



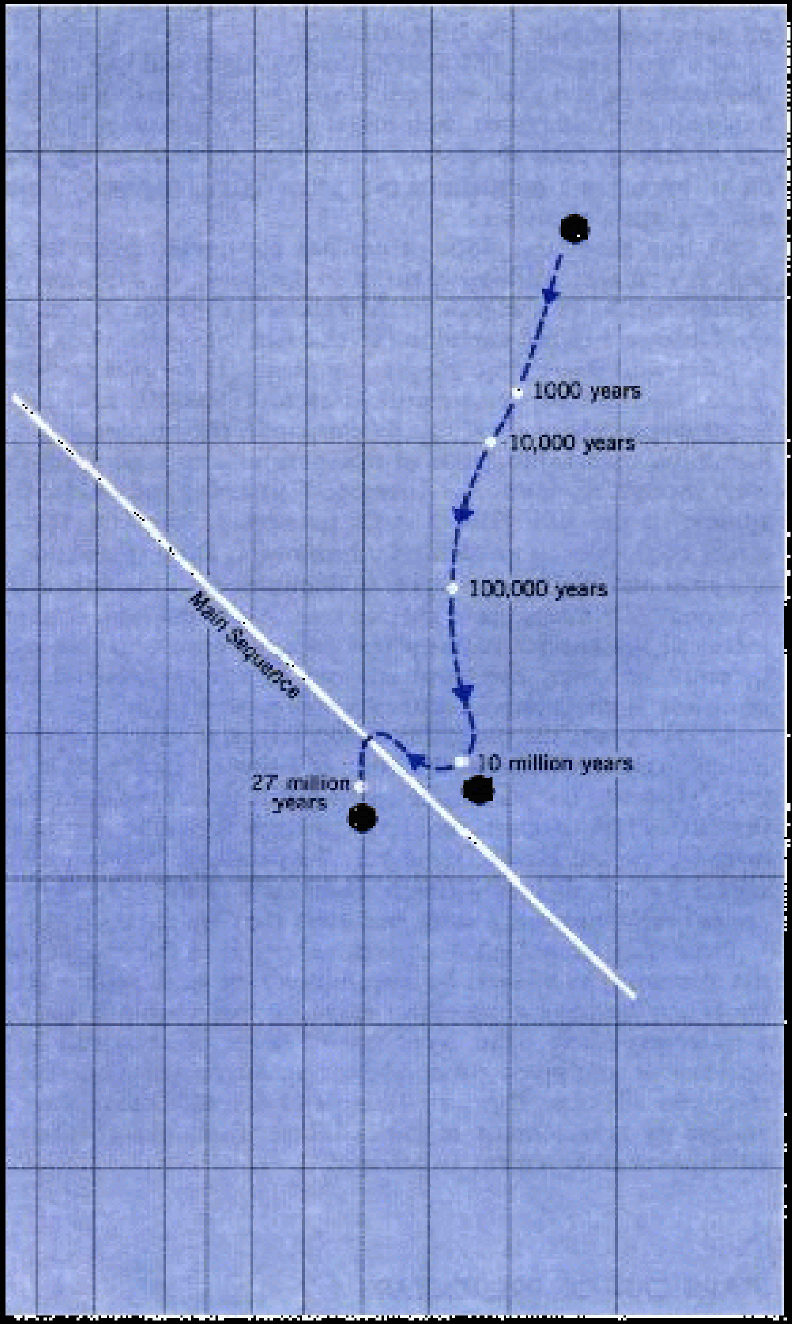
Pre MS

- Age: 10 million yrs
- R ~ 1.33 R_{sun}
- T_{core} = 10,000,000K
- $T_{surface}$ = 4500K
- Energy Source: *P-P Chain* turns on.



ZAMS

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



- When the track of a gravitationally contracting star intersects the main sequence, the star has reached a point in its life when it will be stable for an extended period of time. This is ensured observationally by the fact that about 90 percent of all stars reside on or very near the main sequence and so must be involved in the utilization of their most prolific and efficient source of energy – the fusion of hydrogen into helium.

Classification of stars

- $M^* < 0.01\ M_{\odot}$ - Planet. Jupiter, for example, has a mass of about $0.001\ M_{\odot}$. Jupiter's temperature is slightly warmer than would be expected from the amount of solar energy it receives; this is interpreted as due to gravitational potential energy stored as heat from Jupiter's contraction out of the proto-solar nebula. But the energy balance for Jupiter and other planets is largely determined by the energy received from the sun and central temperatures never come close to the 10^6 million K required for even the simplest nuclear reactions.

- $0.01\ M_\odot < M^* < 0.085\ M_\odot$ - Brown Dwarf; these objects will never become hot enough in their cores to ignite the P-P Chain. Release gravitational potential energy will cause them to heat up to core temperatures as hot as 3 million K, hot enough for the first stages of nuclear reactions, perhaps, but never hot enough to establish stable hydrogen burning. With atmospheric temperatures $T_{surface} < 2000K$, *brown dwarfs* will be very faint, radiating the vast majority of their luminous energy in the infrared, and very hard to detect.

- $0.085\ M_{\odot} < M^* < 0.4\ M_{\odot}$ - these stars will be very long lived, but will never reach temperatures hot enough for the Triple-alpha process to occur. They will not have a helium flash in the red giant stage nor a helium-burning main-sequence phase.

- 0.4 $M_{\odot}$ < M* < 1.2 $M_{\odot}$ - these stars like the sun will burn hydrogen to helium via the P-P Chain and will burn helium to carbon via the triple-alpha process.
- M* > 1.2 $M_{\odot}$ - these stars will reach high enough core temperatures to burn hydrogen via the CNO cycle.

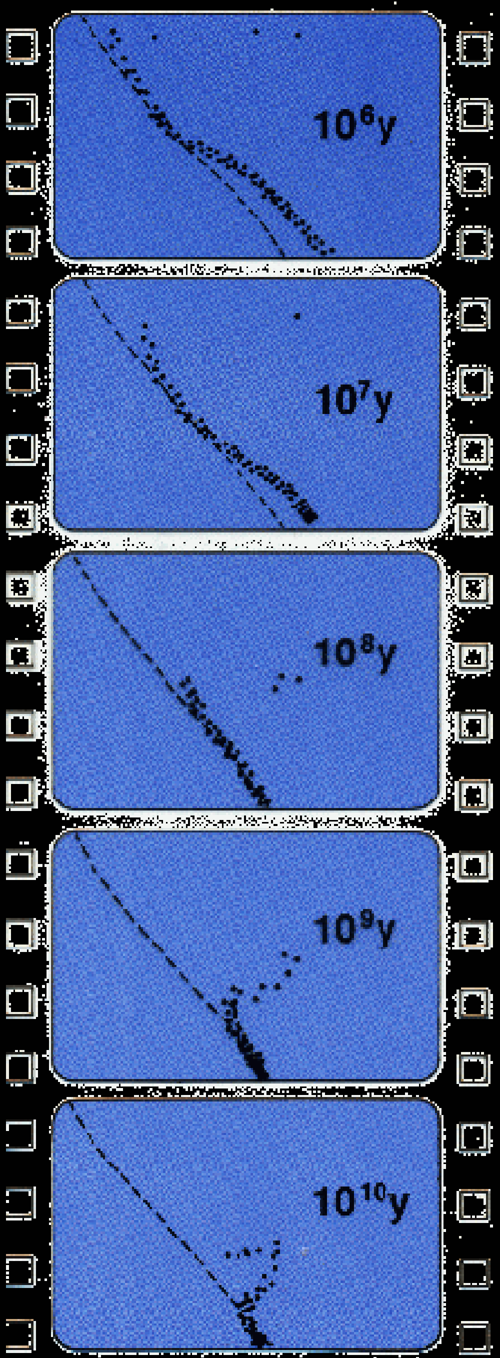
- $M^* > 8\ M_\odot$ - stars more massive than about 8 solar masses (this number is very uncertain compared with those above) will have a larger number of nuclear burning cycles and their cores will be more massive than the limiting mass of 1.4M , the largest mass that can be supported by electron degeneracy, and thus the largest possible mass for a white dwarf. As we shall see these stars end their lives with a cataclysmic explosion called a *supernova*.

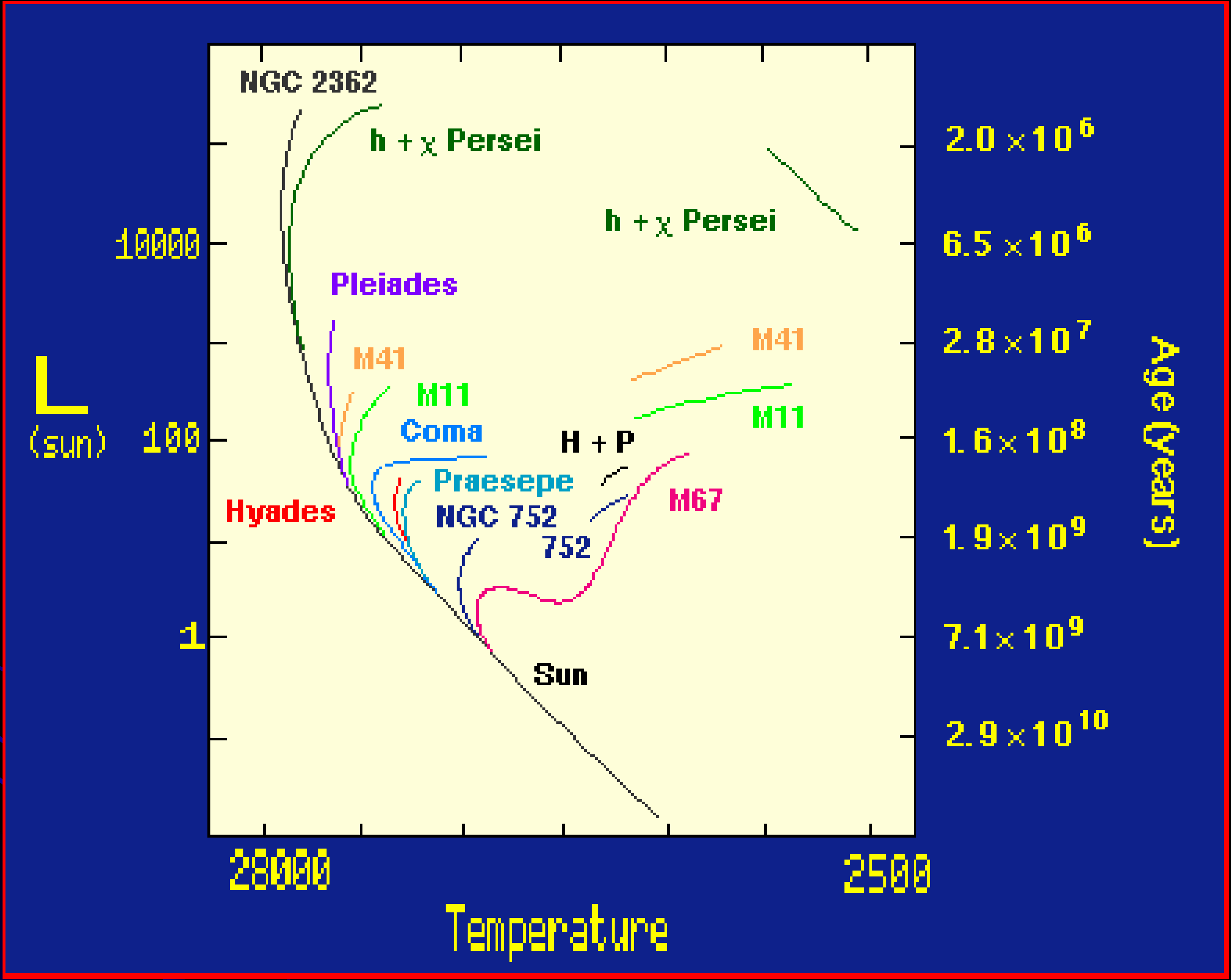
MS stars: basic physical principles

- 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 $\sim T^4$ 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.

