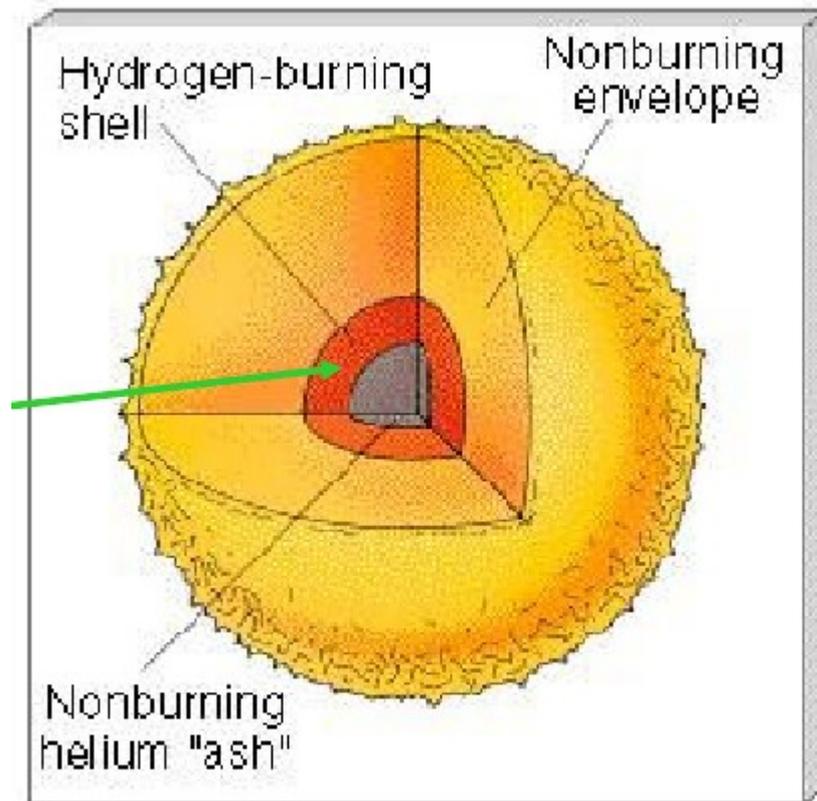


Saída da Sequência Principal

Na Sequência Principal ocorre uma lenta transformação de H em He ~ 10 bilhões de ano



Estrela em camadas

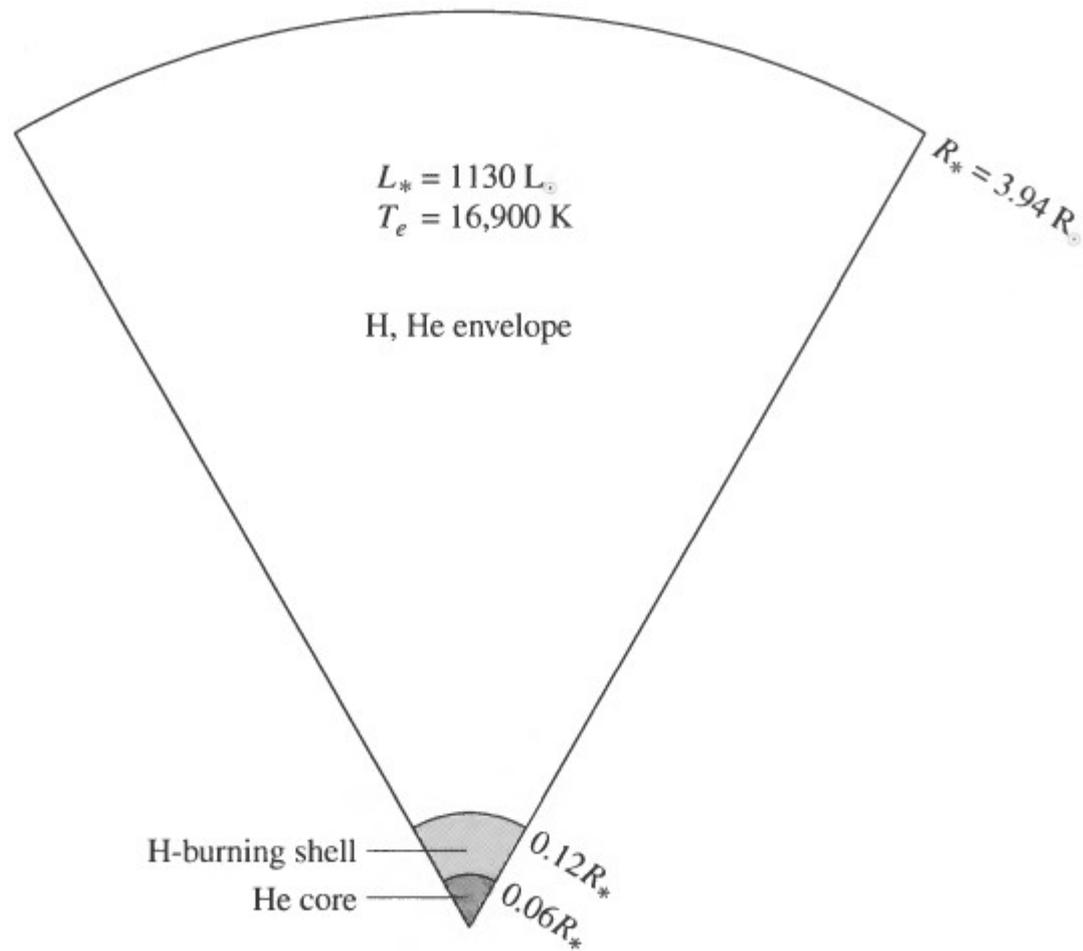


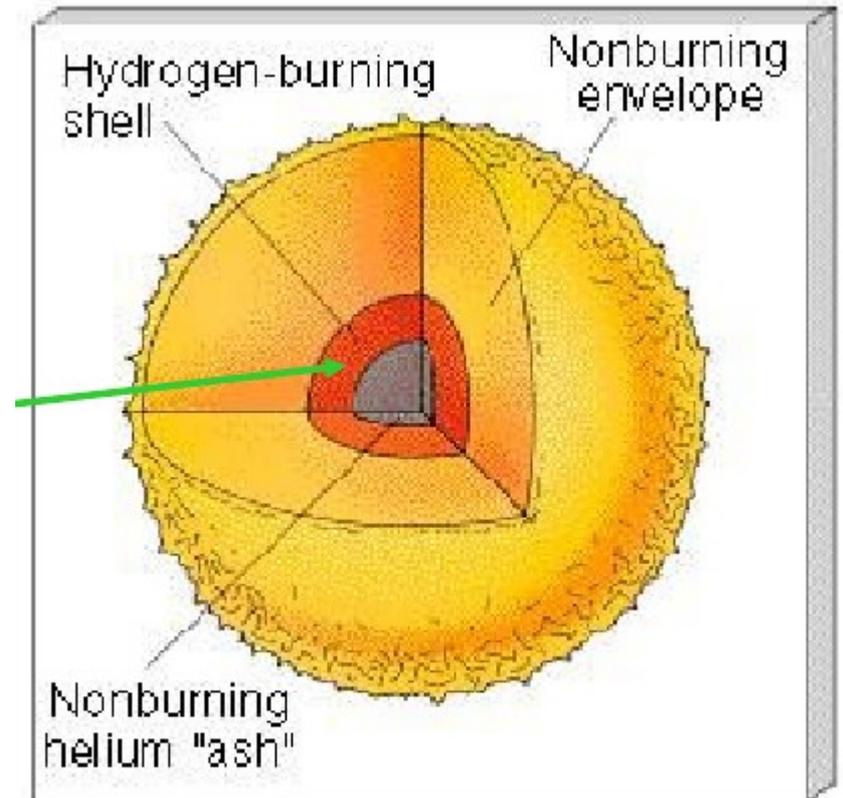
FIGURE 13.7 A $5 M_{\odot}$ star with a helium core and a hydrogen-burning shell shortly after shell ignition (point 3 in Fig. 13.1). (Data from Iben, *Ap. J.*, 143, 483, 1966.)

Começa a acabar o H em condições de fazer reações nucleares

- Diminui a produção de energia
- Reajuste do equilíbrio entre gravitação e pressão
- Pressão diminui
- A gravitação prevalece
- A estrela começa a se contrair
- Pressão aumenta para reestabelecer equilíbrio
- Temperatura interna aumenta ($10^7 \rightarrow 10^8$ Kelvin)
- Aumento da temperatura faz o hidrogênio queimar mais rápido
- Estrela tem menos combustível (H) mas queima mais rápido - > Luminosidade aumenta

Estrela em camadas

- Núcleo
 - He não interagente
 - Se contraindo por ação da gravidade.
 - Não existe pressão de radiação para equilibrar porque a temperatura ainda não é suficiente para iniciar a queima do He
- Camada intermediária
 - H queimando rapidamente
 - Alta produção de energia
- Camada externa
 - H não interagente
 - recebe a energia da camada intermediária e expande
 - A temperatura na superfície diminui devido a expansão

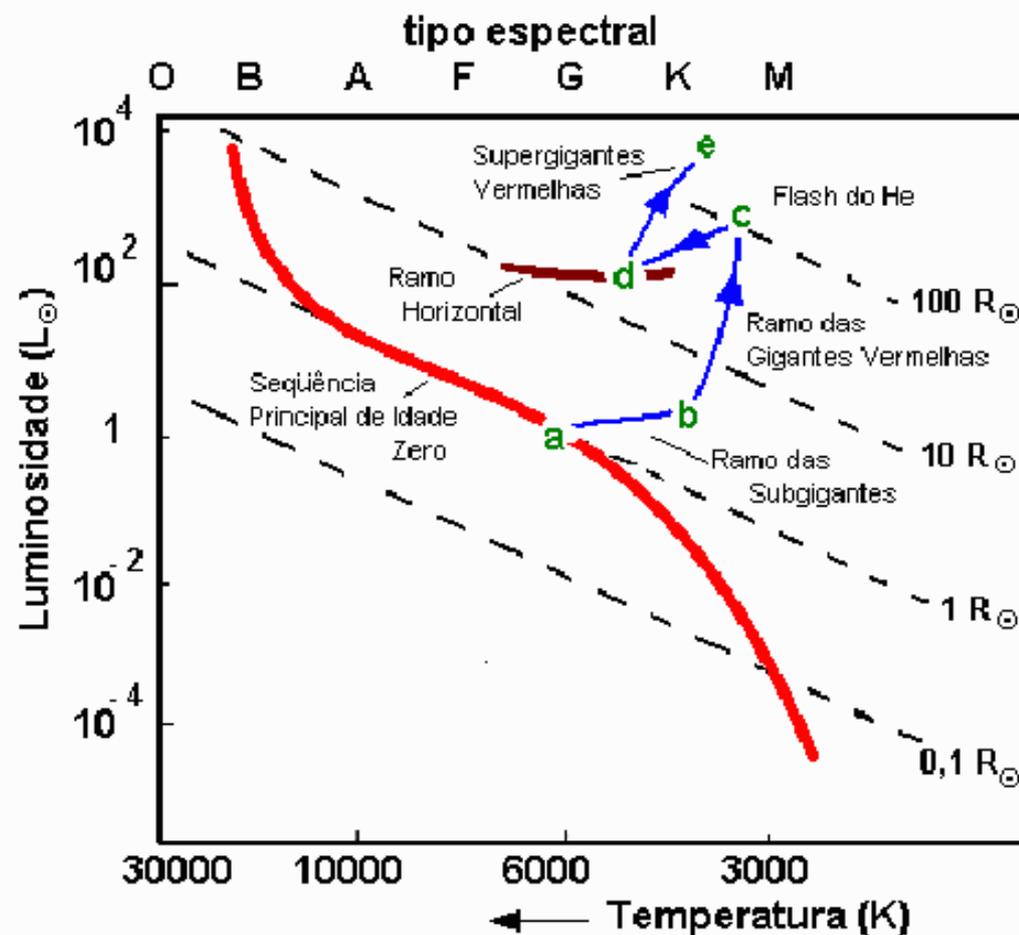


Caminho do diagrama HR

a -> b Hidrogênio começa a acabar

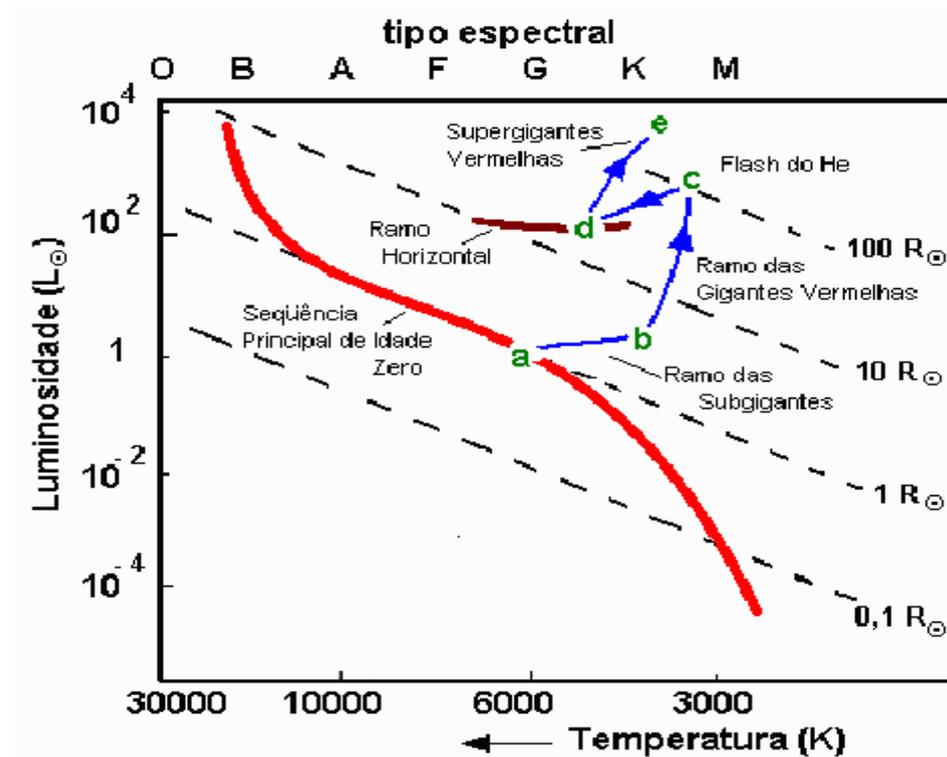
Contração: gravidade vencendo

b -> c Hidrogênio queima rapidamente



Evolução do Núcleo b->c

- Se contraindo, temperatura interna e pressão aumentando
- Energia Térmica arranca os elétrons dos átomos
- Núcleo de He não interage com elétrons livres
- Continua se contraindo, temperatura e pressão aumentando
- Elétrons degenerados pelo aumento da pressão
- Ignição do Hélio (Ponto c)



