MAIN SEQUENCE TO OBLIVION
FOR LOW MASS STARS ($m \leq 8 M_{SUN}$)

- (AS FOR HIGH MASS STARS) He CORE CONTRACTS & HEATS UP, H BURNS IN A SHELL AROUND CORE
- STAR BECOMES A RED GIANT BEFORE He IS IGNITED
  - FOR $m < 2.3 M_{SUN}$, He BURNING BEGUN WHEN ELECTRONS ARE DEGENERATE
    (≃ CONTAINED EXPLOSION)
    HELIUM CORE FLASH

HELIUM CORE FLASH

- CORE
  GRAVITY = PRESSURE FROM DEGENERATE ELECTRONS

  He NUCLEI = NEGLIGIBLE CONTRIBUTION TO PRESSURE

- HE-BURNS
  He NUCLEI HEATED, BURNING ACCELERATED

  TAKES A LOT OF ENERGY TO REMOVE e DEGENERACY

- EVENTUALLY (RAPIDLY!) ELECTRONS → NON-DEG. & PRESSURE INCREASE EXPANDS CORE

- HE-BURNING → C,O CORE

- C,O CORE COLLAPSES BUT COLLAPSE IS ARRESTED BY DEGENERATE ELECTRONS

  ∴ C,O DO NOT BURN

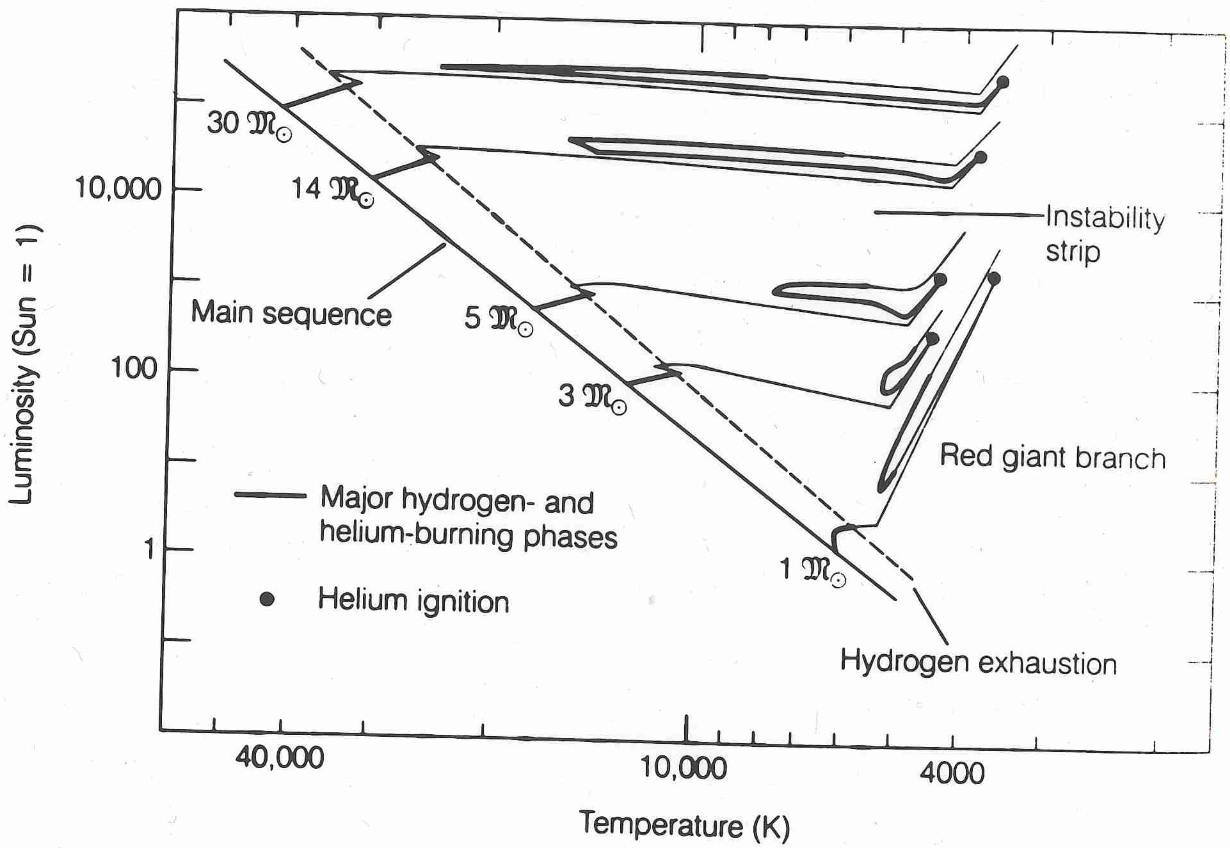
- "ASYMPTOTIC" GIANT

  NUCLEAR ENERGY FROM

  H AND He BURNING SHELLS

- STAR SWELLS, LOSES ENVELOPE IN WIND, EXPOSES HOT CORE → WHITE DWARF

  PLANETARY NEBULA



30 $\mathfrak{M}_\odot$
14 $\mathfrak{M}_\odot$
5 $\mathfrak{M}_\odot$
3 $\mathfrak{M}_\odot$
1 $\mathfrak{M}_\odot$
Main sequence
Instability strip
Red giant branch
Hydrogen exhaustion
Major hydrogen- and helium-burning phases
Helium ignition
10,000
100
1
Luminosity (Sun = 1)
40,000
10,000
4000
Temperature (K)