Stellar clusters

All the stars in the cluster were born basically at the same time. Observing clusters of different ages, we can follow evolution of stars of different mass.

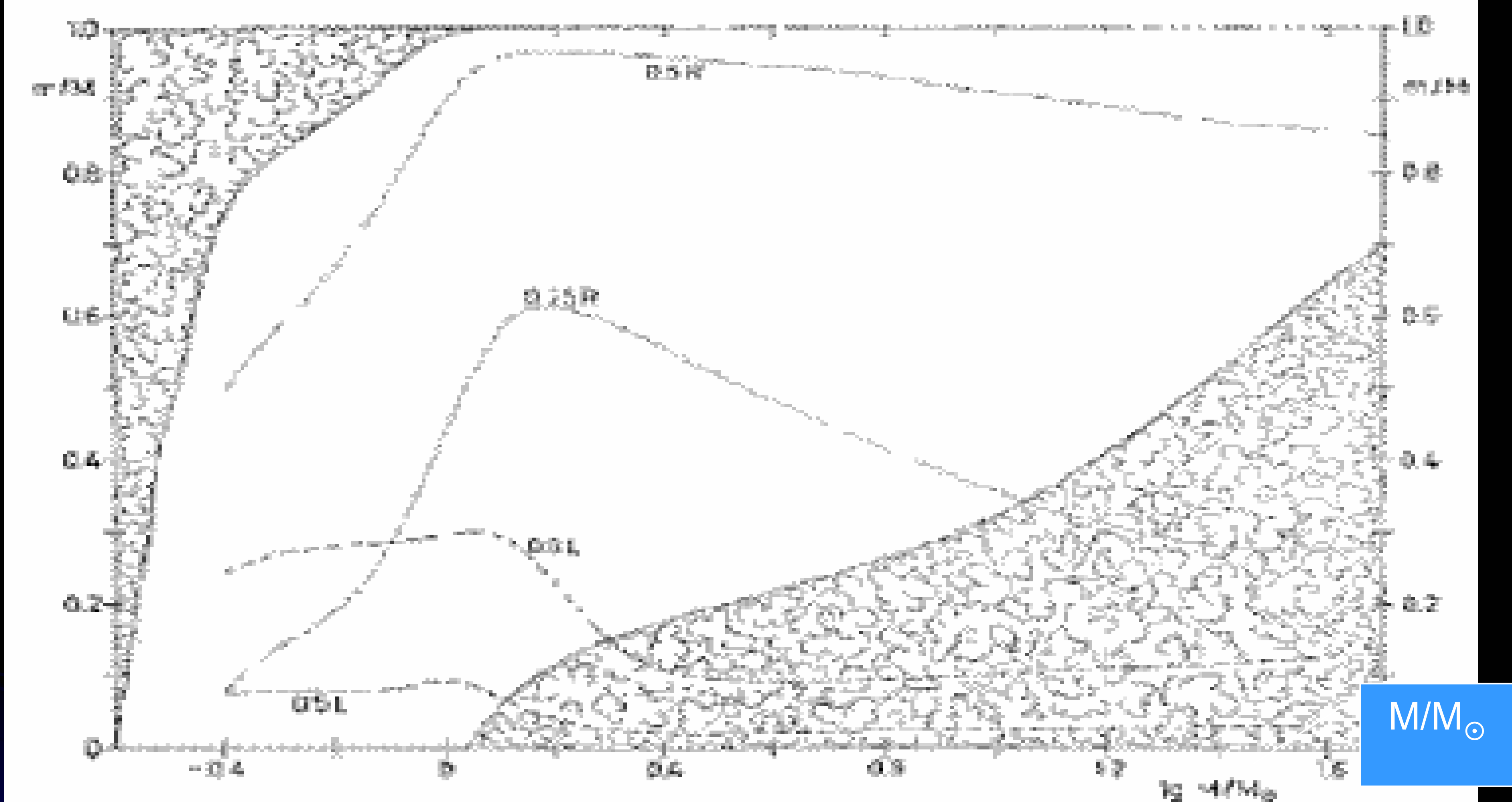



NGC 2362
h + χ Persei
h + χ Persei
Pleiades
M41
M41
M11
M11
Coma
H + P
Praesepe
M67
Hyades
NGC 752
752
Sun
L
(sun)
10000
100
1
28000
2500
Temperature
2.0 × 10^6
6.5 × 10^6
2.8 × 10^7
1.6 × 10^8
1.9 × 10^9
7.1 × 10^9
2.9 × 10^10
Age (years)

Energy transport in stars

- Energy transport determines the temperature gradient in the star; heat flows towards lower temperature, at the rate determined by effective thermal conductivity and the decrease of temperature.

- In large parts of most stars energy is transported by radiation; the rate of energy transport is characterized by the opacity κ, defined such that the mean free path of a photon is $1/\kappa\rho$.



the vertical axis indicates position in the star, in terms of the mass *m* interior to a given point. ‘Cloudy’ areas indicate the presence of convection. The two solid curves show the positions where the distance *r* to the center is 0.25 and 0.5 times the surface radius. The dashed curves show the positions interior to which 50% and 90% of the stellar luminosity is generated.

- However in some parts of the star the temperature gradient required for radiative transport may become so steep that the unstable situation arises: matter displaced outwards, adiabatically, finds itself lighter than the surrounding and thus continues to rise. In this way convective motion is set up.

Lower Main Sequence Stars

- *Lower main sequence* are stars with masses less than about 2 solar masses. For these stars, after the trace elements with low ignition temperatures have been exhausted and hydrogen fusion has begun, the equilibrium structure is established in about a million years. The mass of these stars is insufficient to produce a central temperature high enough to initiate the CNO cycle, so the primary source of energy is the proton-proton cycle. Models indicate that in the sun, 98 percent of the energy is supplied by the proton-proton cycle.

- These stars have a central core which is in radiative equilibrium.
- However, the conditions for convective instability are met in the outer regions of these stars resulting in the formation of a convective envelope. In the sun, this point is reached at about $0.75R_{\odot}$, so that about 98.8 percent of the mass is included in the radiative core.

- The existence of the radiative core in stars of the lower main sequence has a significant effect on the subsequent evolution of the star. The ^4He, which is the end product of hydrogen burning, remains in the locale in which it is produced. However, since the production rate is strongly dependent on temperature, the helium abundance increases more rapidly as one approaches the center of the star. The helium must be supported against its own gravity while it contributes nothing to the support of the remainder of the star. As a result, the internal temperature will increase to maintain the luminosity in the face of decreasing hydrogen abundance

Evolution of MS stars

- If stellar matter satisfies the ideal gas law,

$$T \approx \frac{M\mu}{R}$$

- This shows that as the star grows older, converting hydrogen into helium and thereby increasing μ there is a general tndency for temperature to increase.

- Thus, we should expect stars like the Sun to slowly increase in brightness, as the internal temperature rises, during their main sequence lifetime. Indeed, the standard solar model indicates that the solar luminosity has increased by about 40 percent since its arrival on the zero age main sequence.

- Toward the end of the star's main sequence life, the helium abundance will rise to the point where a core of helium, surrounded by a hydrogen burning shell, will form in the center of the star.

- Therefore, the main sequence lifetime of a low mass star consists of a steady energy output from hydrogen burning in an environment of steadily increasing helium. On a nuclear time scale, the helium abundance increases preferentially in the most central regions causing the temperature to rise which results in a slow increase in the luminosity throughout the main sequence lifetime of the star. After about 10 percent of the radiative core mass has been consumed, an isothermal helium core begins to form and structural changes begin to occur very rapidly. This signals the end of the main sequence lifetime.

Upper Main Sequence Stars

- For stars on the main sequence, the observed mass-radius relation is approximately

$$M \approx R^{4/3}$$

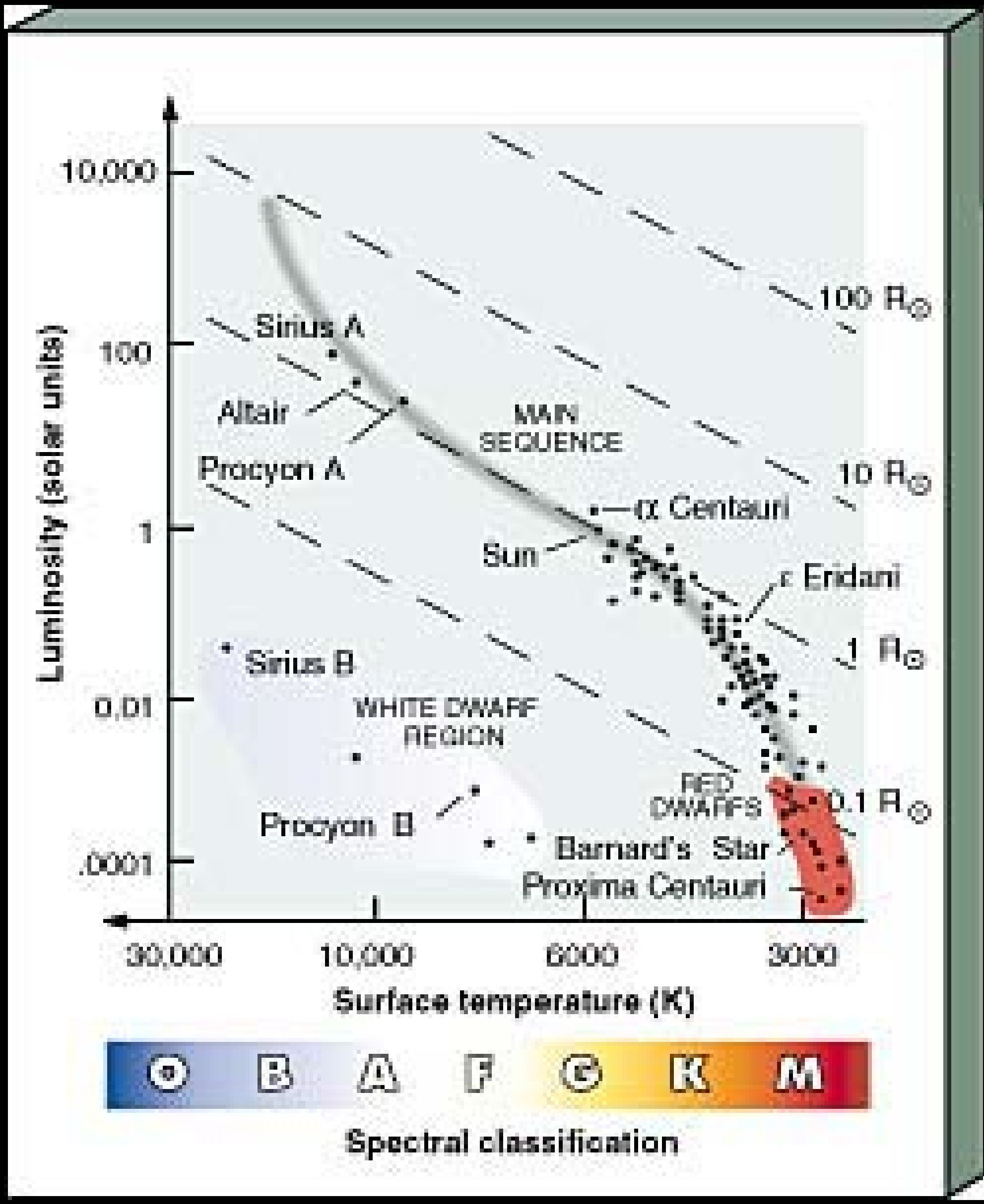
- However

$$T \approx M/R$$

- So that the central temperature

$$T_c \approx R^{1/3} \approx M^{1/4}$$

- This slow rise in the central temperature, as we proceed up the main sequence, will result in a greater fraction of the energy being produced by the more temperature-sensitive CNO cycle.