Degenerescência de elétrons

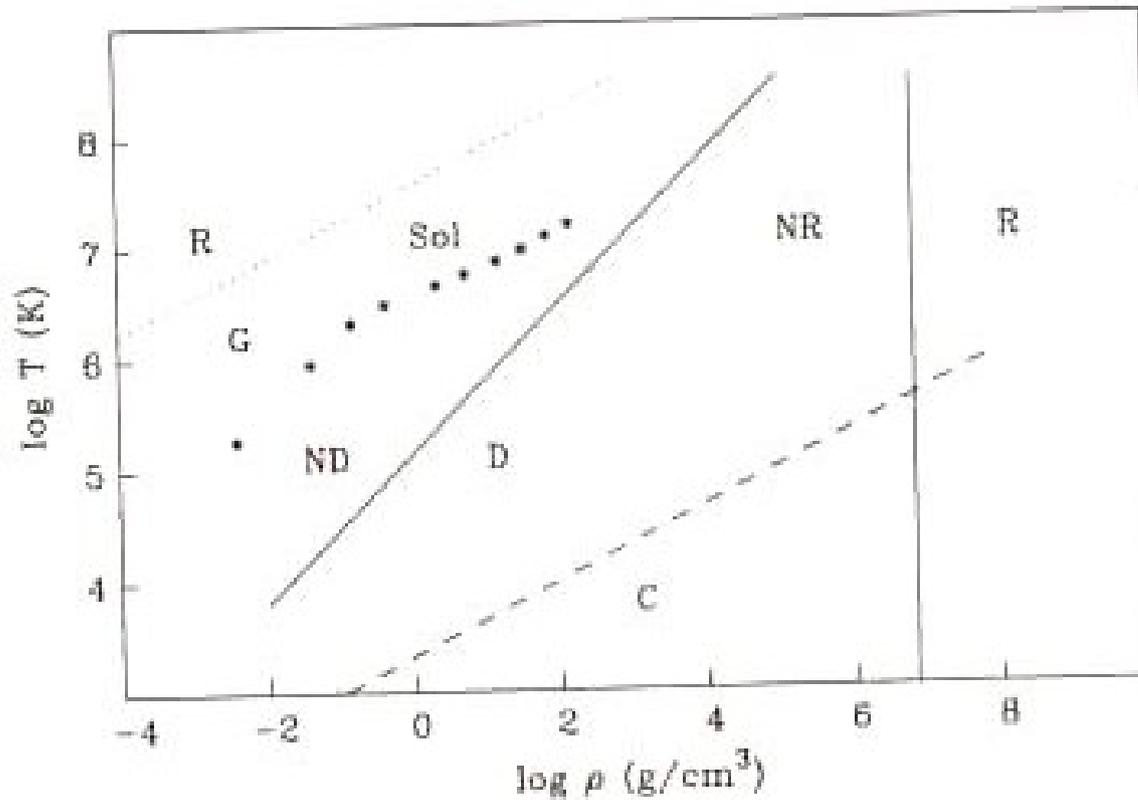
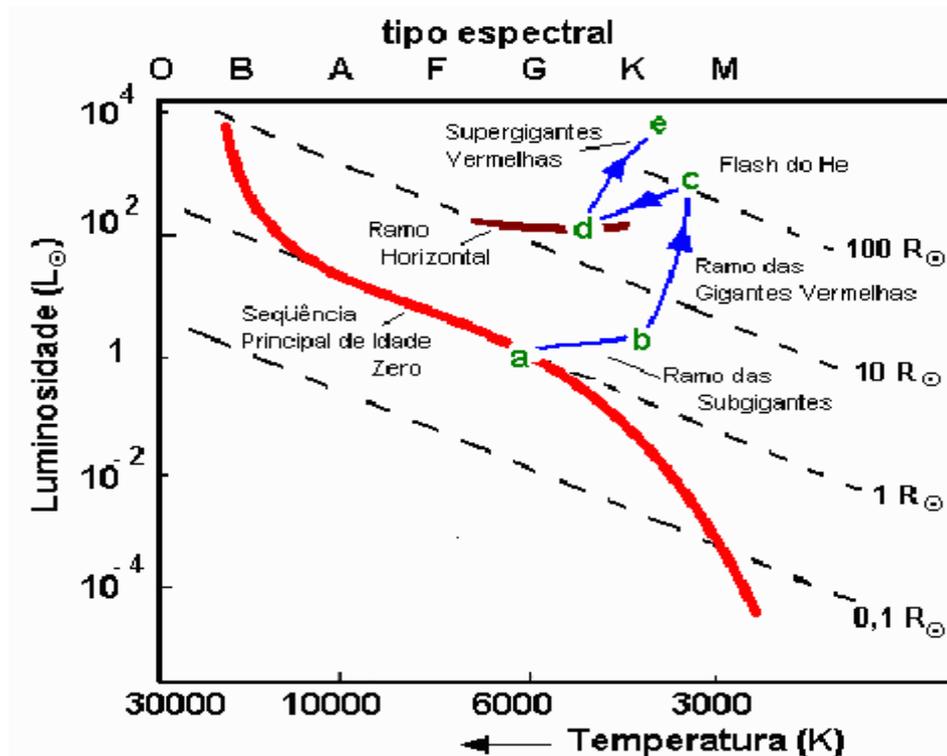


fig 3.6 pag 82 livro Walter Maciel

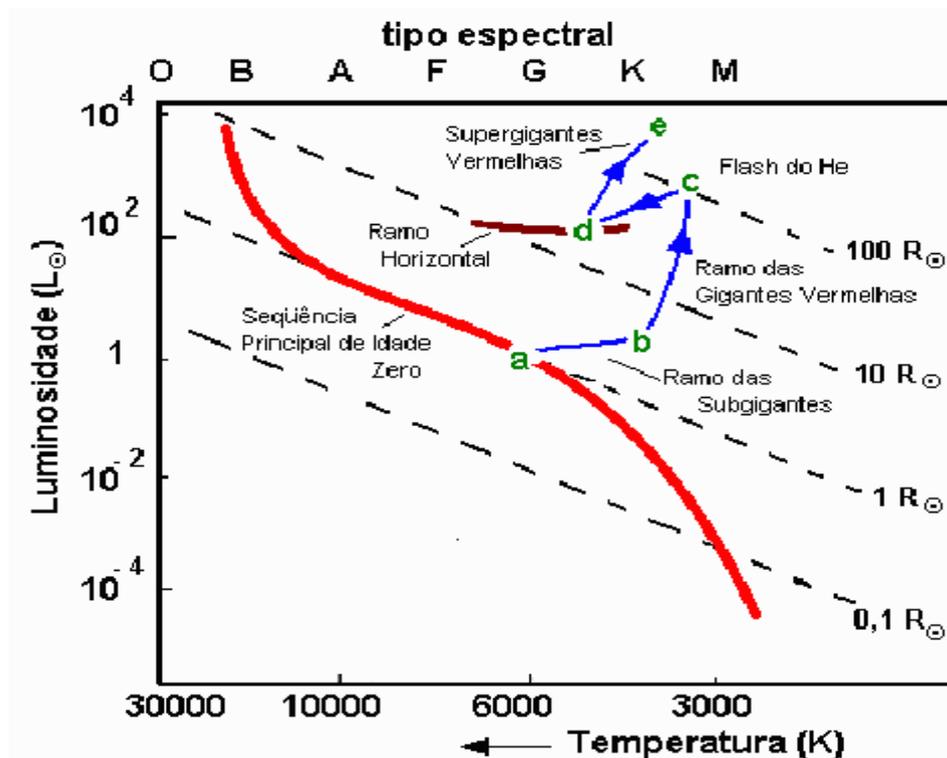
Flash do Hélio c->d

- Aumenta a energia produzida no núcleo
- Temperatura aumenta no núcleo
- Mas não aumenta a pressão, porque os elétrons estão livres
- O núcleo não expande
- A temperatura no núcleo segue crescendo rapidamente
- A taxa de produção de energia aumenta -> explosão chamada de flash do He



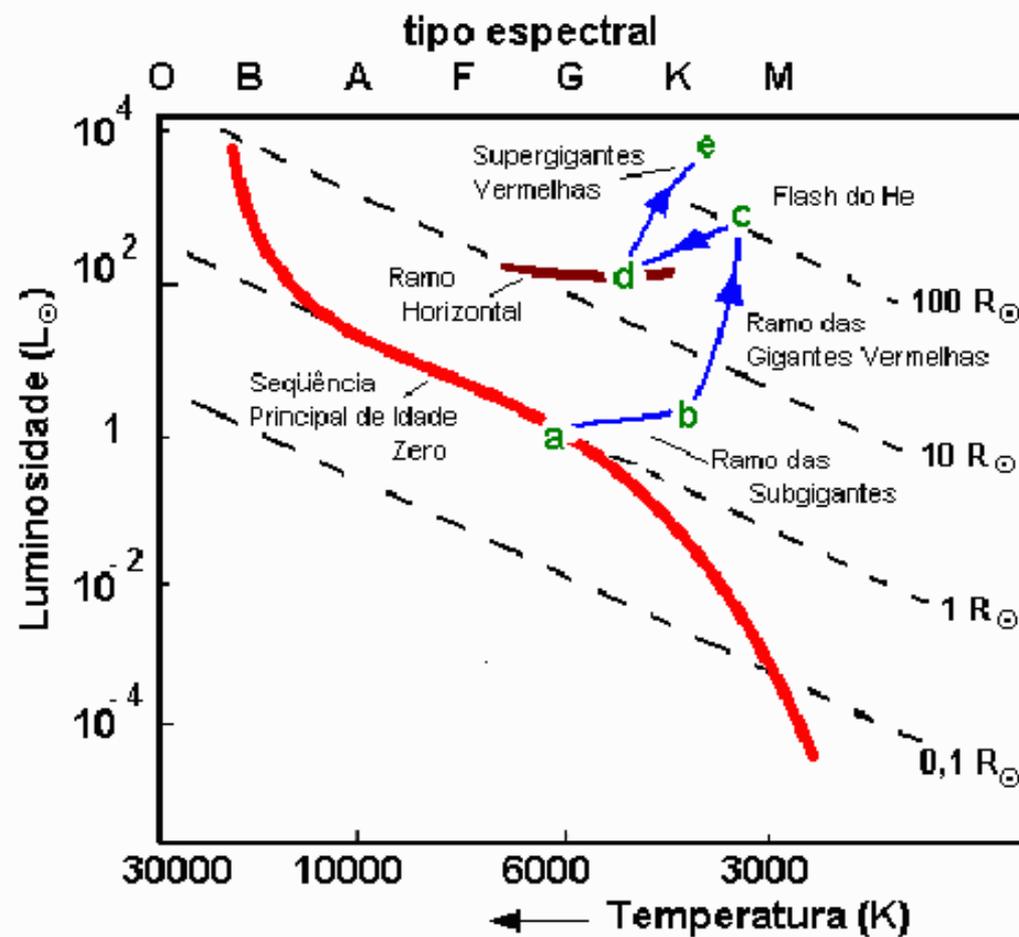
Flash do Hélio c->d

- A temperatura no núcleo segue crescendo rapidamente
- Os elétrons deixam de ser degenerados
- O núcleo se re-aranja, movimento das camadas para criação de um núcleo de Carbono.
- A energia é consumida neste processo e não chega à superfície
- A luminosidade não aumenta



Caminho do diagrama HR

c -> d Flash He, degenerescência



Em detalhes

STELLAR EVOLUTION. II. THE EVOLUTION OF A $3 M_{\odot}$ STAR FROM THE MAIN SEQUENCE THROUGH CORE HELIUM BURNING*

ICKO IBEN, JR.†

California Institute of Technology, Pasadena, California

Received February 19, 1965; revised June 18, 1965

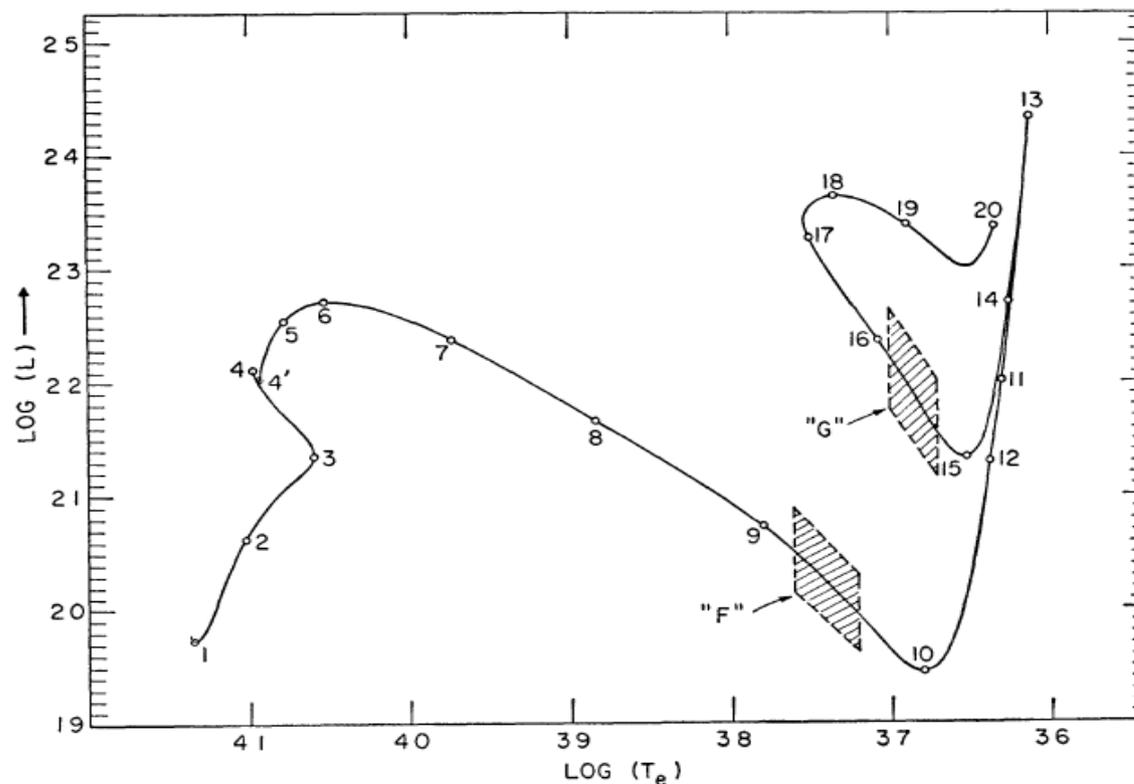


FIG. 1.—Path in the theoretical Hertzsprung-Russell diagram for a $3 M_{\odot}$ population I star. Luminosity L is in units of 3.86×10^{33} erg/sec and surface temperature T_e is in units of $^{\circ}\text{K}$.

Em detalhes

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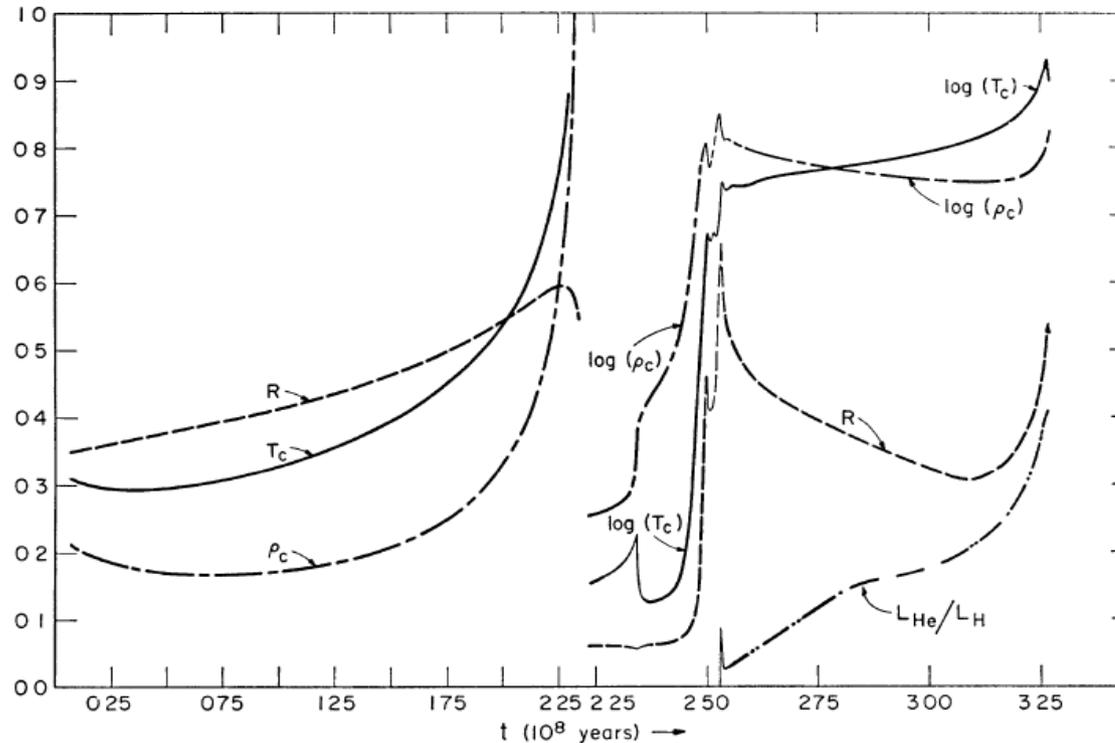


FIG. 3.—The variation with time (units of 10^8 yr) of radius (R), central density (ρ_c), central temperature (T_c), and the rate of energy production by helium-burning relative to the rate of energy production by hydrogen-burning ($L_{\text{He}}/L_{\text{H}}$). Units are $R_{\odot} = 6.96 \times 10^{10}$ cm for radius, 10^6 °K for temperature, and gm/cm^3 for density. To the left of the break in t , scale limits correspond to $0 \leq R \leq 5$, $21 \leq T_c \leq 31$, and $30 \leq \rho_c \leq 80$. To the right of the break in t , scale limits correspond to $0 \leq R \leq 50$, $1.3 \leq \log T_c \leq 2.3$, and $0.5 \leq \log \rho_c \leq 5.5$. The ratio $L_{\text{He}}/L_{\text{H}}$ is allowed to vary from 0 to 1.

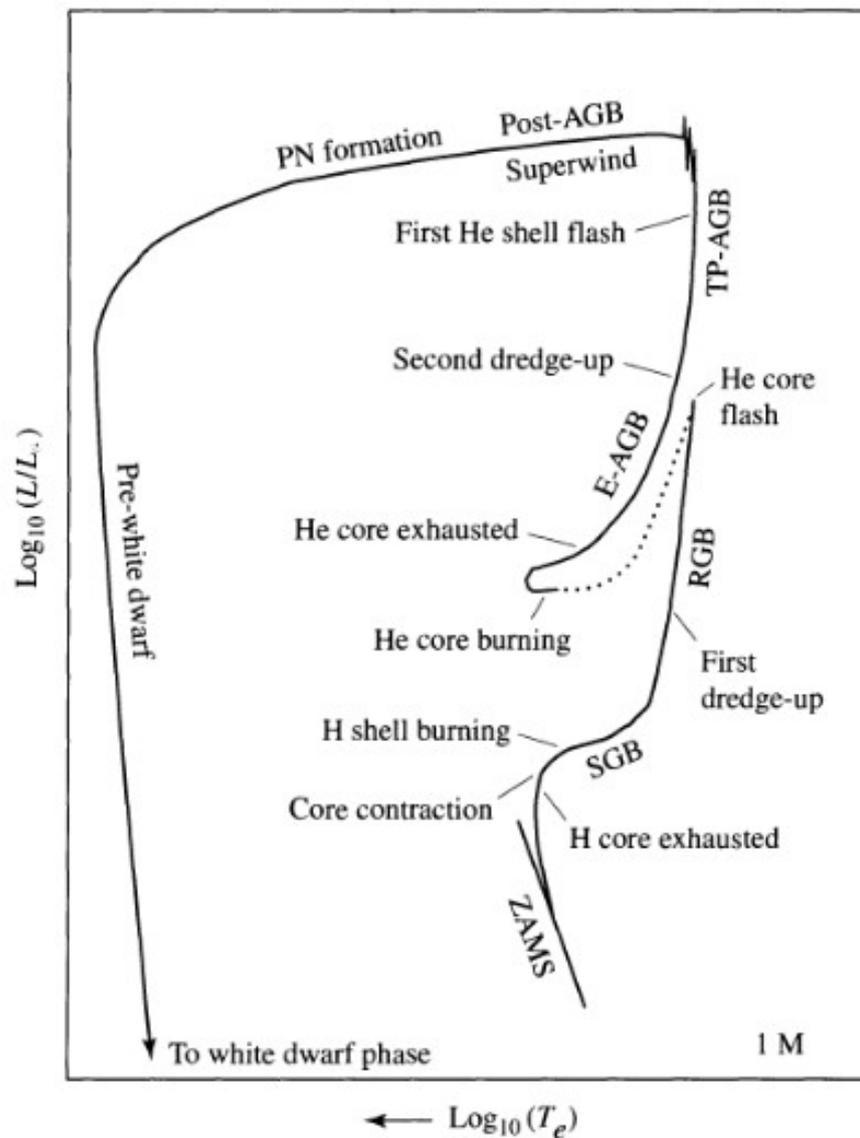


FIGURE 13.4 A schematic diagram of the evolution of a low-mass star of $1 M_{\odot}$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The dotted phase of evolution represents rapid evolution following the helium core flash. The various phases of evolution are labeled as follows: Zero-Age-Main-Sequence (ZAMS), Sub-Giant Branch (SGB), Red Giant Branch (RGB), Early Asymptotic Giant Branch (E-AGB), Thermal Pulse Asymptotic Giant Branch (TP-AGB), Post-Asymptotic Giant Branch (Post-AGB), Planetary Nebula formation (PN formation), and Pre-white dwarf phase leading to white dwarf phase.

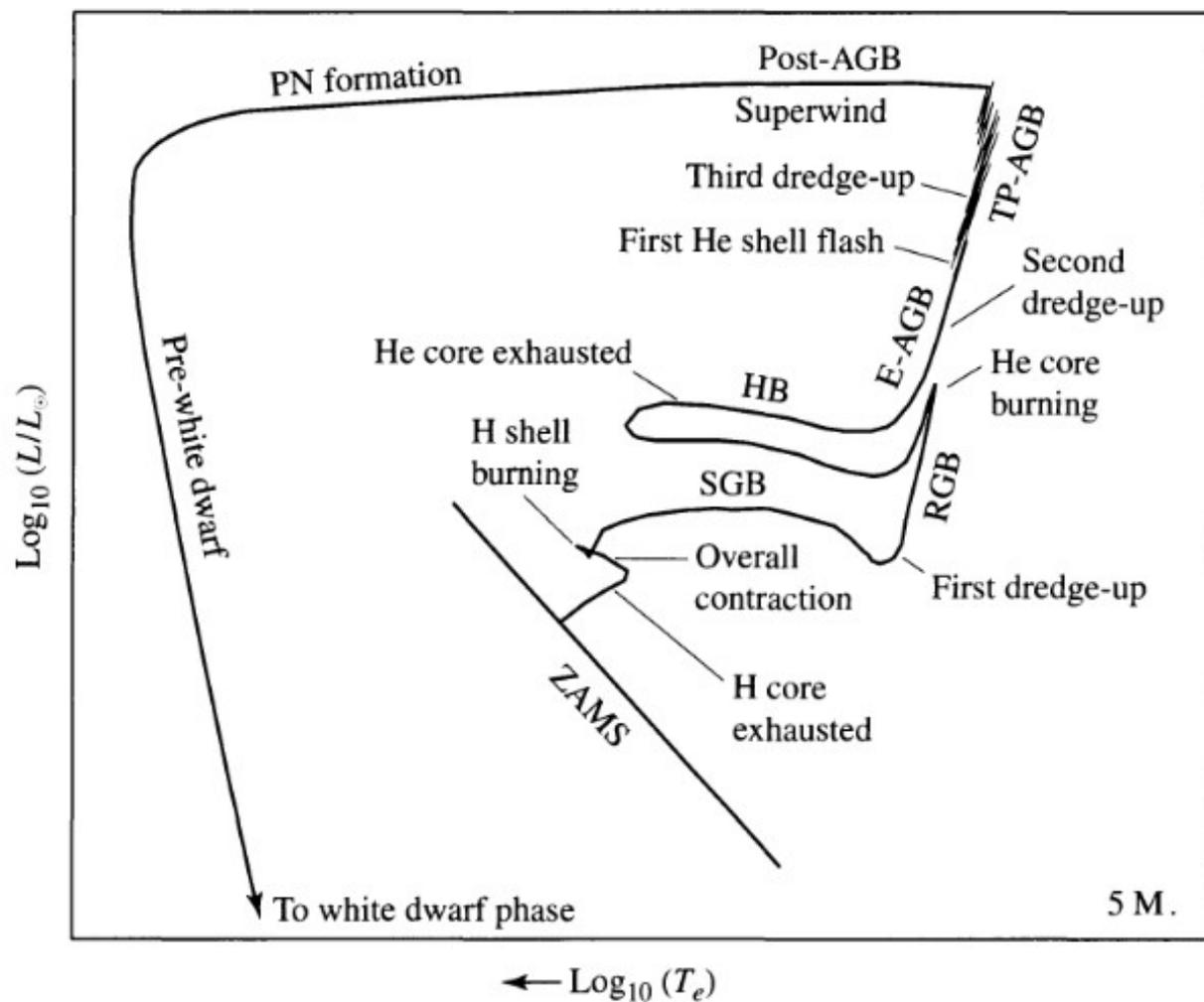


FIGURE 13.5 A schematic diagram of the evolution of an intermediate-mass star of $5 M_{\odot}$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The diagram is labeled according to Fig. 13.4 with the addition of the Horizontal Branch (HB).

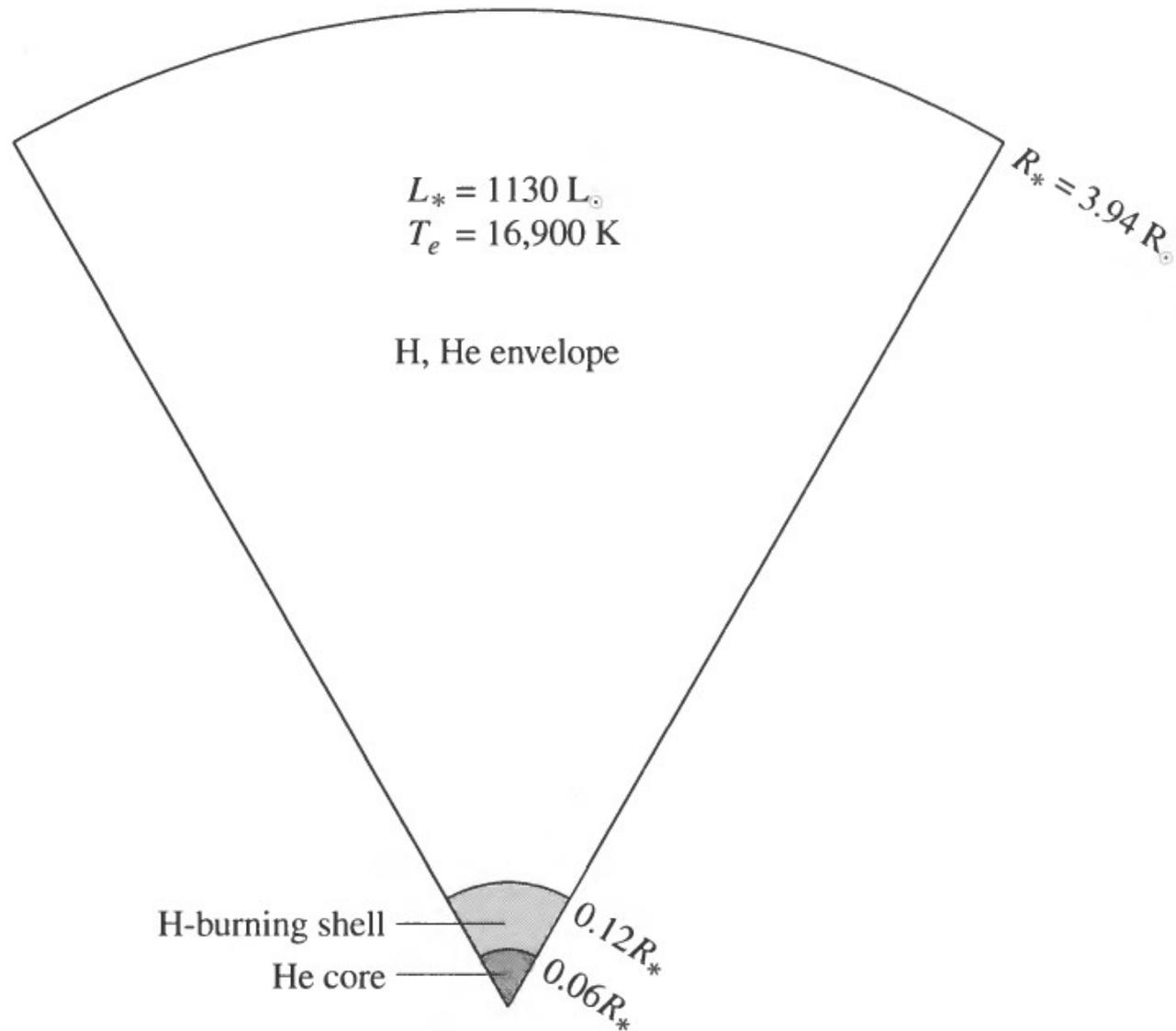


FIGURE 13.7 A $5 M_{\odot}$ star with a helium core and a hydrogen-burning shell shortly after shell ignition (point 3 in Fig. 13.1). (Data from Iben, *Ap. J.*, 143, 483, 1966.)

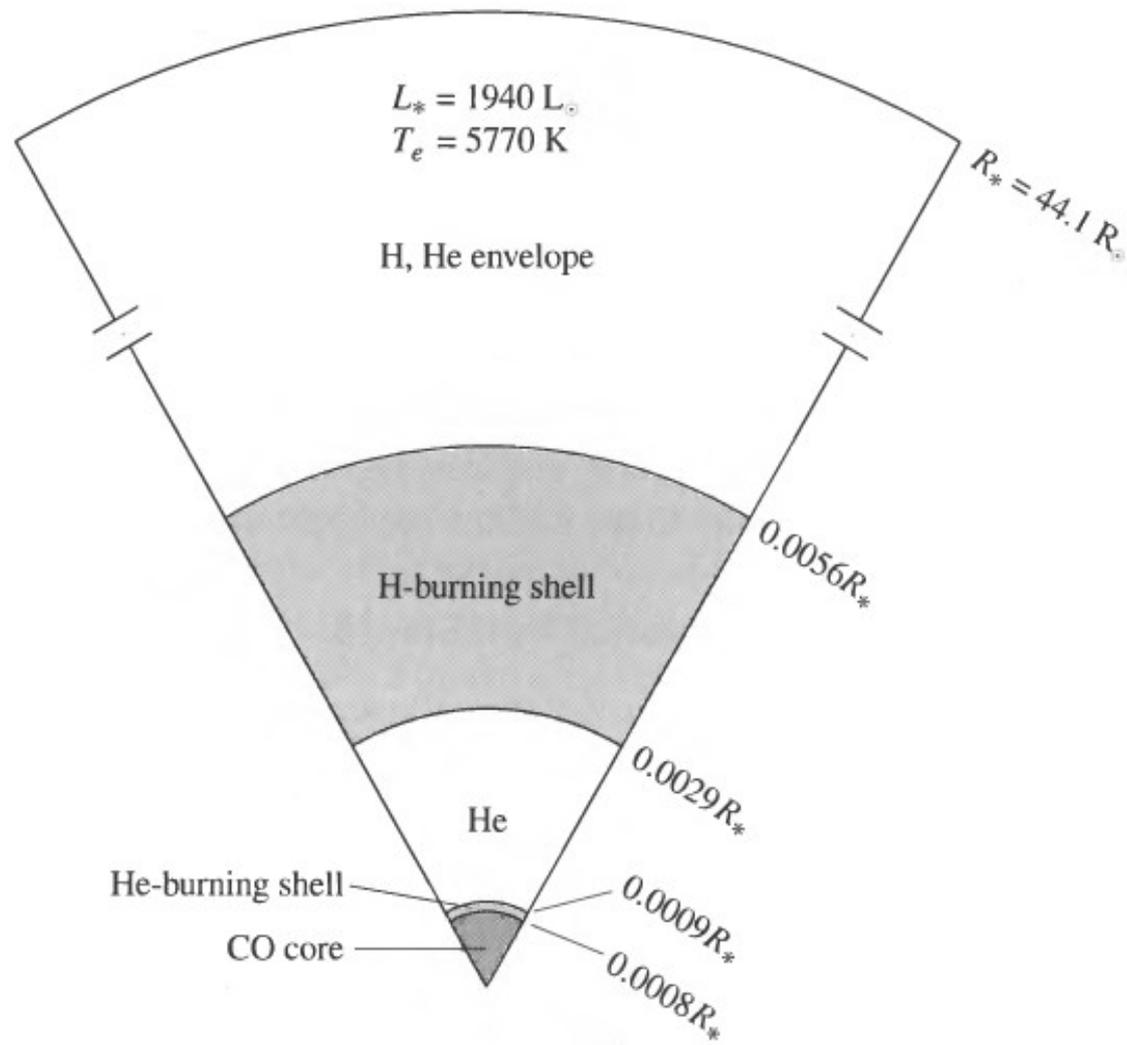
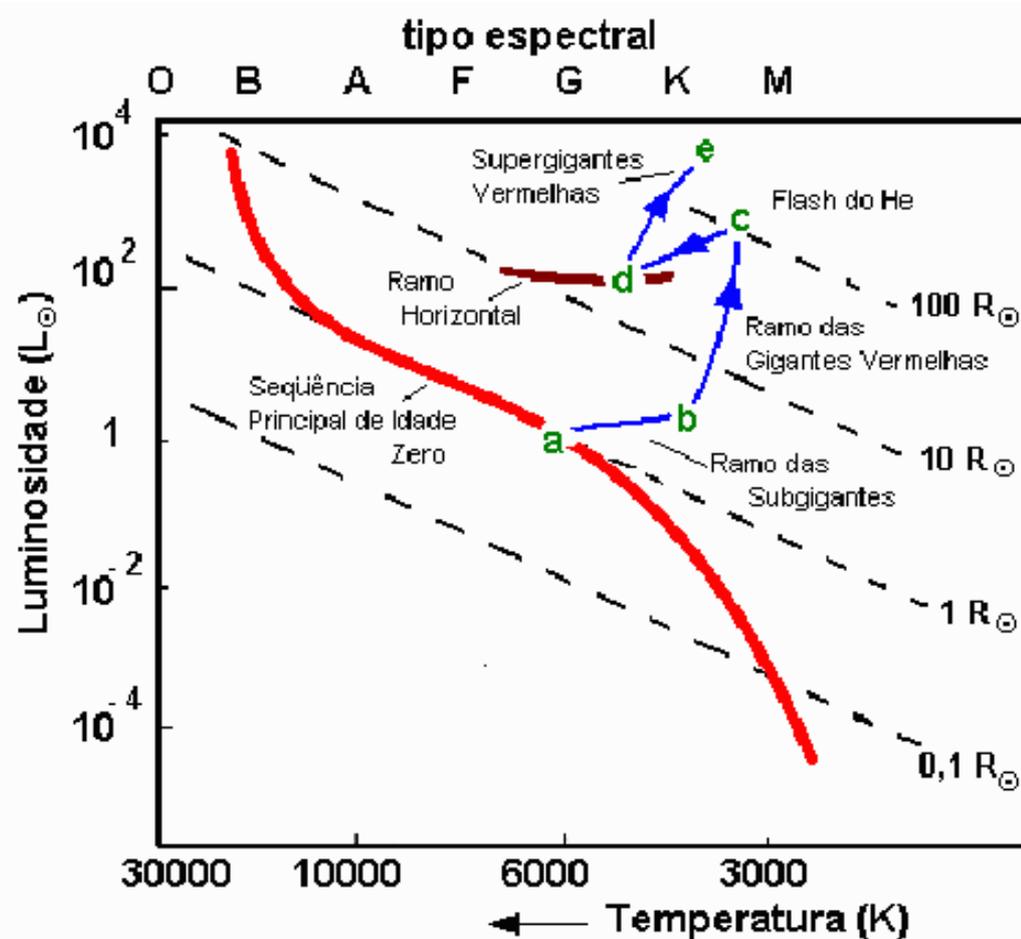


FIGURE 13.8 A $5 M_{\odot}$ star on the early asymptotic giant branch with a carbon–oxygen core and hydrogen- and helium-burning shells. Note that relative to the surface radius, the scale of the shells and core has been increased by a factor of 100 for clarity. (Data from Iben, *Ap. J.*, 143, 483, 1966.)