Main sequence stars

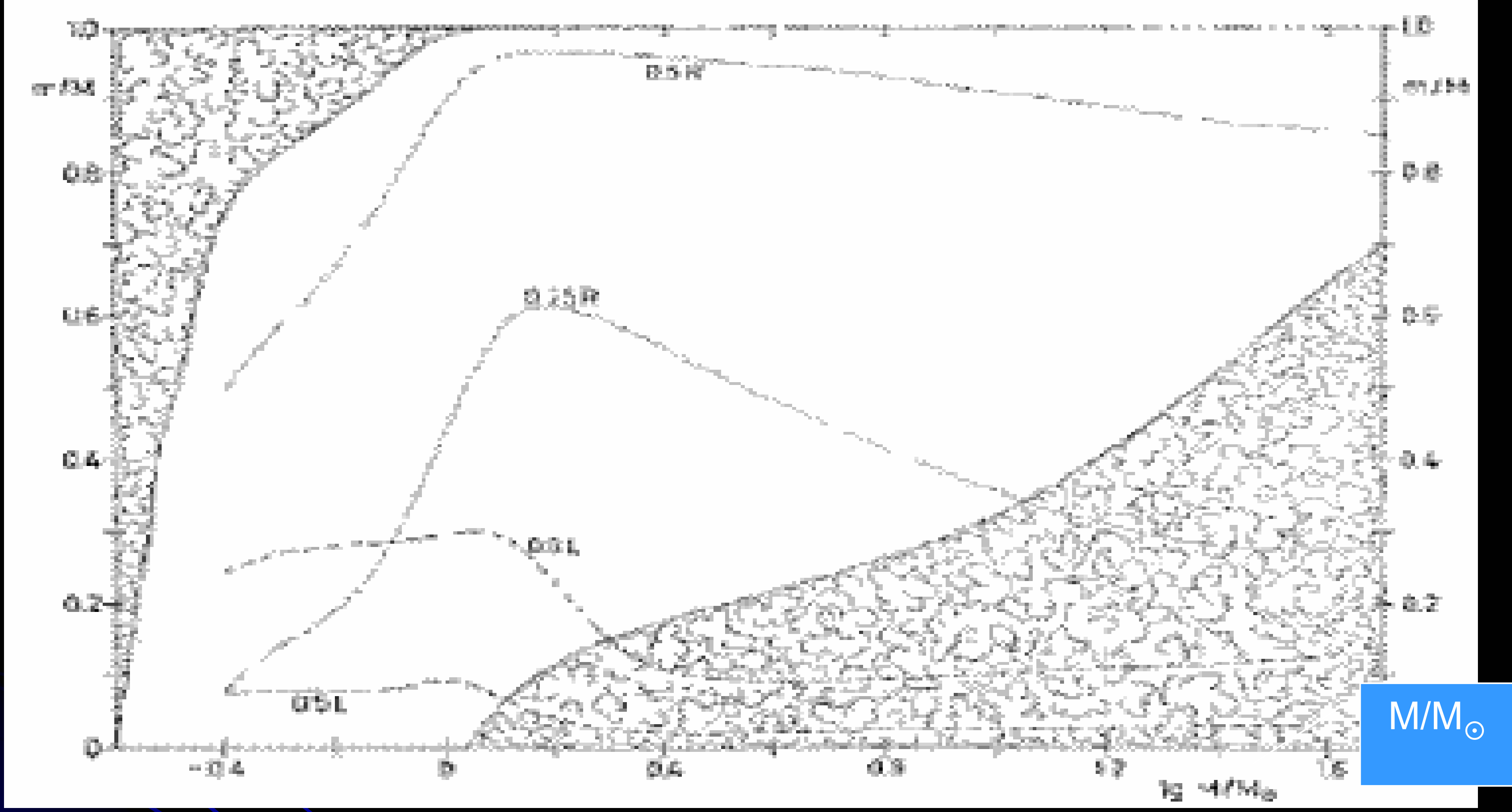
Spectral Type	Temperature [K]	Luminosity [L_{sun}]	Mass [M_{sun}]	Main-Sequence Lifetime [yr]
O7	37,500°	80,000	25	3×10^6
B0	30,000°	10,000	15	15×10^6
A0	9,500°	60	3.0	500×10^6
F0	7,200°	6	1.5	3×10^9
G0	6,000°	1	1.0	10×10^9
K0	5,200°	0.6	0.8	20×10^9
M0	3,800°	0.02	0.4	200×10^9

Thermonuclear burning

Main-Sequence Mass	Thermonuclear Burning Phases
$M_{star} << M_{sun}$	hydrogen
$M_{star} < M_{sun}$	hydrogen and possibly helium
$M_{star} = M_{sun}$	hydrogen and helium
$M_{star} > M_{sun}$	hydrogen, helium, carbon and possibly oxygen, neon, and silicon
$M_{star} >> M_{sun}$	hydrogen, helium, carbon, oxygen, neon, and silicon

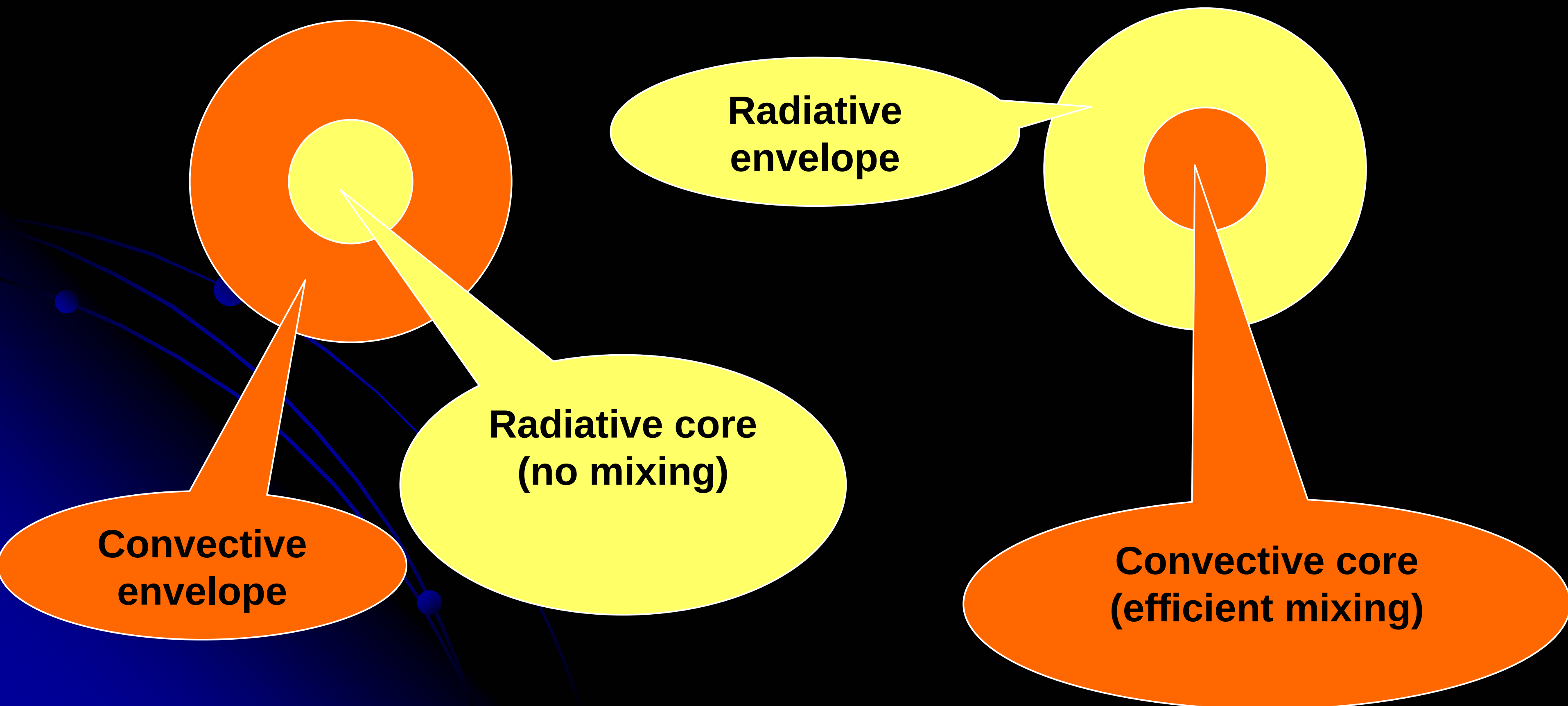
- For stars of mass greater than about two solar masses, the CNO cycle is the dominant source of energy production.
- The much larger temperature sensitivity of the CNO cycle as compared to the p-p cycle means that the region of energy production will be rather more centrally concentrated than in stars of less mass.
- This, in turn, requires a steeper temperature gradient in order to transport the energy to the outer parts of the star.

- Thus, we have a star composed of a convective core surrounded by an envelope in radiative equilibrium. This role reversal for the core and envelope has a profound effect on the evolution of the star.



the vertical axis indicates position in the star, in terms of the mass m interior to a given point. 'Cloudy' areas indicate the presence of convection. The two solid curves show the positions where the distance r to the center is 0.25 and 0.5 times the surface radius. The dashed curves show the positions interior to which 50% and 90% of the stellar luminosity is generated.

- Low mass star
- High mass star



- The presence of a convective core ensures that the inner regions of the star is well mixed. As helium is produced from the burning of hydrogen, it is mixed throughout the entire core. Thus, we do not have a buildup of a helium core that increases in helium abundance toward the center in these stars. Instead, the entire convective core is available as a fuel source for energy production at the center of the star. For this reason, energy production is remarkably steady in these stars until the entire convective core is nearly exhausted of hydrogen.