He chegando ao fim: d -> e

- O processo se repete igual ao fim do H
- Contração do núcleo
- Expansão do envelope
- Degenerescência



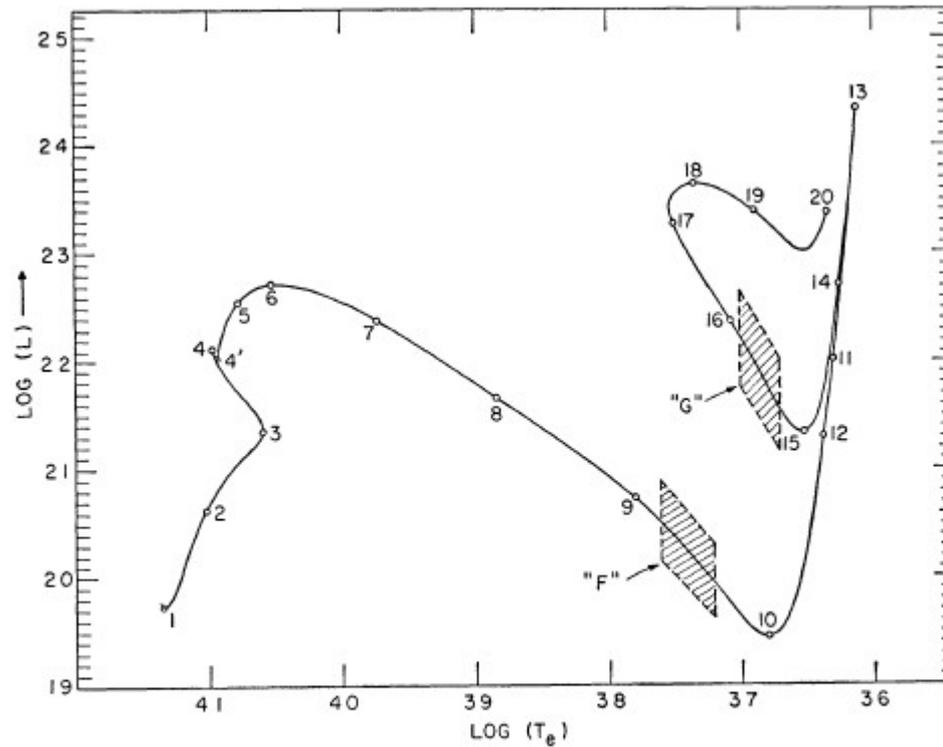


FIG. 1.—Path in the theoretical Hertzsprung-Russell diagram for a $3 M_{\odot}$ population I star. Luminosity L is in units of 3.86×10^{33} erg/sec and surface temperature T_e is in units of $^{\circ}\text{K}$.

EVOLUTIONARY LIFETIMES

Point	Time	Point	Time	Point	Time
1 ..	0 024586	7...	2 47004	14 ..	2 55850
2 ..	1 38921	8...	2 47865	15 ..	2 78295
3 .	2 23669	9 .	2 48429	16	2 94233
4. .	2 34089	10	2 48925	17 .	3 06968
4' .	2 34222	11	2 49817	18 .	3 19043
5 ..	2 40119	12	2 50728	19	3 23566
6....	2 44420	13 ..	2 53163	20	3 26323

10^8 anos

Se $M < 8 M_{\text{solares}}$
o Carbono não começa a ser queimado

Re alimentações

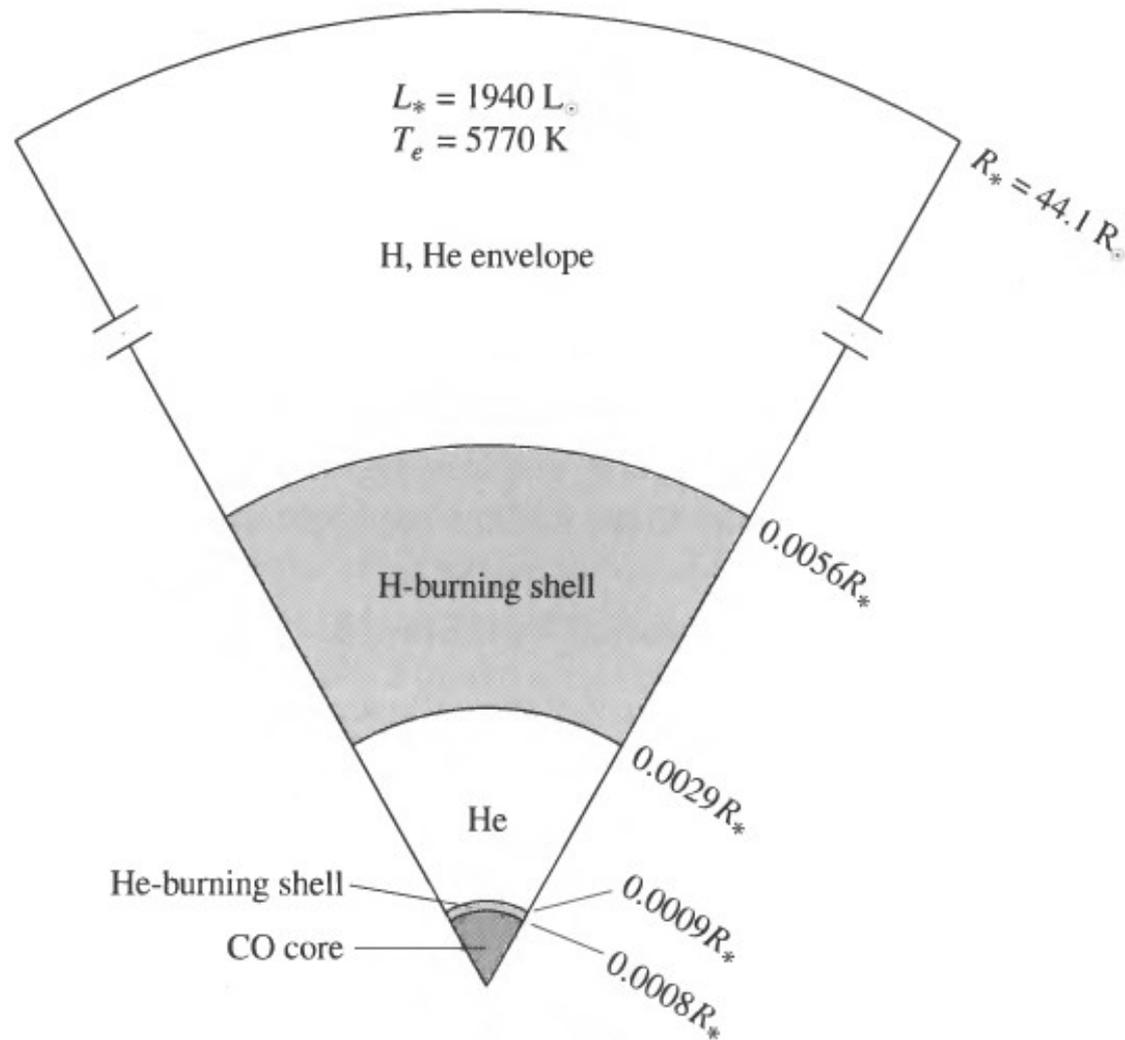


FIGURE 13.8 A $5 M_{\odot}$ star on the early asymptotic giant branch with a carbon–oxygen core and hydrogen- and helium-burning shells. Note that relative to the surface radius, the scale of the shells and core has been increased by a factor of 100 for clarity. (Data from Iben, *Ap. J.*, 143, 483, 1966.)

Instabilidades

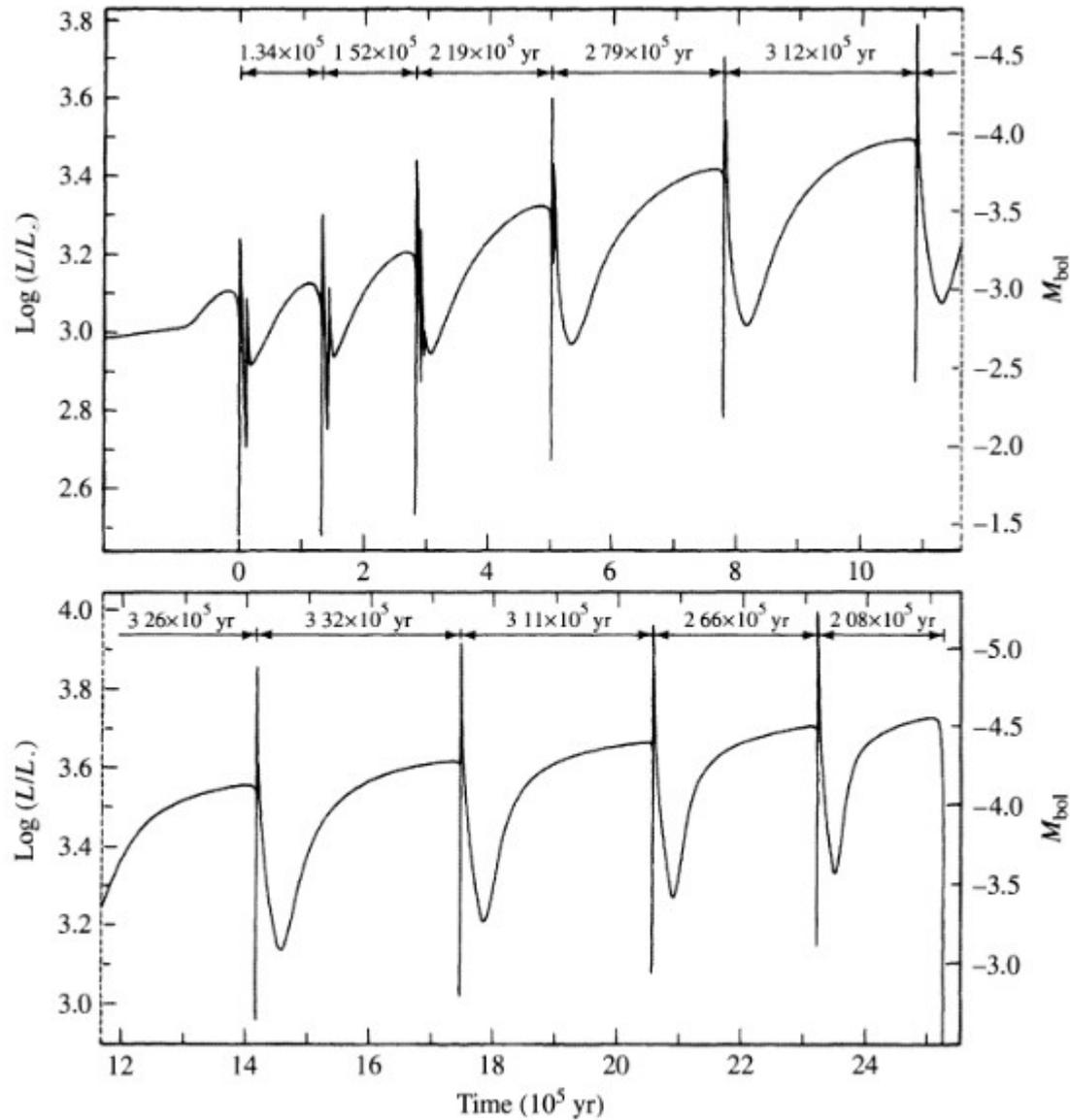
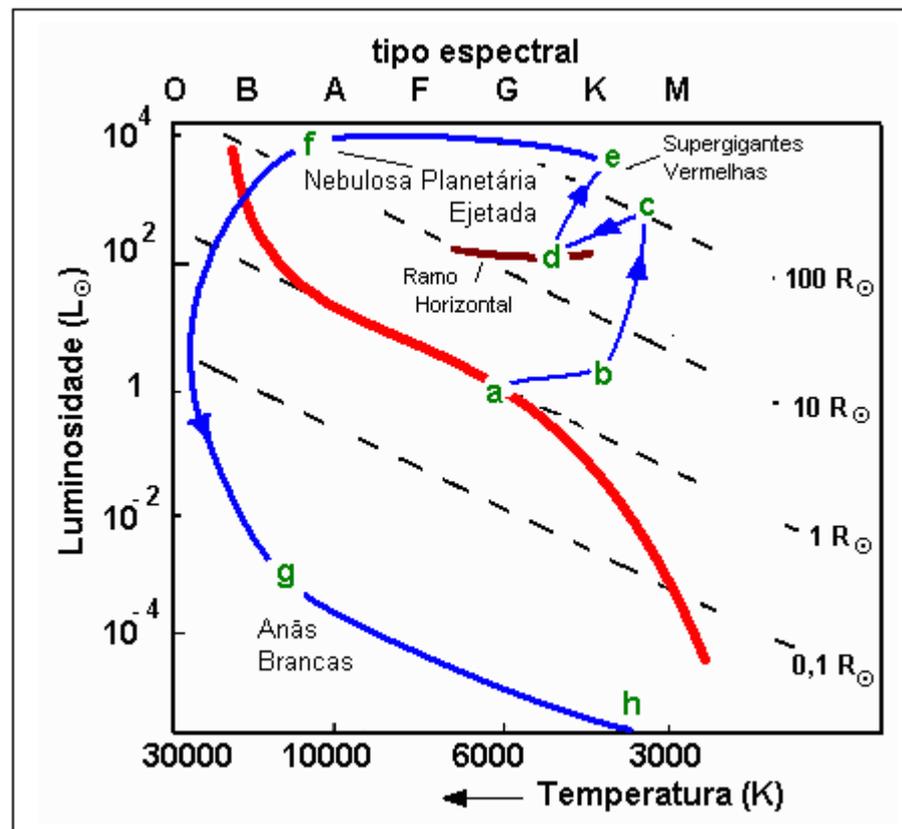


FIGURE 13.9 The surface luminosity as a function of time for a $0.6 M_{\odot}$ stellar model that is undergoing helium shell flashes on the TP-AGB. (Figure adapted from Iben, *Ap. J.*, 260, 821, 1982.)