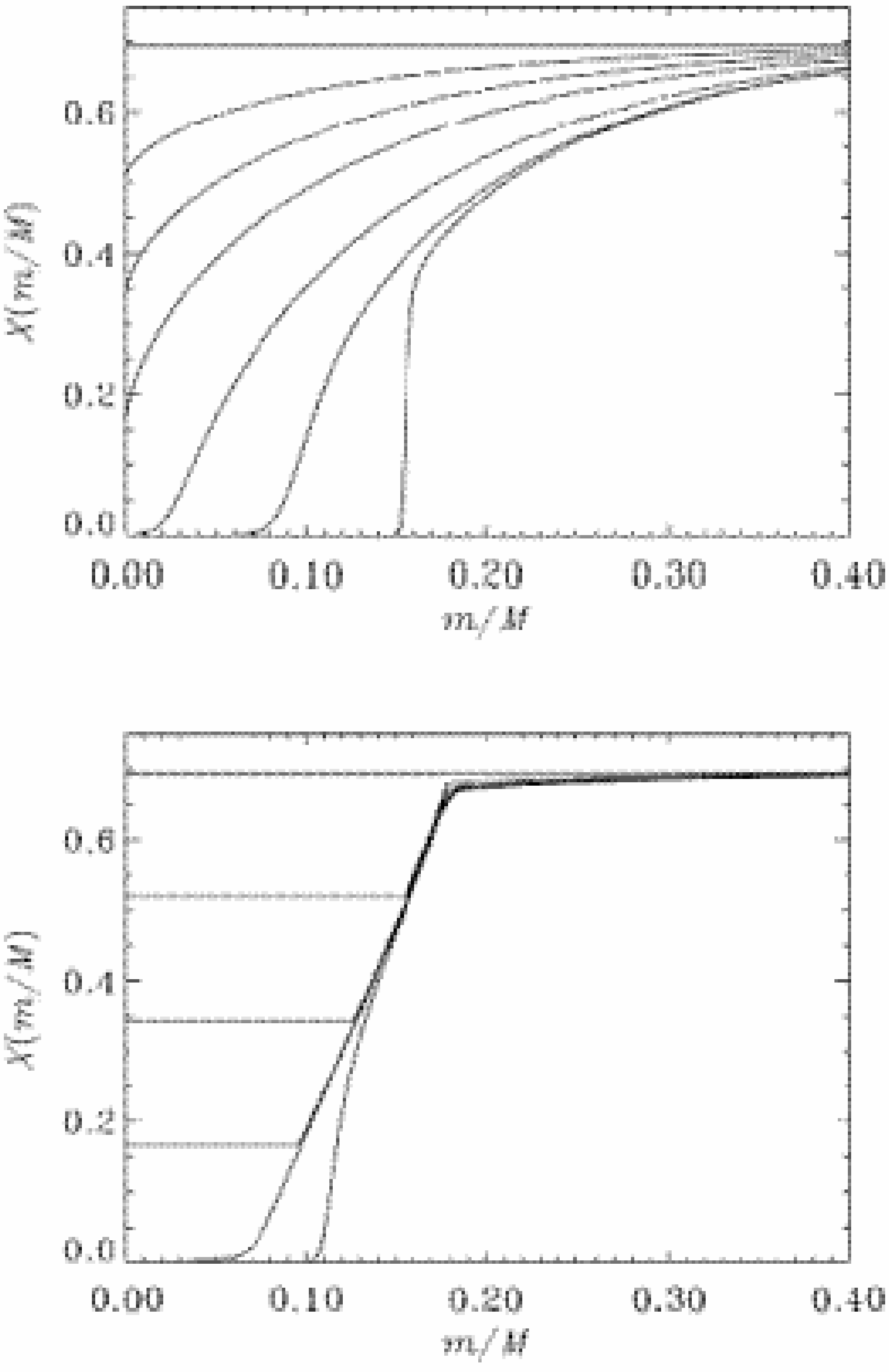


Figure 4. Evolution in the hydrogen abundance X by mass, as a function of time, against the fractional mass m/M in the star. The homogeneous initial models had $X = 0.692$. Top panel: $1M_{\odot}$, at ages 0, 2.47 Gyr, 4.53 Gyr, 6.49 Gyr, 9.29 Gyr, 10.81 Gyr and 11.62 Gyr. Lower panel: $2.5M_{\odot}$, at ages 0, 174 Myr, 306 Myr, 400 Myr, 462 Myr and 487 Myr.

- Even as exhaustion approaches, the extreme temperature dependence of the CNO cycle implies that deficits produced by the declining availability of hydrogen fuel can be made up by modest increases in the temperature and hence minor changes in the structure of the star.

CNO Cycle

ϵ_0 (cgs)	ν
3×10^{-4}	22.9
4.5×10^{2}	18
3×10^{7}	14.1
2×10^{11}	11.1
2×10^{12}	10.2

- Indeed, it is not until more than 99 percent of the convective core mass has been converted to helium that truly significant changes occur in the structure of the star and the star can be said to be leaving the main sequence.

Post-MS evolution

Main-Sequence Mass	Death Sequence of Star
$0.1 < M < 0.8\ M_{sun}$	spend entire life in H-burning and cool to white dwarf eventually
$0.8 < M < 11\ M_{sun}$	go through red-giant phase and end as white dwarfs (99% of all stars)
$11 < M < 50\ M_{sun}$	undergo supernova outburst and end as neutron star (1% or less of all stars)
$M > 50\ M_{sun}$	undergo supernova outburst and end as black hole

Evolution off the lower main sequence

- At the onset of post main sequence evolution the helium core is surrounded by a thin hydrogen-burning shell. The hydrogen burning continues in a shell around the helium core which steadily grows outward, in mass, through the star. However, the helium core must be supported against its own gravity as well as support the weight of the remaining star, and its energy sources are all on the outside.

- As a result, it is impossible for the hydrogen-burning shell to establish a temperature gradient within the helium core. Only gravitational contraction of the core will result in the release of energy inside the helium core, and except for this source of energy the helium core must be isothermal, with its temperature set by the burning of hydrogen surrounding it. But the rate of hydrogen burning is dictated largely by the mass of material lying above the burning zone, because this is the material that must kept in equilibrium. As the mass of the isothermal helium core increases, the equilibrium temperature of the core will also rise and this demand can be met only by a slow contraction of the helium core.

- As the isothermal core grows through the addition of He from the hydrogen-burning shell, the core temperature must rise in order for it to remain in equilibrium and support the outer layers of the star.

Degenerate core

- For stars with masses $M \leq 1.3M_{\odot}$ the slowly developing isothermal core will be degenerate. Under these conditions the added pressure of the degenerate electron gas is sufficient to support nearly any additional mass.

- Thus, the isothermal helium cores of lower main sequence stars can increase to virtually any mass. As mass is added to the core, we can expect the core to contract according to the mass-radius law for degenerate configurations

Core contraction – envelope expansion

- A star goes through several different phases as it evolves from the main sequence to the giant branch of the H-R diagram, and all result in an expansion of the envelope accompanying some contraction of the core.
- This can be qualitatively explained in simple terms.

Energy conservation

$$E = \langle \Omega \rangle + \langle U \rangle - \int_0^t L dt + \int_V \int_0^t \varepsilon dV dt$$

- On not too long time scales these integrals cancel (energy produced = energy emmited). Therefore

$$E = \langle \Omega \rangle + \langle U \rangle$$

- On the other hand, for such time scales virial theorem applies

$$0 = \langle \Omega \rangle + 2 \langle U \rangle$$

- This implies that the potential and internal energy are constant, separately. The potential energy is

$$\Omega = \Omega_c + \Omega_e$$

- For upper main sequence stars, the mass of the core substantially exceeds that of the envelope,

$$\Omega = \frac{GM_c^2}{R_c} + \frac{GM_c M_e}{R_*}$$

- If, for simplicity, we further hold the masses of the core and envelope constant during the core contraction, we have

$$\frac{dR_*}{dR_c} \approx -\left(\frac{M_c}{M_e}\right)\left(\frac{R_*}{R_c}\right)^2 \ll -1$$

Post MS evolution

4. End of Main Sequence

Age: 10 billion yrs

Energy Source: *P-P Chain* in shell around core.