Anãs brancas

- Hidrogênio e Hélio é expelido e forma uma nebulosa planetária (e->f)
- Núcleo de carbono sobrevive mas sem fonte de energia (f-> g)
- O núcleo vai esfriando e vira uma anã branca



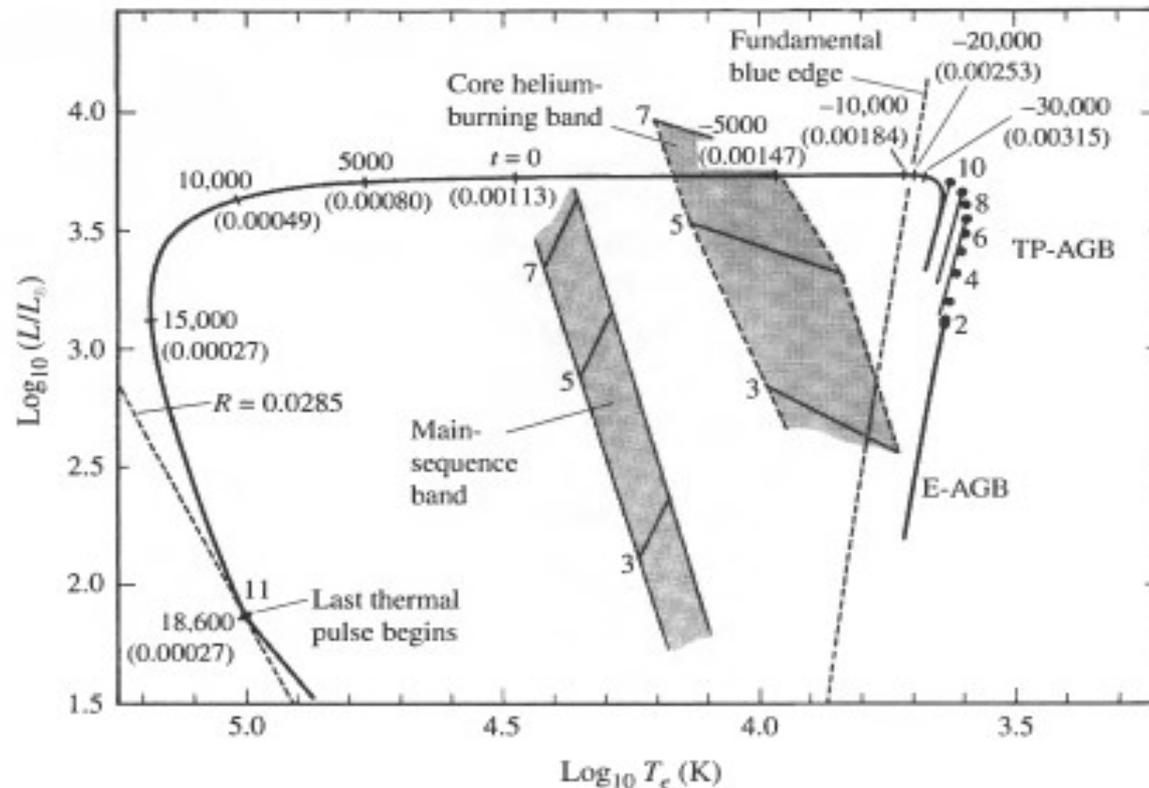


FIGURE 13.12 The AGB and post-AGB evolution of a $0.6 M_{\odot}$ star undergoing mass loss. The initial composition of the model is $X = 0.749$, $Y = 0.25$, and $Z = 0.001$. The main-sequence and horizontal branches of 3, 5, and $7 M_{\odot}$ stars are shown for reference. Details of the figure are discussed in the body of the text. (Figure adapted from Iben, *Ap. J.*, 260, 821, 1982.)

across the H-R diagram. The amount of mass remaining in the hydrogen-rich envelope is indicated in parentheses along the evolutionary track (in M_{\odot}). Also indicated is the amount of time before (negative) or after (positive) the point when the star's effective temperature was 30,000 K (the time is measured in years). Following the eleventh helium shell flash, the star finally loses the last remnants of its envelope and becomes a white dwarf of radius $0.0285 R_{\odot}$.¹²

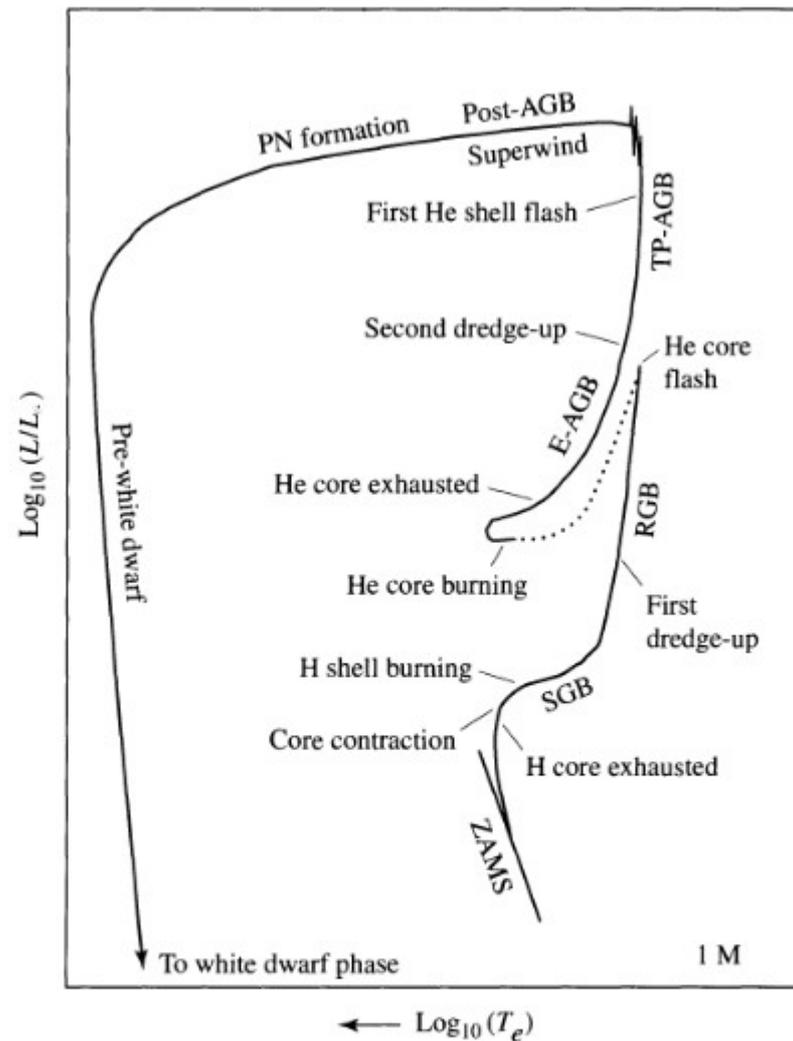


FIGURE 13.4 A schematic diagram of the evolution of a low-mass star of $1 M_{\odot}$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The dotted phase of evolution represents rapid evolution following the helium core flash. The various phases of evolution are labeled as follows: Zero-Age-Main-Sequence (ZAMS), Sub-Giant Branch (SGB), Red Giant Branch (RGB), Early Asymptotic Giant Branch (E-AGB), Thermal Pulse Asymptotic Giant Branch (TP-AGB), Post-Asymptotic Giant Branch (Post-AGB), Planetary Nebula formation (PN formation), and Pre-white dwarf phase leading to white dwarf phase.

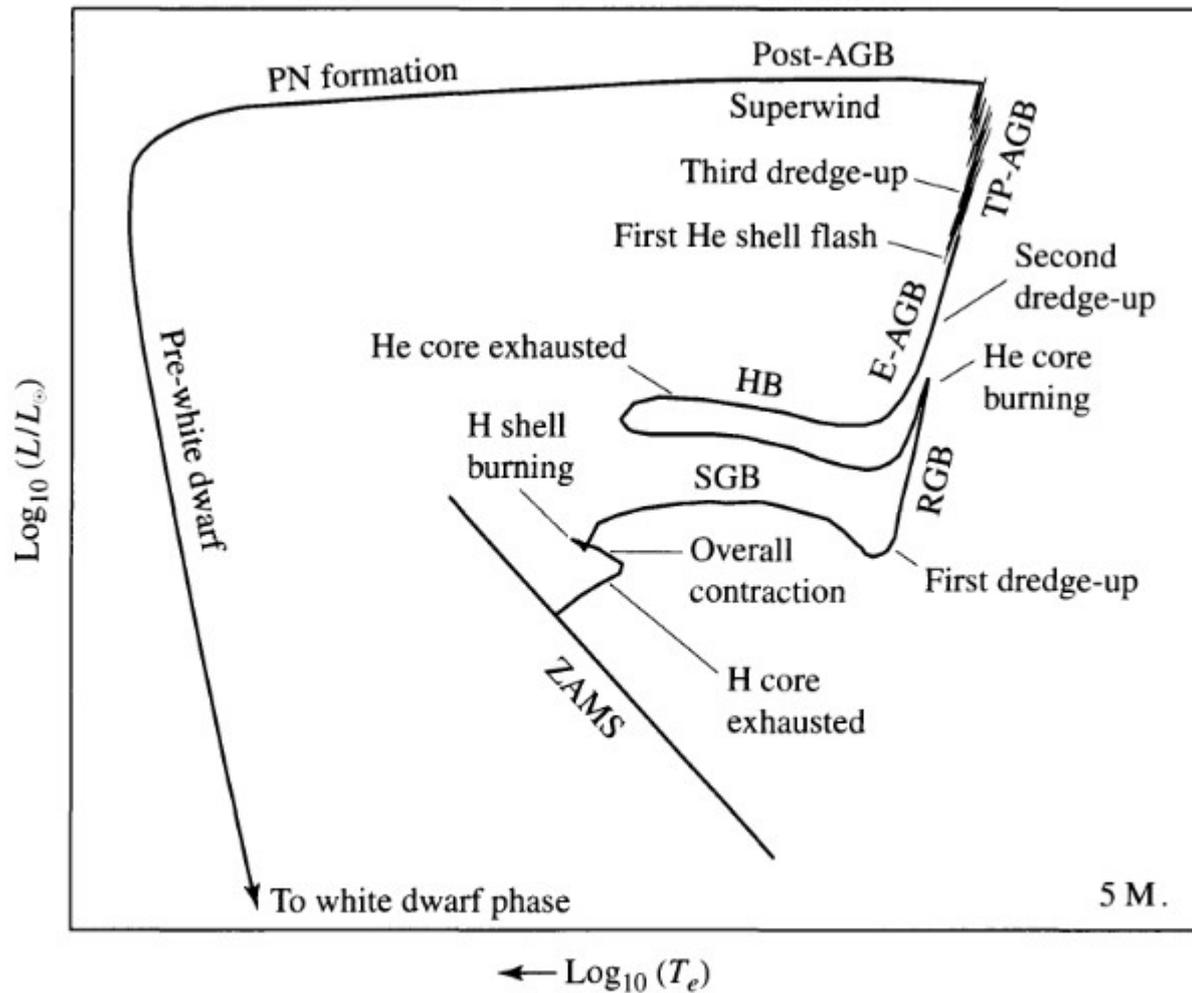
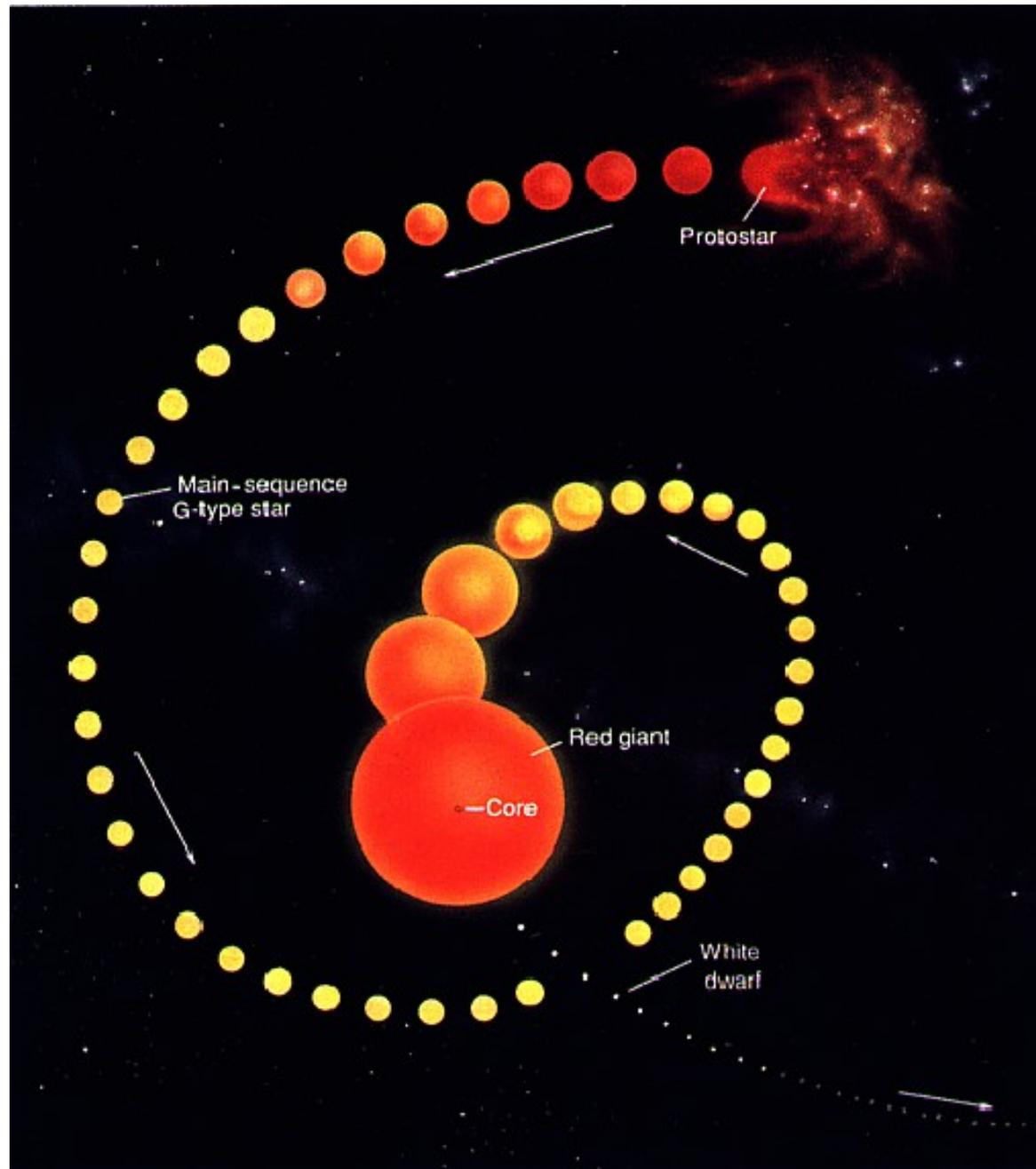
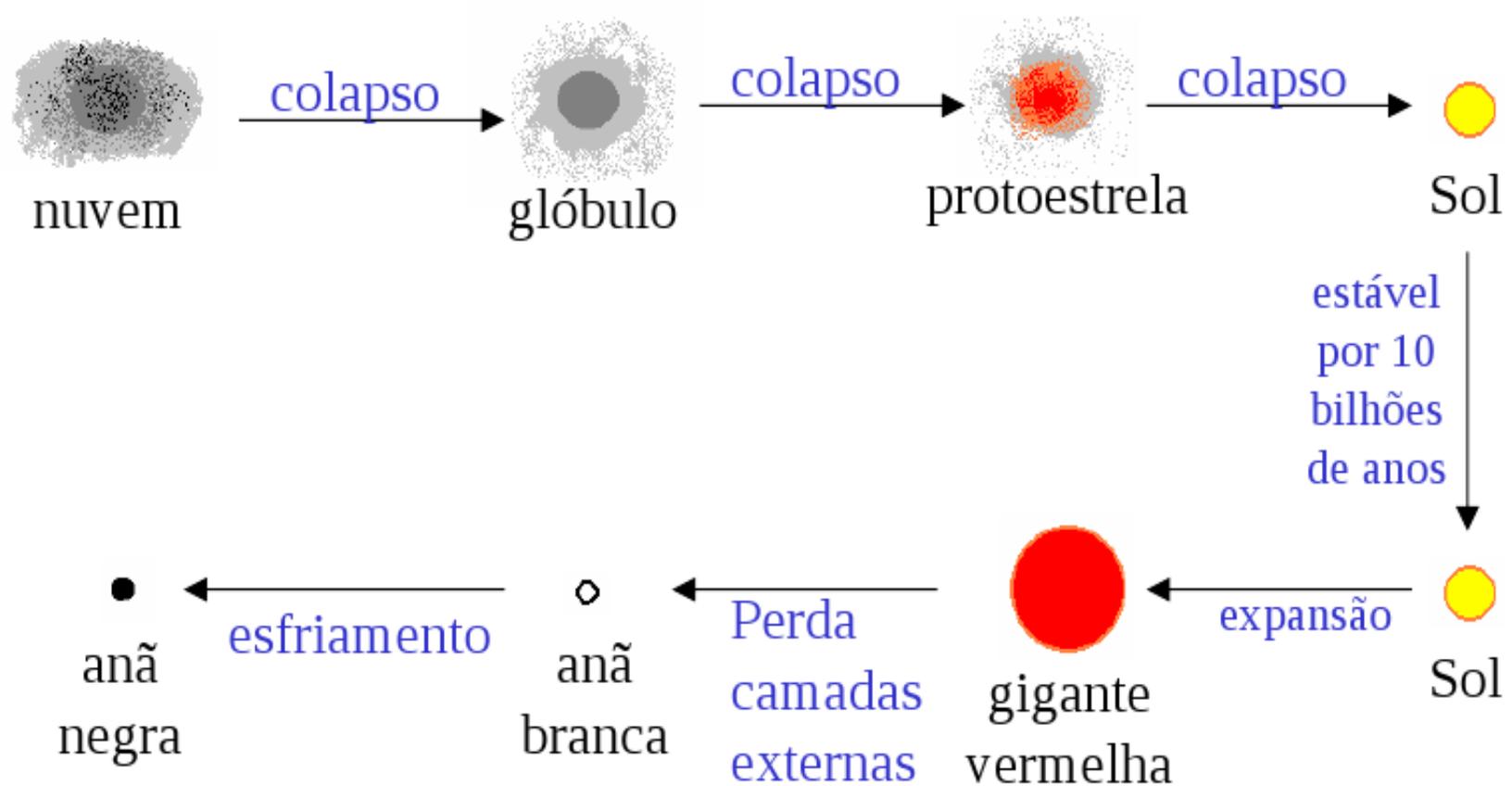


FIGURE 13.5 A schematic diagram of the evolution of an intermediate-mass star of $5 M_{\odot}$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The diagram is labeled according to Fig. 13.4 with the addition of the Horizontal Branch (HB).

$M < 8 M_{\text{solares}}$



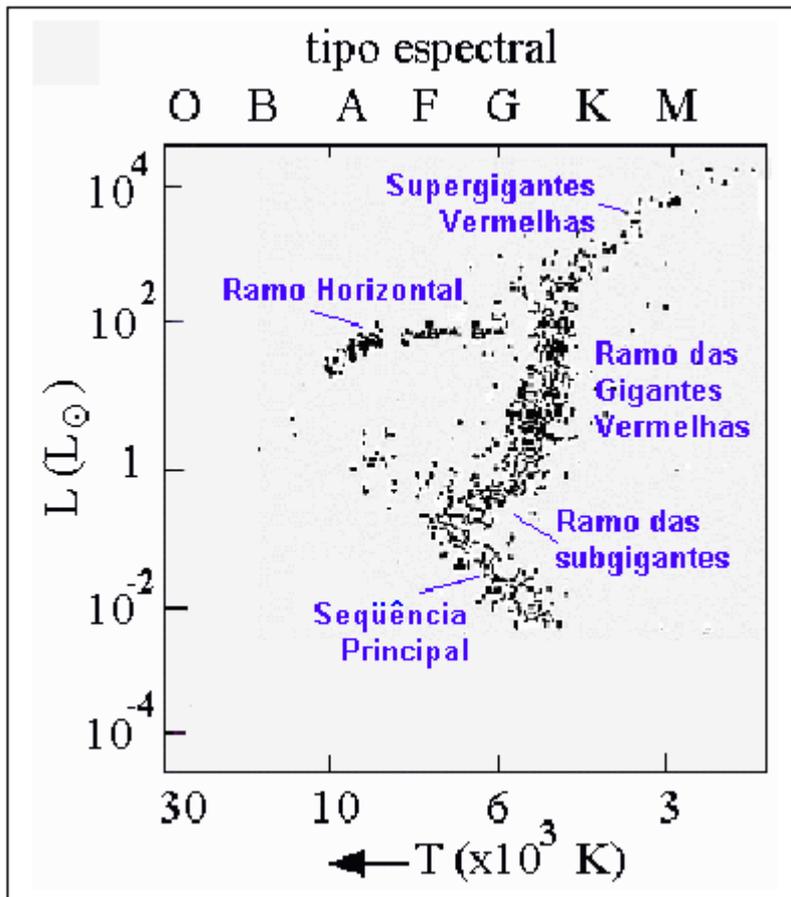
Ciclo de vida do Sol



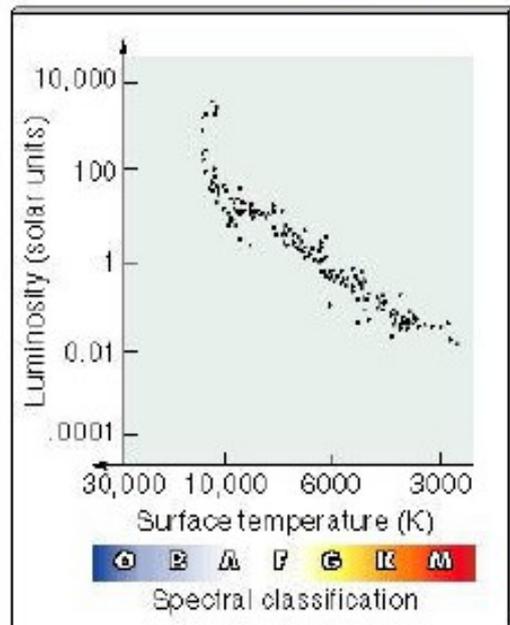
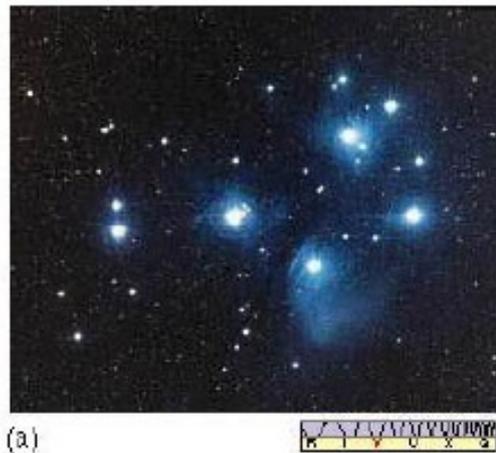
Evidências

Aglomerados estelares:

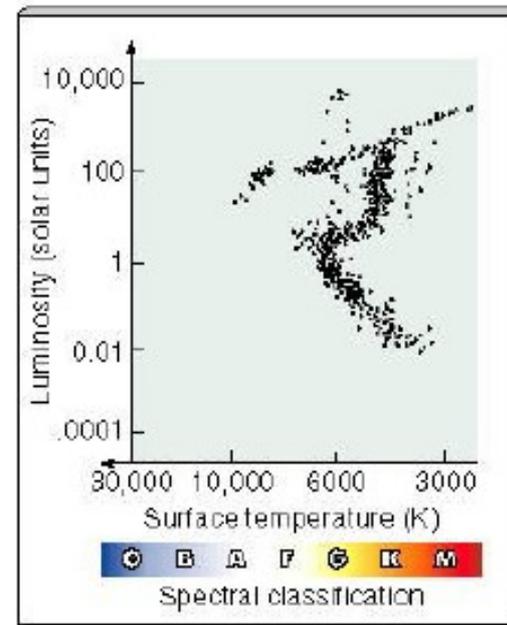
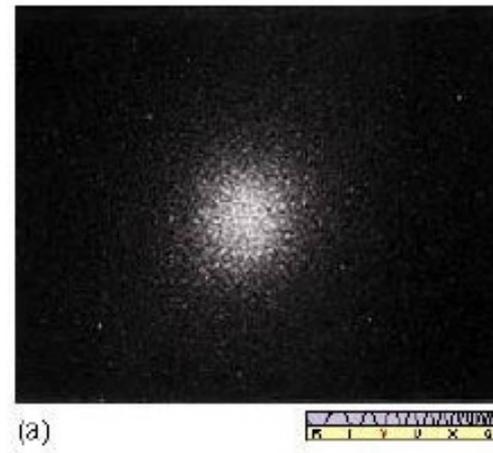
- Estrelas se formam ao mesmo tempo
- Estão aproximadamente a mesma distância



Aglomerados

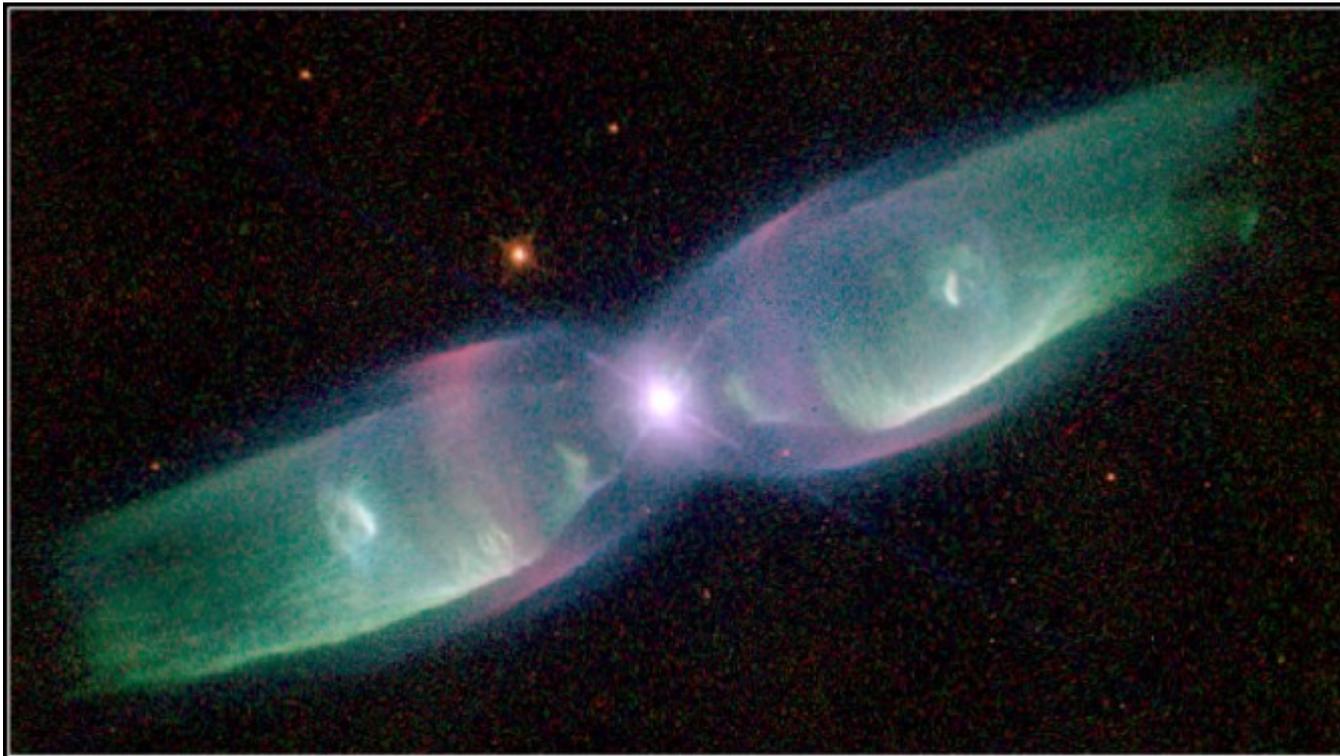


Agl. Pleiades: Jovem



Agl. Omega Cen: Velho

Nebulosas e Anã Branca



Planetary Nebula M2-9
PRC97-38a • ST ScI OPO • December 17, 1997
B. Balick (University of Washington) and NASA

HST • WFPC2

Nebulosas e Anã Branca

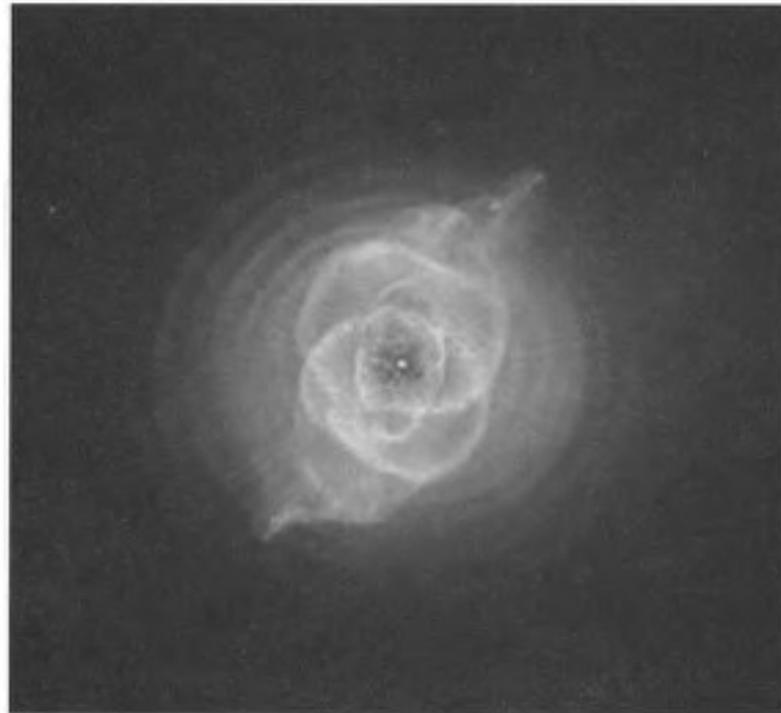


FIGURE 13.14 NGC 6543 (the “Cat’s Eye”) is a planetary nebula in Draco, 900 pc away. The complex structure may be due to high-speed jets and the presence of a companion star, making NGC 6543 part of a binary star system. The jets are clearly visible in the upper right-hand and lower left-hand portions of the image. Note the central star in the image. [Credit: NASA, ESA, HEIC, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: R. Corradi (Isaac Newton Group of Telescopes, Spain) and Z. Tsvetanov (NASA).]



(a)



(b)

FIGURE 13.15 Examples of two “butterfly” planetary nebulae. (a) M2-9 is a bipolar planetary nebula 800 pc distant in Ophiucus. [Credit: Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA.] (b) Menzel 3 (Mz 3), in Norma, is also known as the Ant nebula. Outflow velocities of 1000 km s^{-1} are much greater than for any other similar object. [Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Acknowledgment: R. Sahai (Jet Propulsion Lab) and B. Balick (University of Washington).]

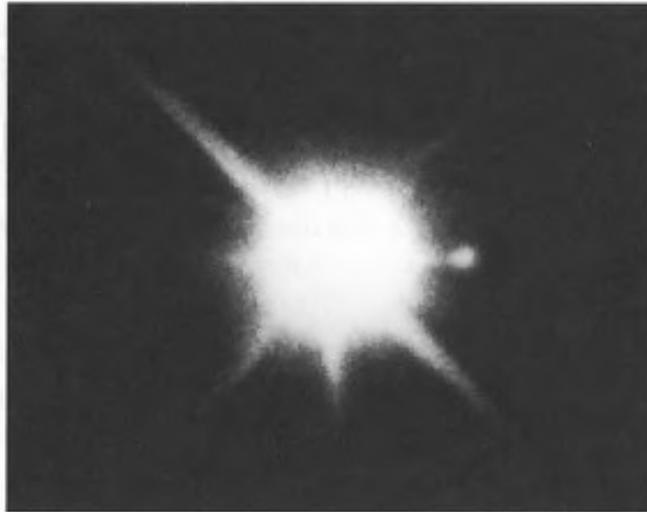


FIGURE 16.1 The white dwarf, Sirius B, beside the overexposed image of Sirius A. (Courtesy of Lick Observatory.)