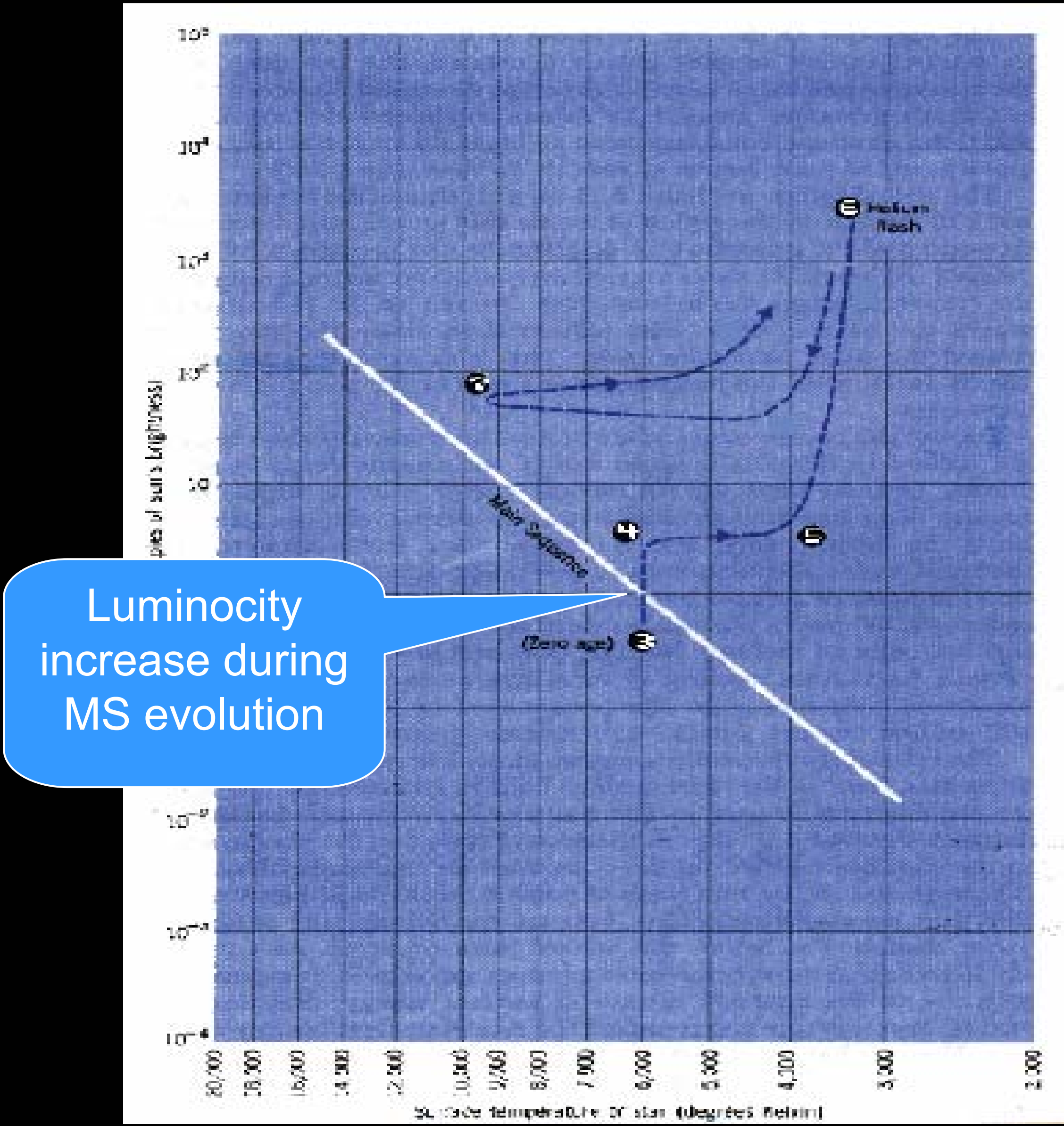
5. Post Main Sequence

Age: About 1 billion years from Point 4

R ~ 2.6Rsun

$T_{surface}$ = 4500K

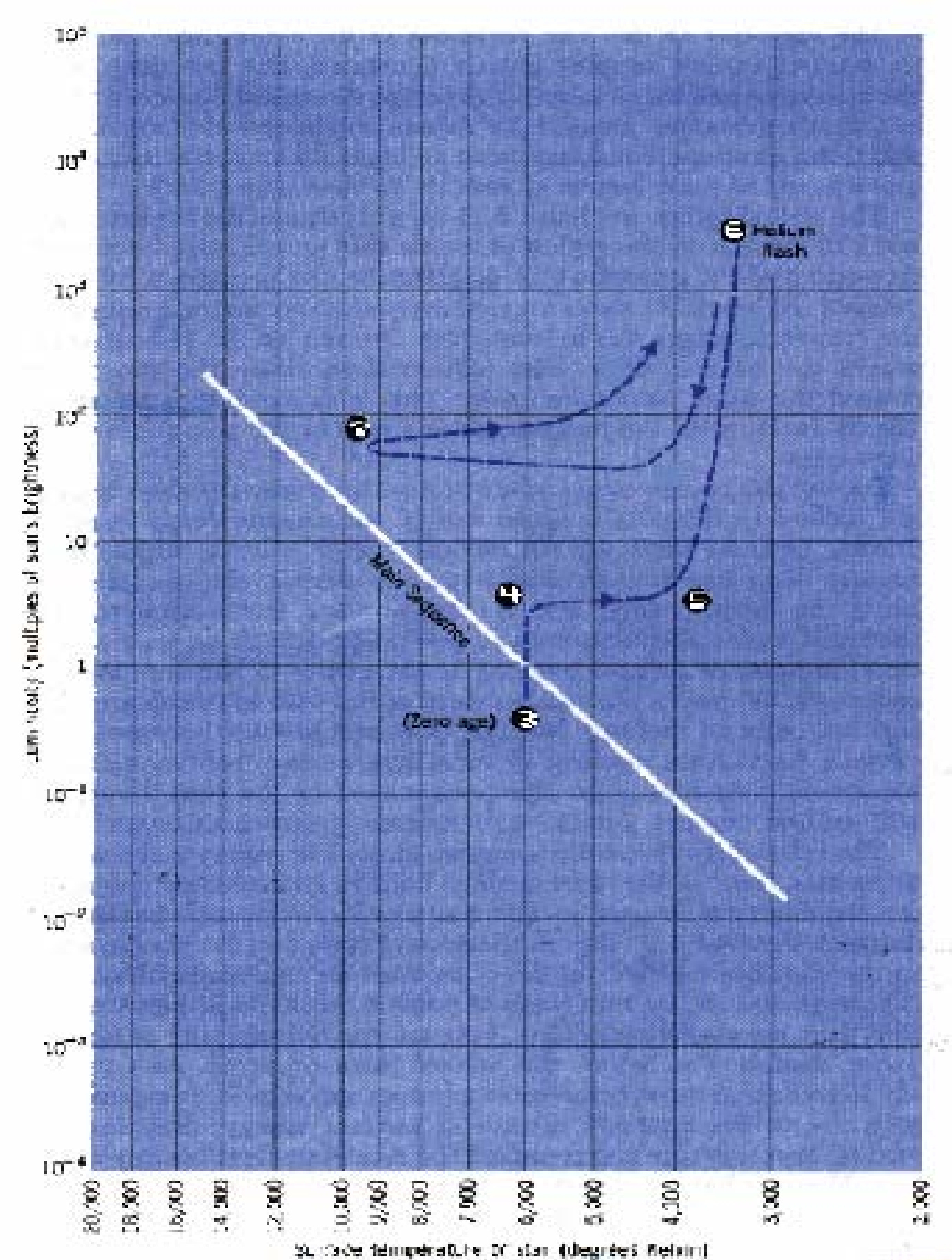
Energy Source: *P-P Chain* in shell, Gravitational contraction of core.



- 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*.

HELIUM FLASH

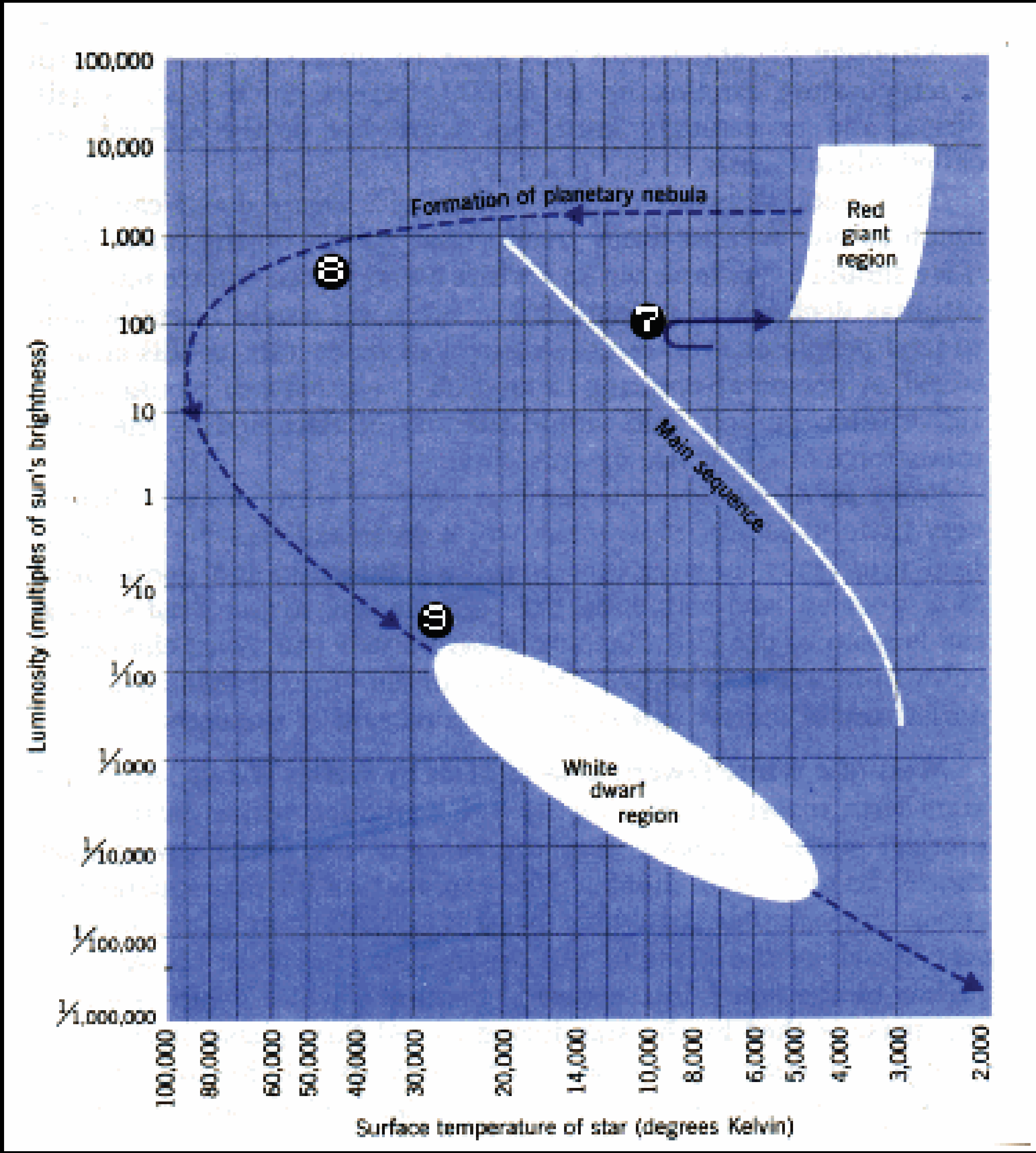
- Age: 100 million yrs from Point 5
- R ~ 200R_{sun}
- T_{core} = 2 ×10^8K
- $T_{surface}$ = 3500K
- Energy Source: *P-P Chain* in shell around core; Ignition of Triple-Alpha Process.



- 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.

Helium burning

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**



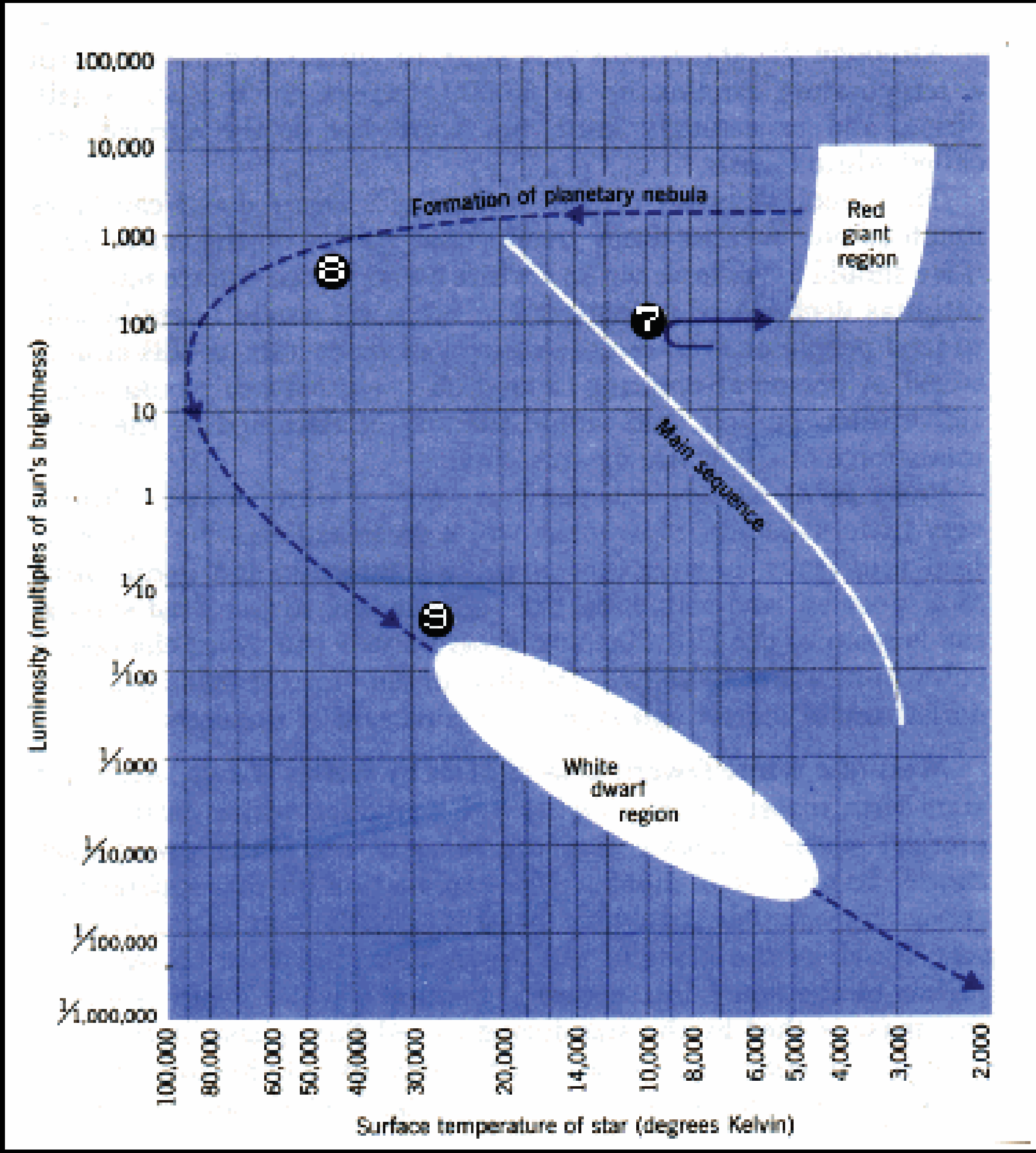
Planetary nebula

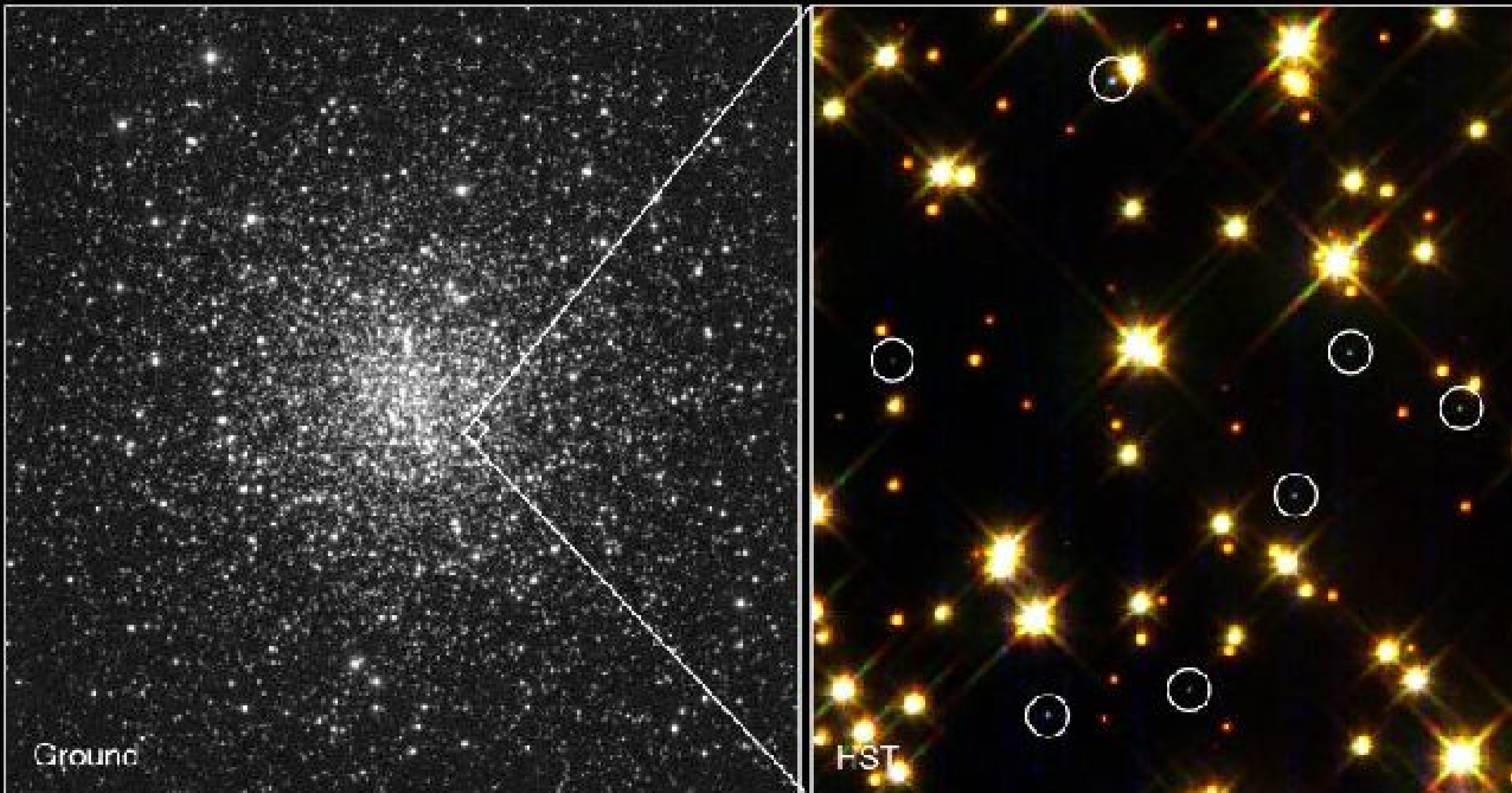
- Throughout the star's lifetime it is losing mass via a stellar wind, like the solar wind. This mass loss increases when the star swells up to the size and low gravity of a Red Giant.