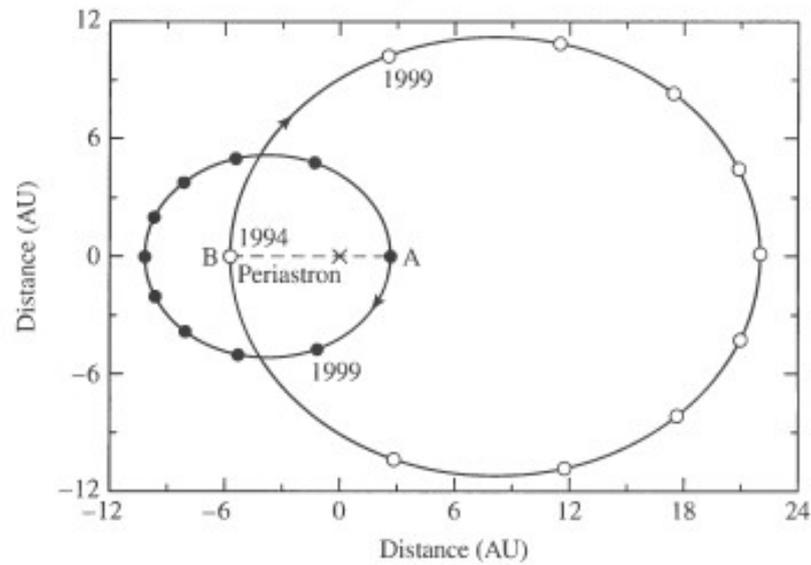
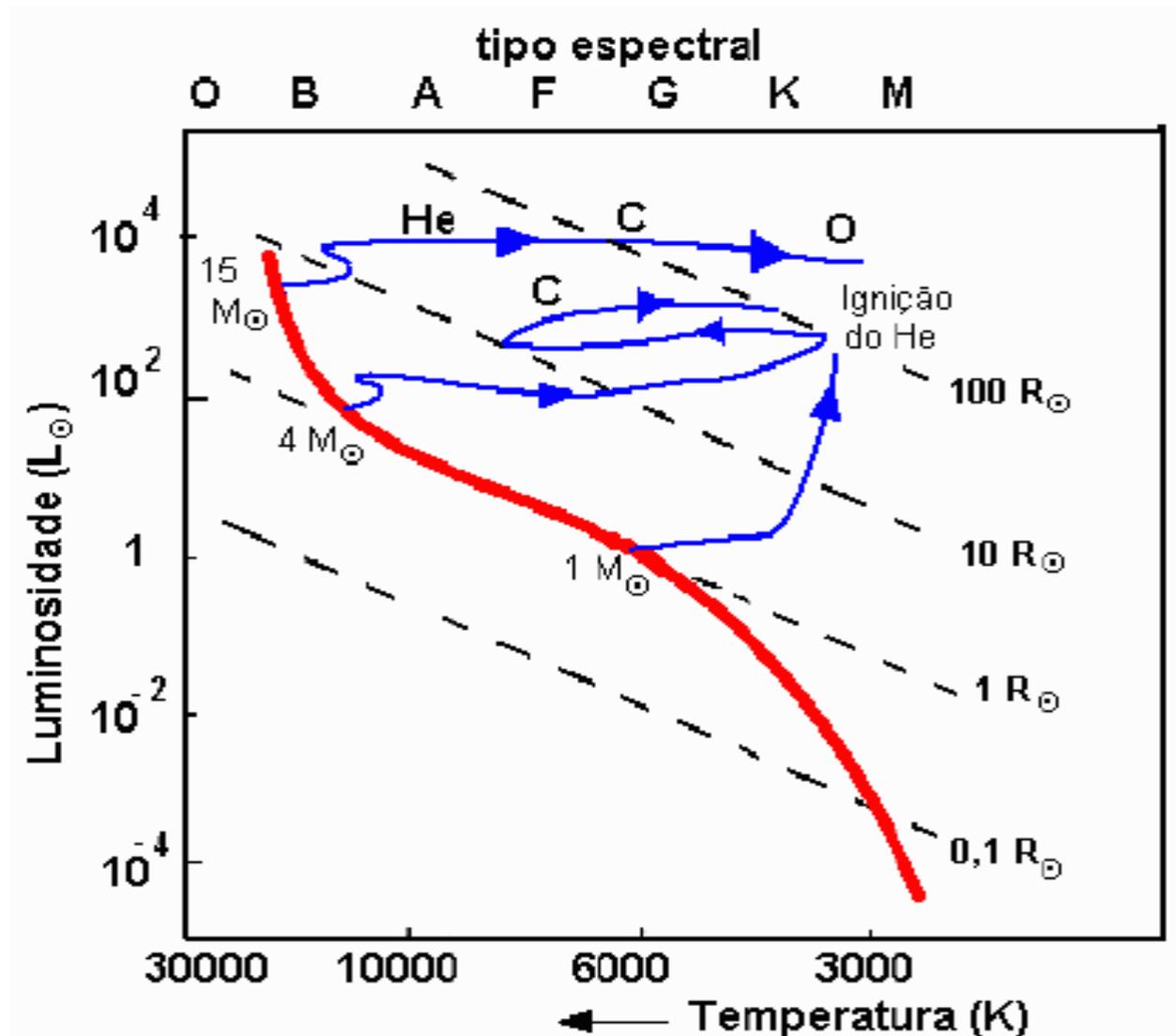
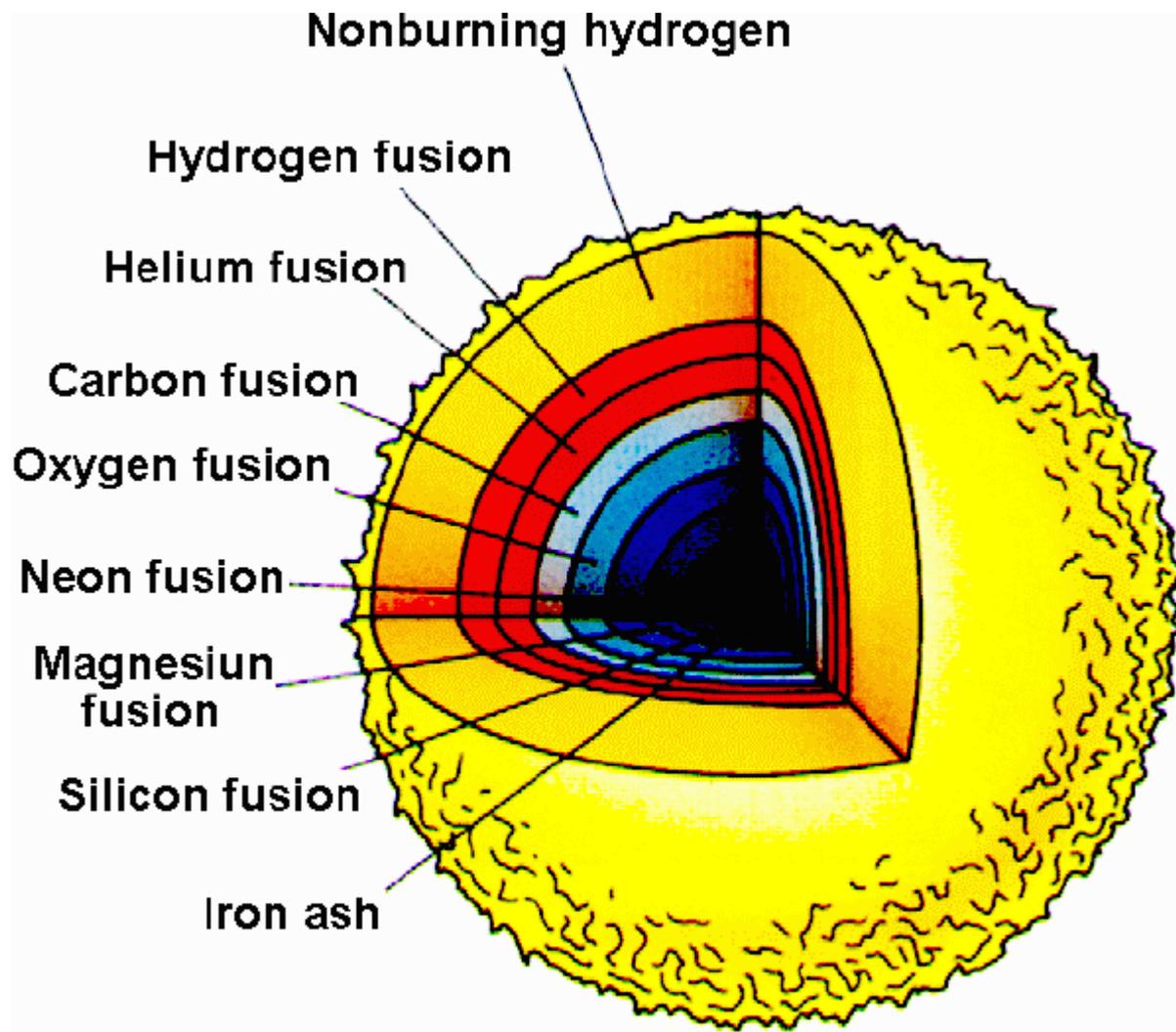


FIGURE 16.2 The orbits of Sirius A and Sirius B. The center of mass of the system is marked with an "x."

Estrelas com massa $> 8 M_{\odot}$



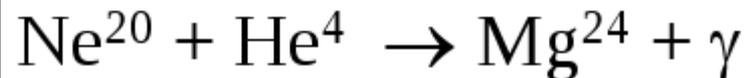
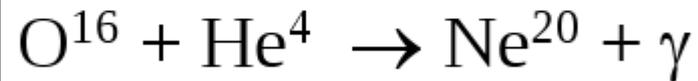
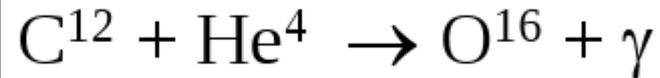


Core-burning nuclear fusion stages for a 25-solar mass star

Process	Main fuel	Main products	25 M _⊙ star ^[5]		
			Temperature (Kelvin)	Density (g/cm ³)	Duration
hydrogen burning	hydrogen	helium	7×10^7	10	10^7 years
triple-alpha process	helium	carbon, oxygen	2×10^8	2000	10^6 years
carbon burning process	carbon	Ne, Na, Mg, Al	8×10^8	10^6	10^3 years
neon burning process	neon	O, Mg	1.6×10^9	10^7	3 years
oxygen burning process	oxygen	Si, S, Ar, Ca	1.8×10^9	10^7	0.3 years
silicon burning process	silicon	nickel (decays into iron)	2.5×10^9	10^8	5 days

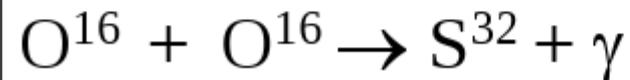
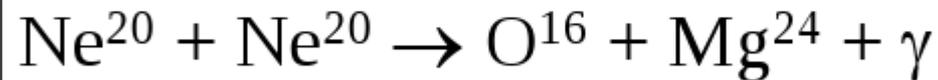
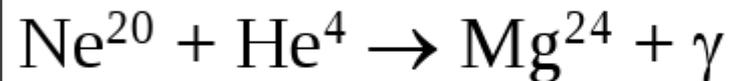
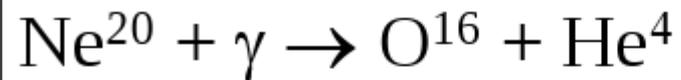
Reações nucleares para estrelas massivas

$$8 < M/M_{\odot} < 100 ; T_c \sim 10^9 \text{ K}$$



Para $T > 10^9$ K

queima do Ne \Leftrightarrow processo de fotodesintegração



Acabando o combustível

- Elétrons degenerados
- Neutrons degenerados
- Colapso gravitacional
- Processo Urca $p + e \rightarrow n + \nu$
 - 10^{38} W em neutrinos
 - 10^{31} W em luz
- Fotodesintegração: $Fe + \gamma \rightarrow He + 4n$
- Núcleo rouba energia térmica e elétrons e transforma em neutrons.

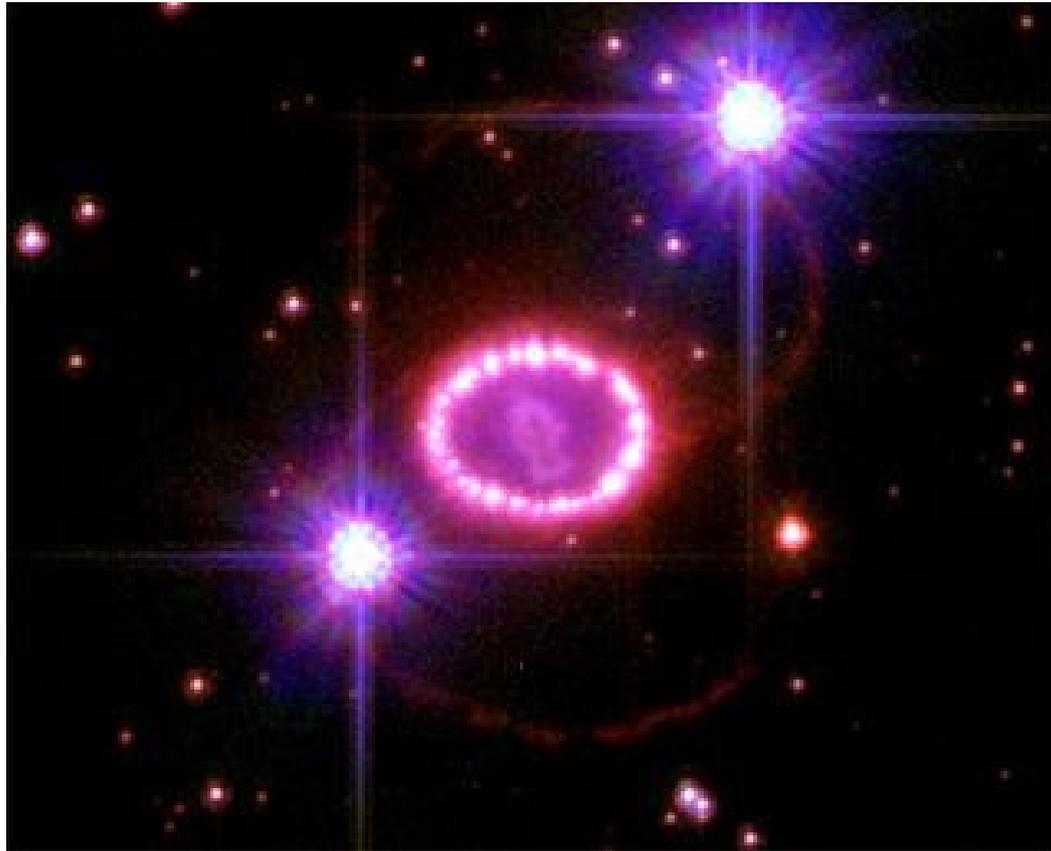
Acabando o combustível

- Núcleo de neutrons segurando o colapso
- Sem pressão do gás
- Se $M_{\text{core}} > 1.4 M_{\text{solares}}$ os eletrons não estão degenerados
- Sem pressão dos elétrons
- Colapso gravitacional (70000 km/s)
- Até que não dá mais pra comprimir ($\rho = 10^{18} \text{ kg/m}^3$)
- O núcleo rebota e explode.
- Supernova (Tipo II) + Estrela de Neutrons

Acabando o combustível

- Núcleo de neutrons segurando o colapso
- Sem pressão do gás
- Se $M_{\text{core}} < 1.4 M_{\text{solares}}$ os eletrons estão degenerados
- Tem pressão dos elétrons
- Anã Branca

1987A



ver filme

Magnitude 3
51 kparsec

Estrela de neutron

- Raio de dezenas de quilômetros
- Massa entre 1.4 e 2.1 Msolares
- Densidade $\sim 10^{17}$ kg/m³
- Caso geral: Pulsar
- Estável = Deg N
- Se $M > 3$ Msolares
- N não seguram colapso
- Buraco Negro

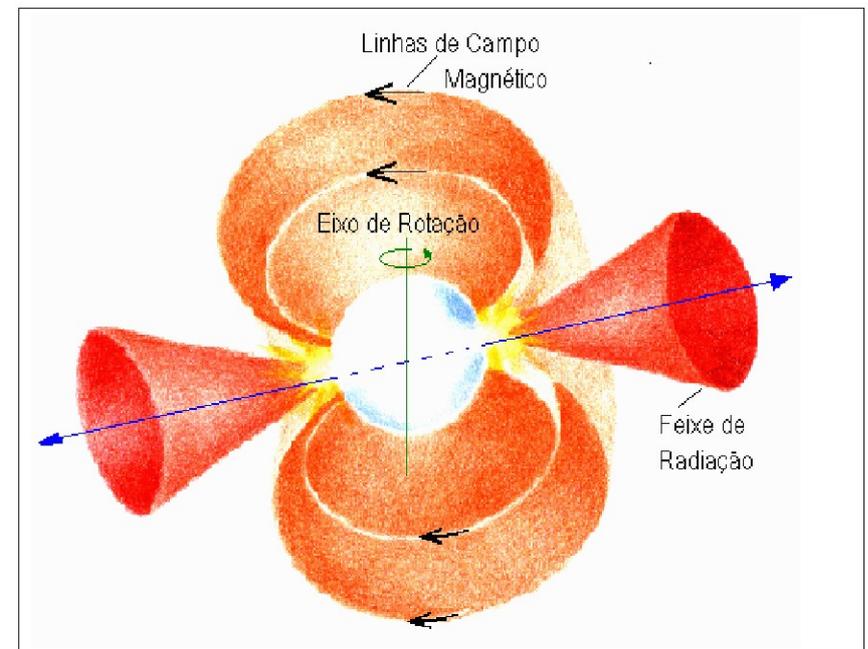


Figura 6. Modelo para uma estrela de nêutrons e suas propriedades de pulsar. As partículas carregadas são aceleradas seguindo as linhas de campo magnético. Um feixe de radiação rádio é formado e emitido na direção do observador.