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

White dwarf

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



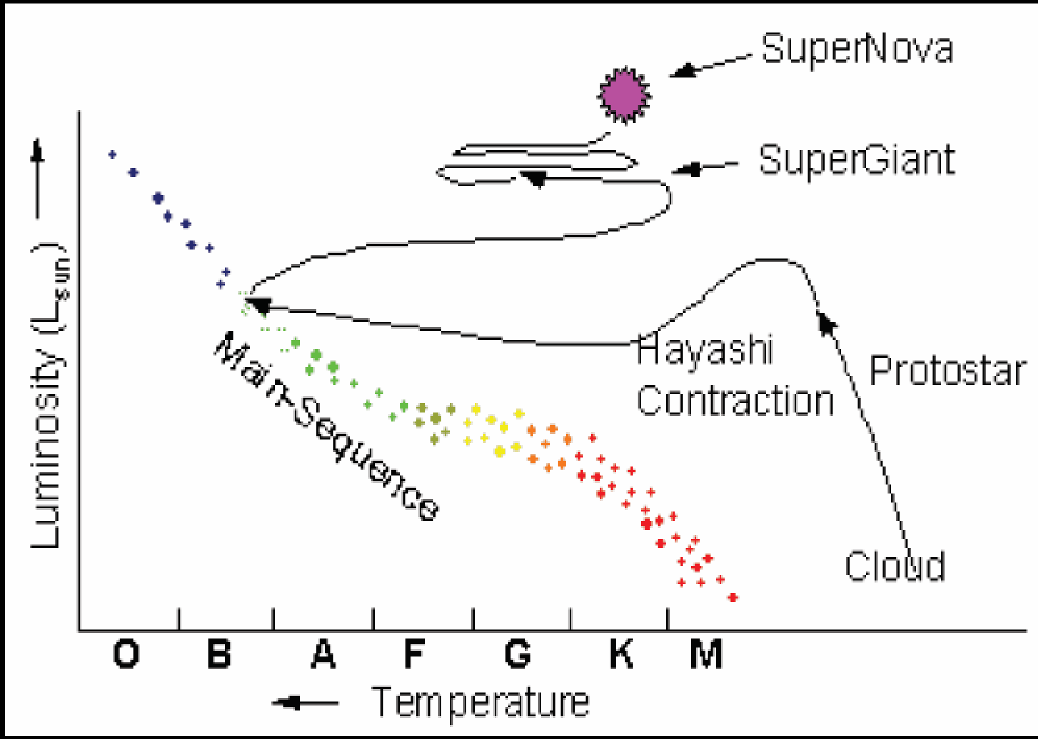


White Dwarf Stars in M4 HST • WFPC2

PRC95-32 • ST ScI OPO • August 28, 1995 • H. Bond (ST ScI), NASA

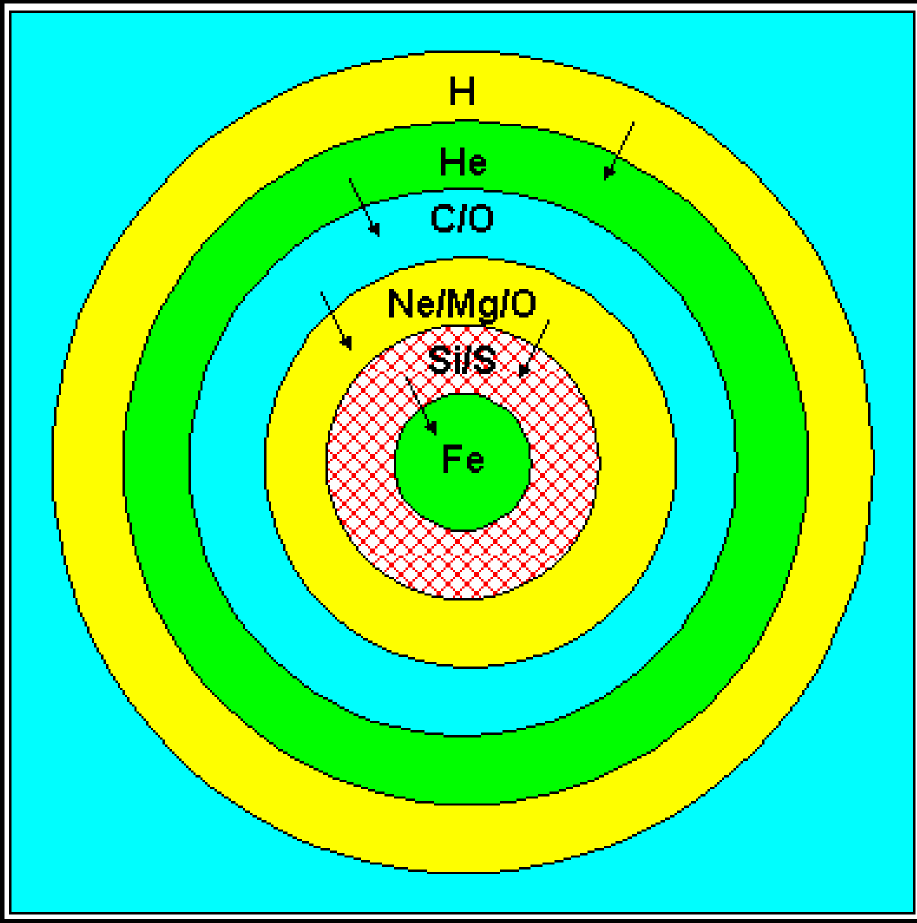
Evolution of massive stars

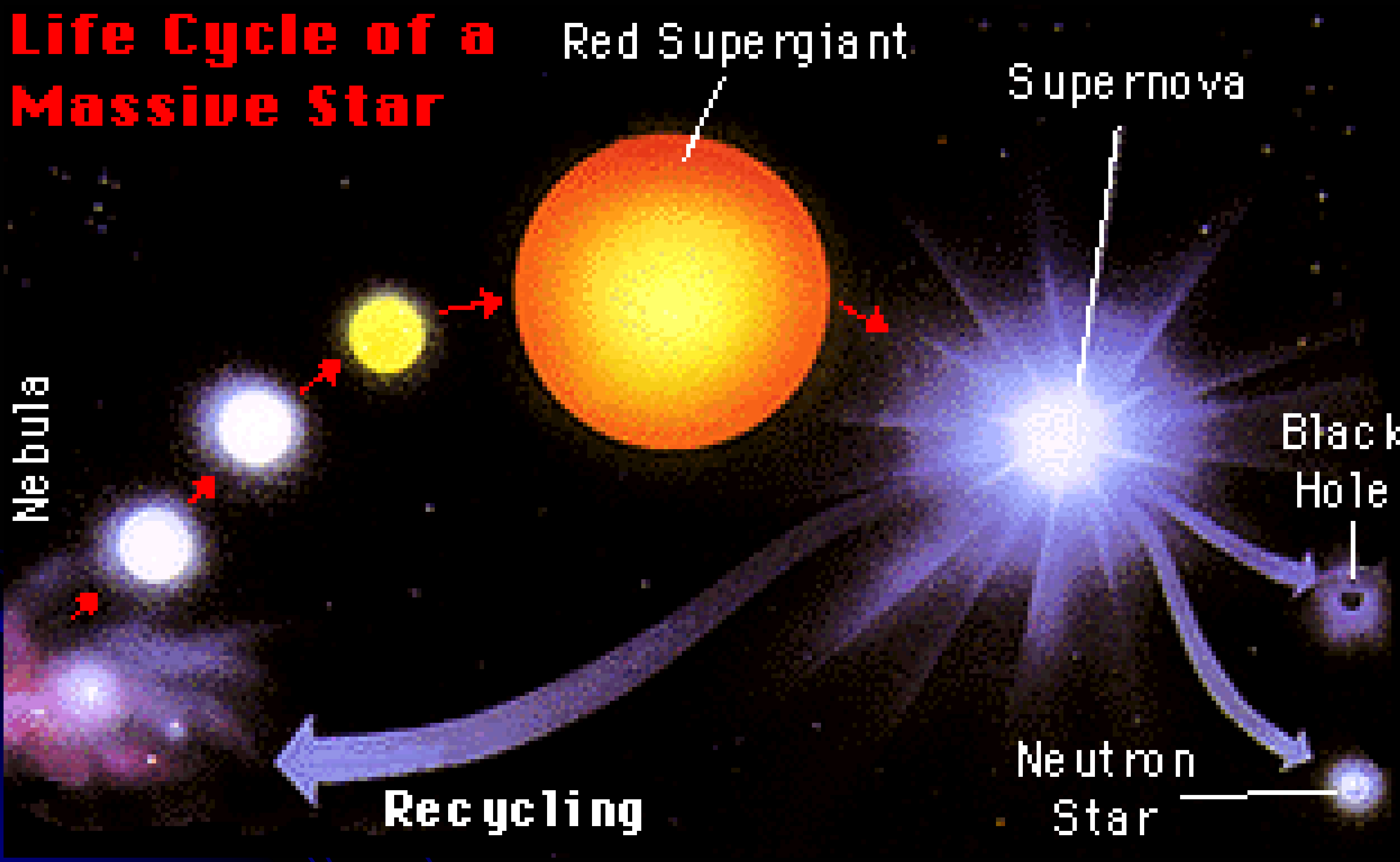
Following the Helium Burning Main Sequence in massive stars, a series of nuclear burning stages transforms the star into an onion-like shell structure, until Silicon and Sulfur burning create a core of iron



20 $M_\odot$ star

Main sequence lifetime ~ 10 million years
Helium burning (3-) ~ 1 million years
Carbon burning ~ 300 years
Oxygen burning ~ 2/3 year
Silicon burning ~ 2 days

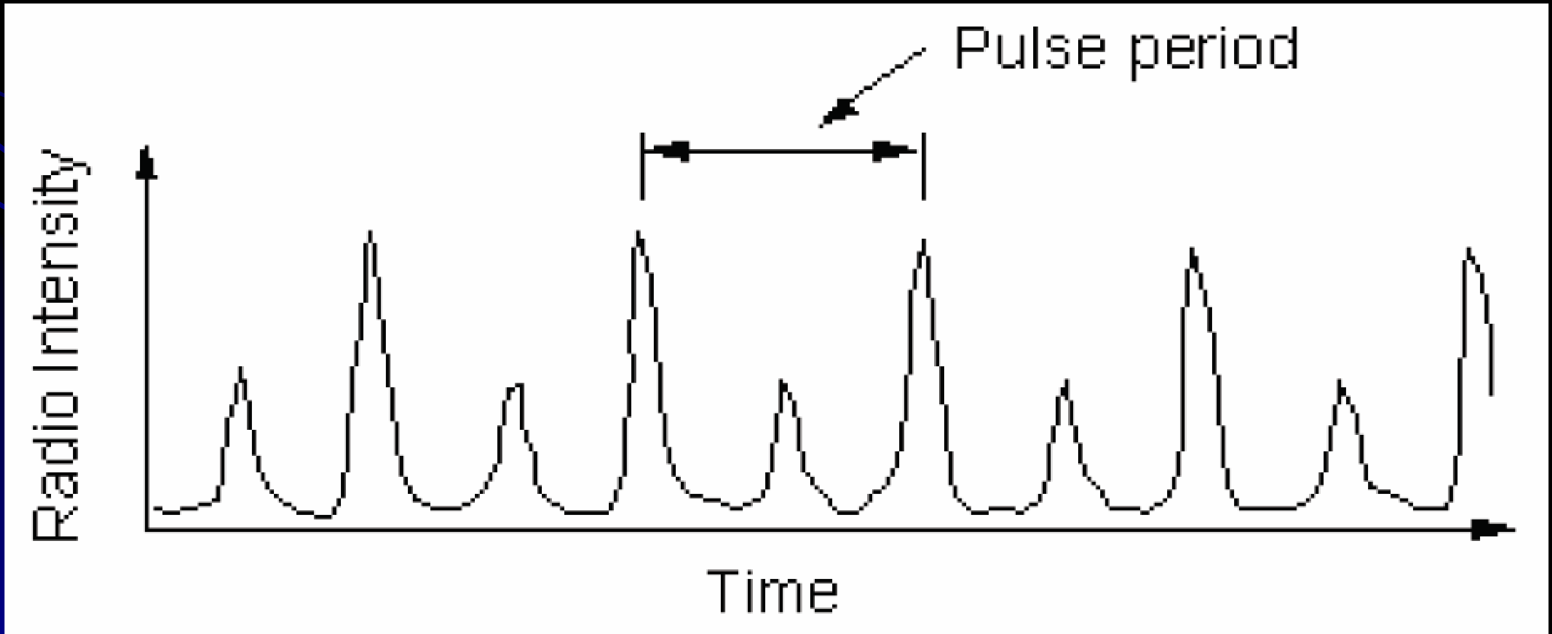


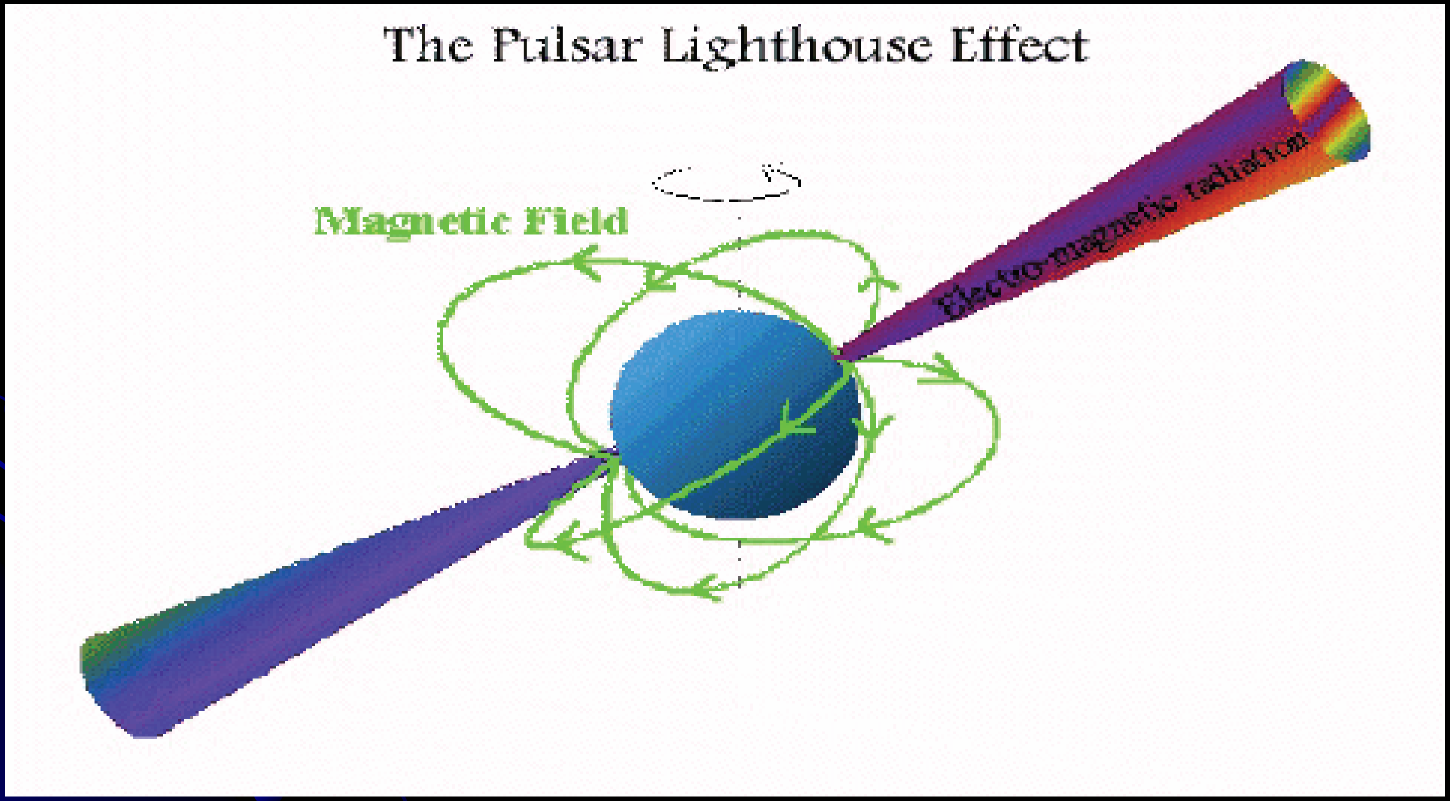

Life Cycle of a Massive Star
Red Supergiant
Supernova
Nebula
Black Hole
Neutron Star
Recycling