Remanescente: Nebulosa Caranguejo



Pulsar de Caranguejo

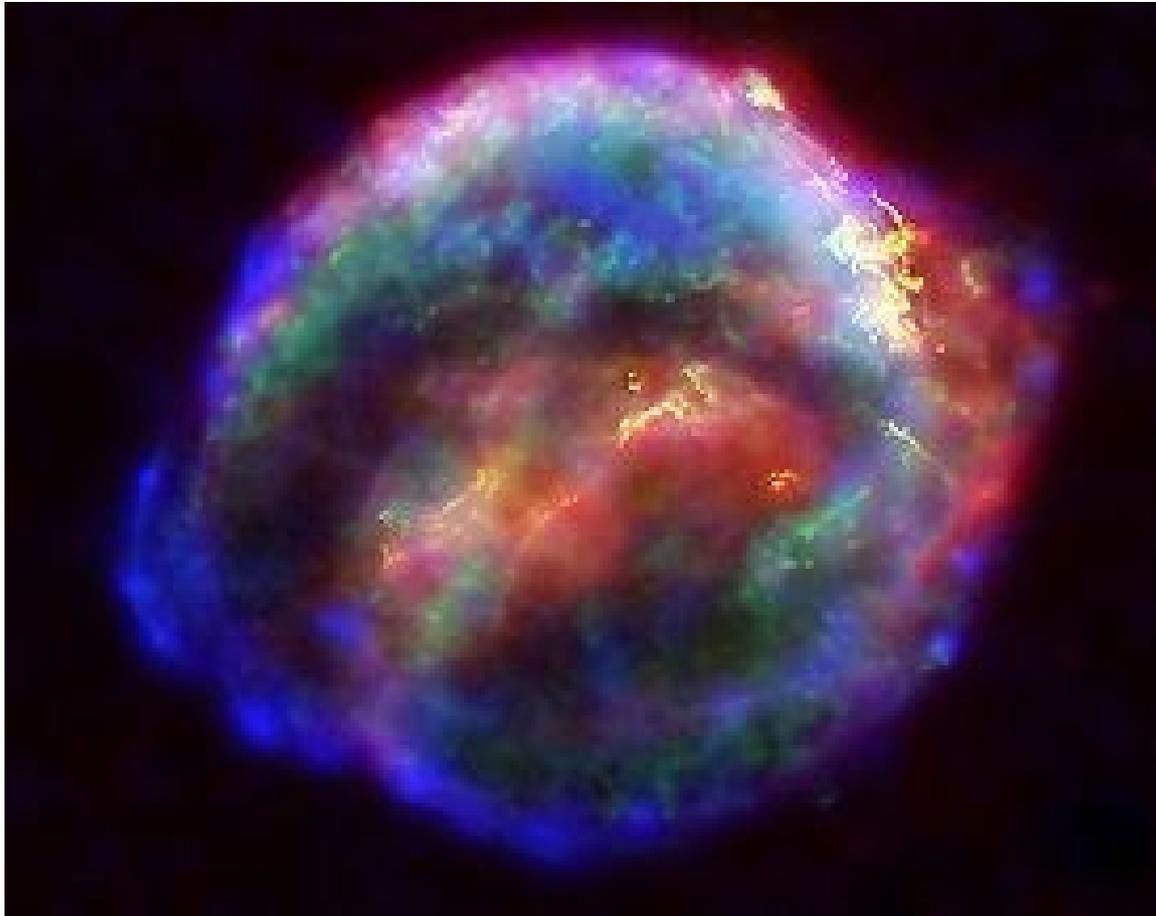


Radio ~ 30 km
Período = 33 ms

Supernovas Tipo I

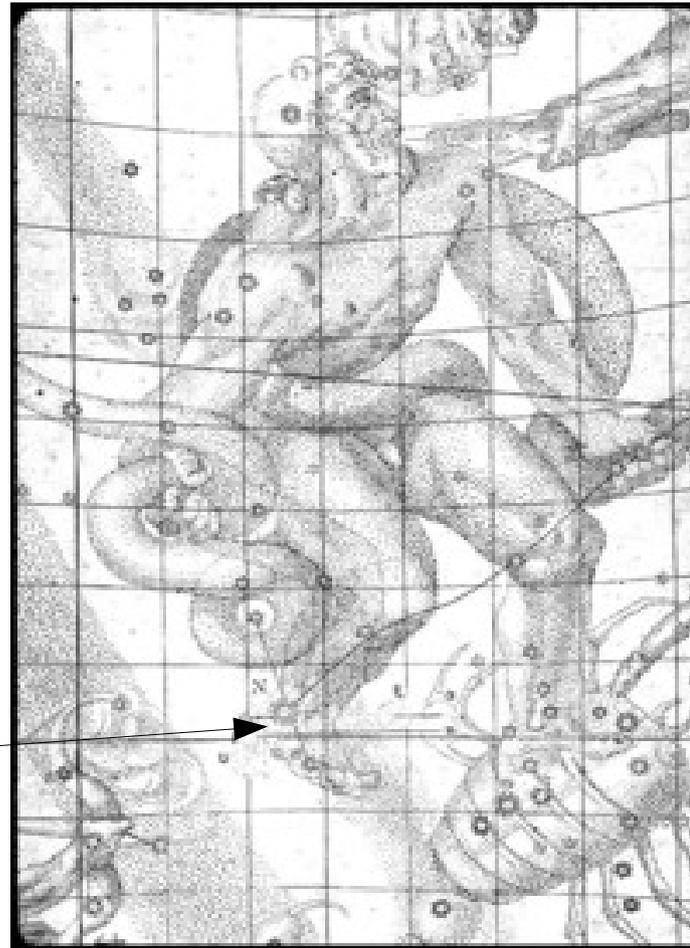
- Anã-branca ganha massa de uma companheira
- Aumenta pressão, aumenta temperatura
- Queima Carbono
- Explode

SN1604

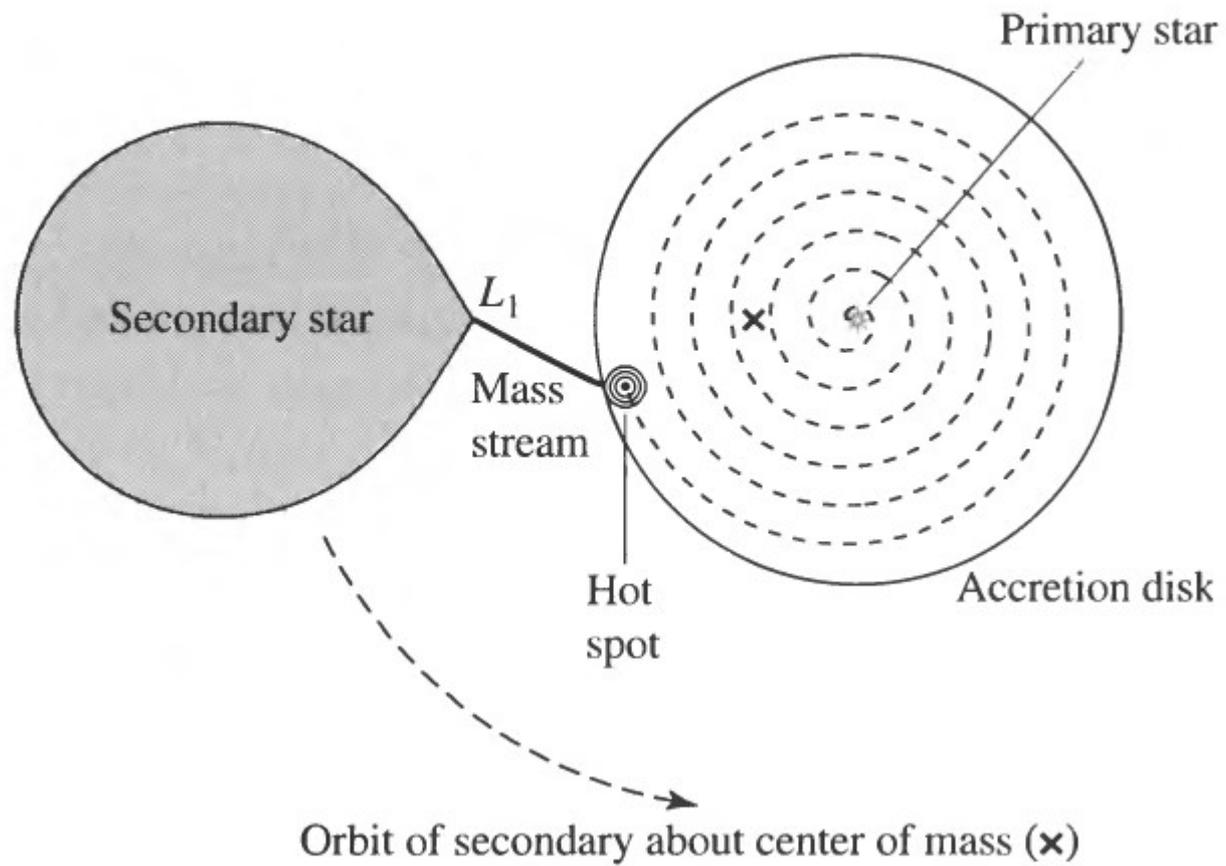


Kepler
Magnitude -2.5
Distância 6 kparsec

SN1604



Chapter 18 Close Binary Star Systems



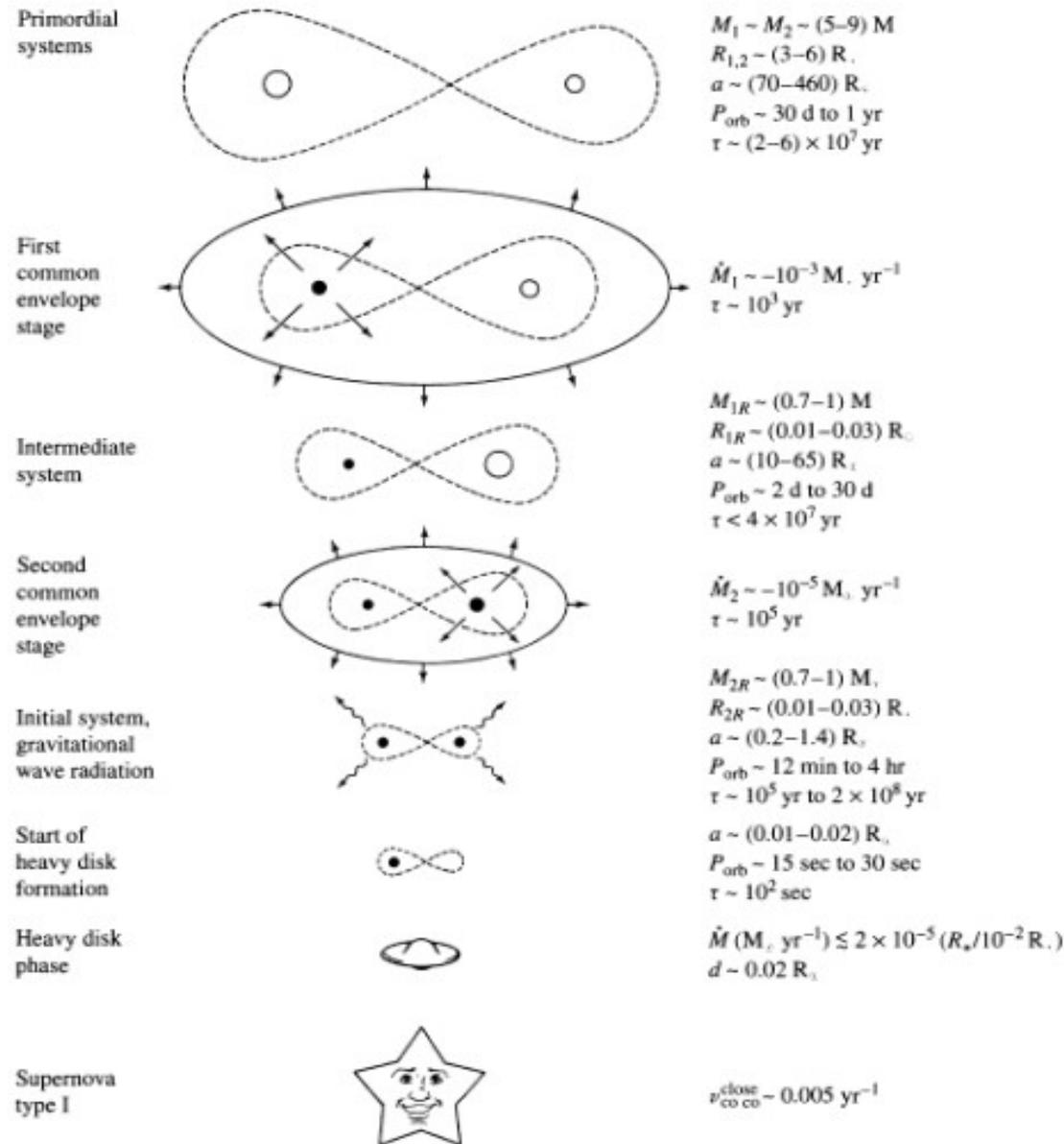


FIGURE 18.11 One possibility for the evolution of a close binary system, ending in a Type Ia supernova. The masses and radii of the stars, and their orbital separation (A), orbital period, and mass transfer rate, are given for some stages, along with the duration (τ). (Figure adapted from Iben and Tutukov, *Ap. J. Suppl.*, 54, 335, 1984.)

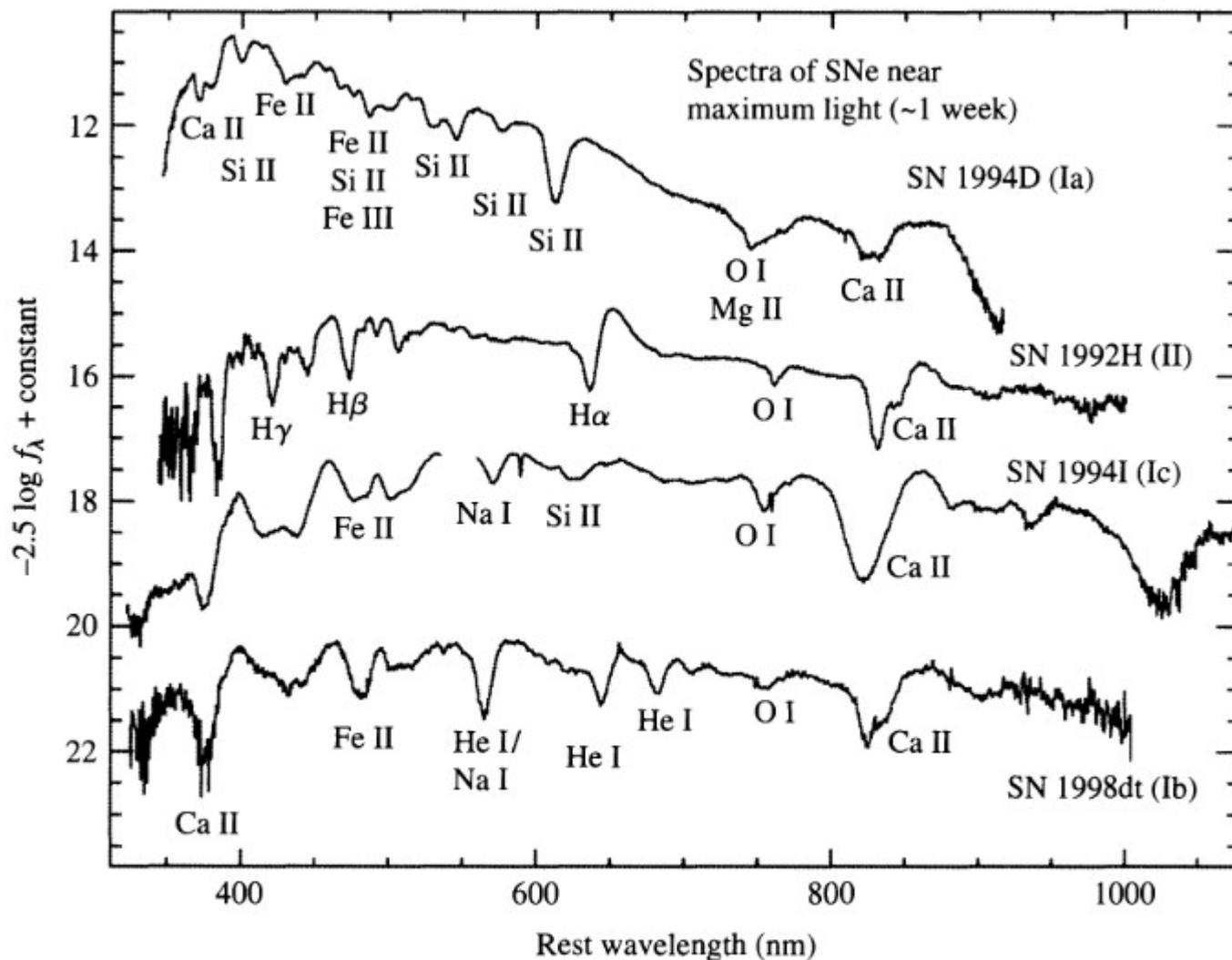


FIGURE 15.6 Representative spectra of the four types of supernovae; Type Ia, Ib, Ic, and II. Note that although SN 1994I (Type Ic) does exhibit a weak Si II absorption line, it is much less prominent than the Si lines in a Type Ia. Brightness is in arbitrary flux units. (Courtesy of Thomas Matheson, National Optical Astronomy Observatory.)

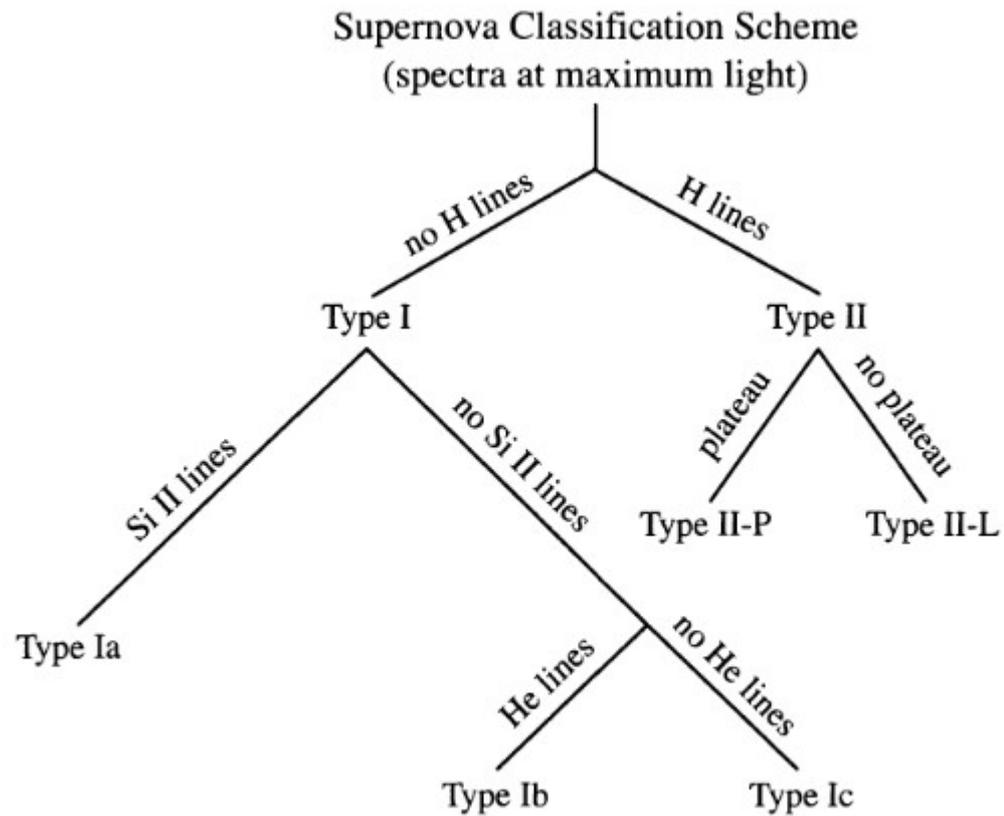


FIGURE 15.9 The classification of supernovae based on their spectra at maximum light and the existence or absence of a plateau in the Type II light curve.