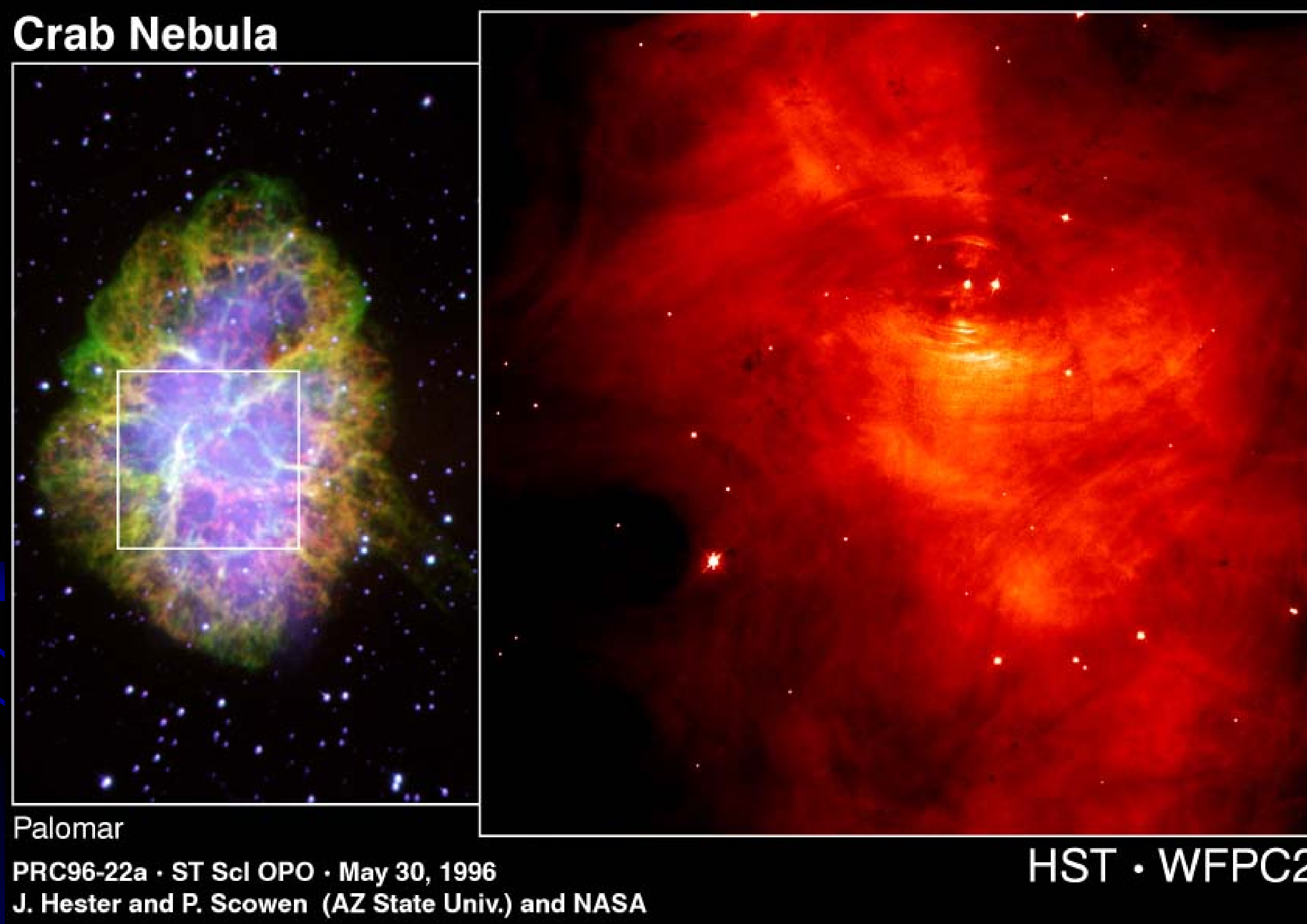
Pulsars

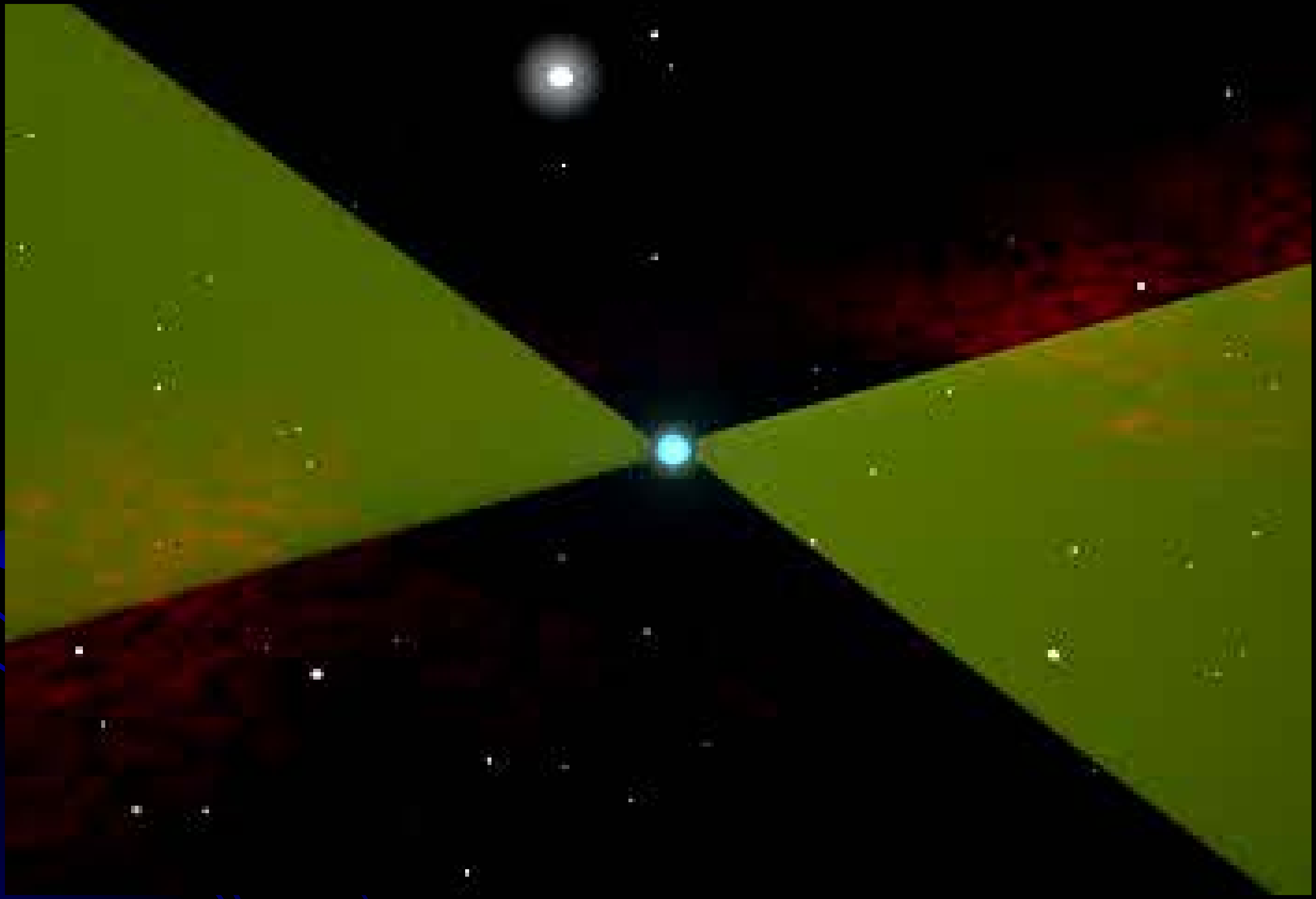
- According to theory, the core of the star that remains after a supernova explosion is a tiny (R ~ 10km) remnant of extremely high density neutrons, supported by neutron degeneracy -- a neutron star. The existence of Neutron Stars was predicted by Baade & Zwicky (1934) and Oppenheimer (1939).

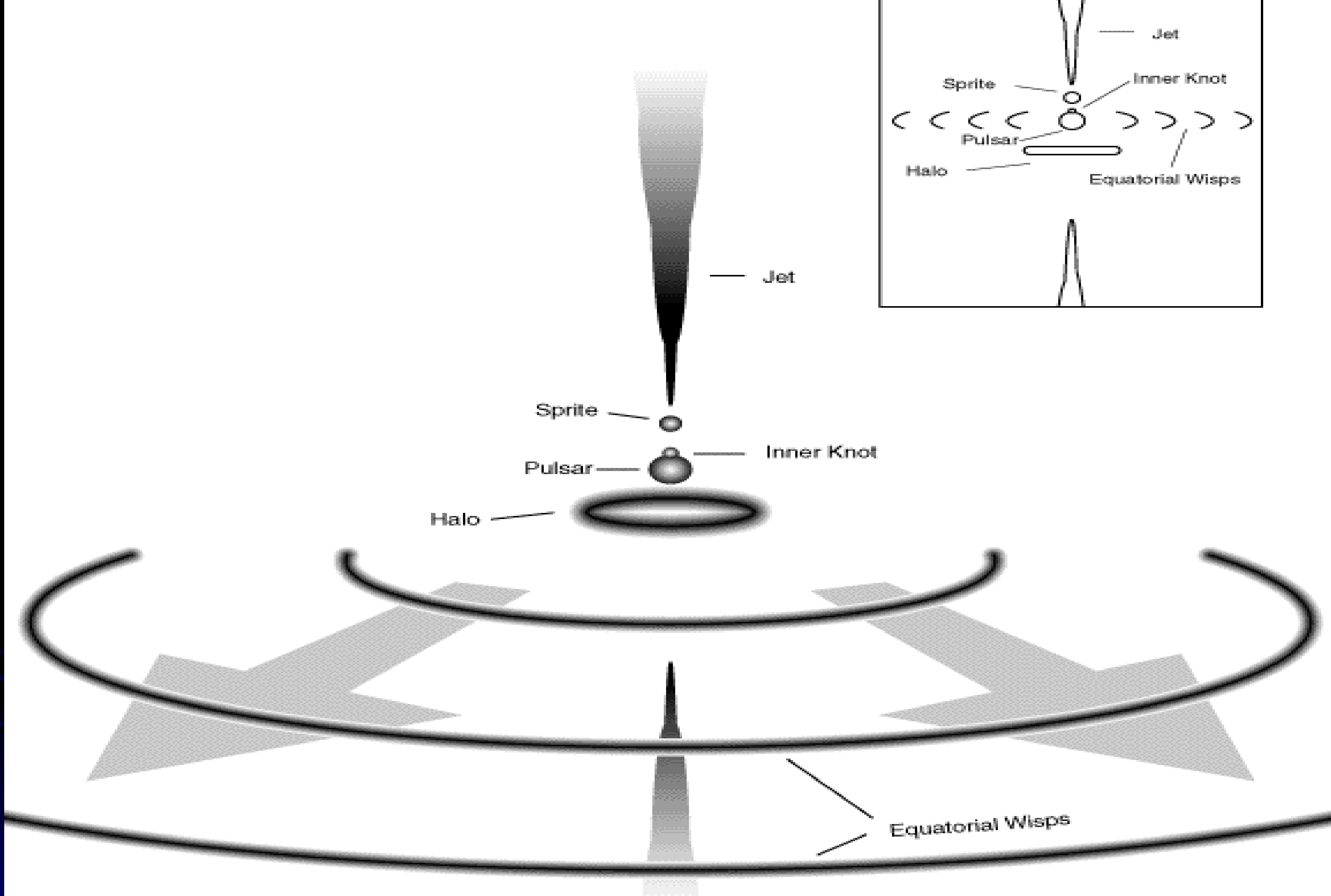
- On November 28 1967 , Jocelyn Bell discovered a source with an exceptionally regular pattern of radio flashes. These radio flashes occurred every 1 1/3 seconds like clockwork.




The Pulsar Lighthouse Effect
Magnetic Field
Electro-magnetic radiation


Crab Nebula
Palomar
PRC96-22a · ST ScI OPO · May 30, 1996
J. Hester and P. Scowen (AZ State Univ.) and NASA
HST · WFPC2





This is a diagram of environment around the pulsar at the heart of the Crab nebula, based on images take by Hubble Space Telescope. The jets of high speed particles, and the outward moving "equatorial wisps," are powered by the pulsar, which is the rapidly rotating crushed remnant of an exploded star.

PR96-22 • ST ScI OPO • May 30, 1996

Summary: End Points of Stellar Evolution

Remnant	Progenitor Mass	Remnant Mass	Size	Density	Means of Support	Final Stage
White Dwarf	$M_* < 8M_\odot$	$M_{WD} < 1.4M_\odot$	$R_{WD} \sim R_{earth}$	1 ton/cm^3 (1 Volkswagen/cm^3)	e^- degeneracy	Planetary Nebula
Neutron Star	$8M < M_* < 20M_\odot$	$M_{NS} < 3M_\odot$	$R_{NS} \sim 10$ km	200 million ton/cm^3 (All Volkswagens/cm^3)	n degeneracy	Supernova
Black Hole	$M_* > 20M_\odot$	$M_{BH} > 3M_\odot$	0 $R_{grav} = 2GM/c^2$	infinite	none	?

Next lecture:

black holes and relativistic stars.