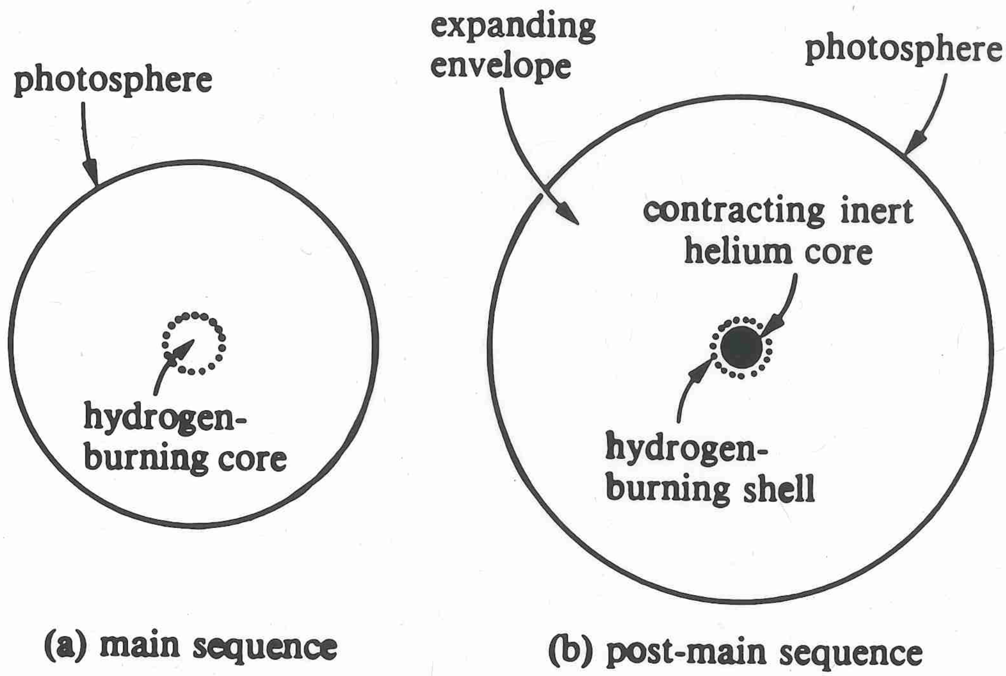


Figure 8.3. The structure of a star (a) on the main sequence and (b) as it begins to leave the main sequence because of core-hydrogen exhaustion.

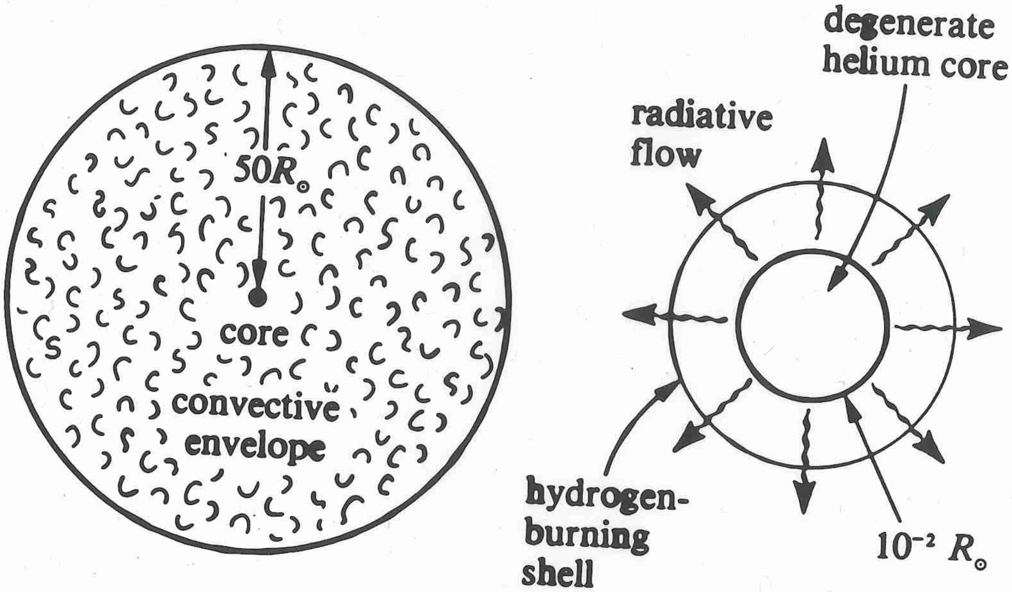


Figure 8.5. The structure of a red giant. The left figure shows the entire star from core to photosphere. The right figure shows an enlarged picture of the region near the core. Notice that the core, which may contain about half the total mass of a low-mass star at this point, occupies only one ten-billionth of the total volume.

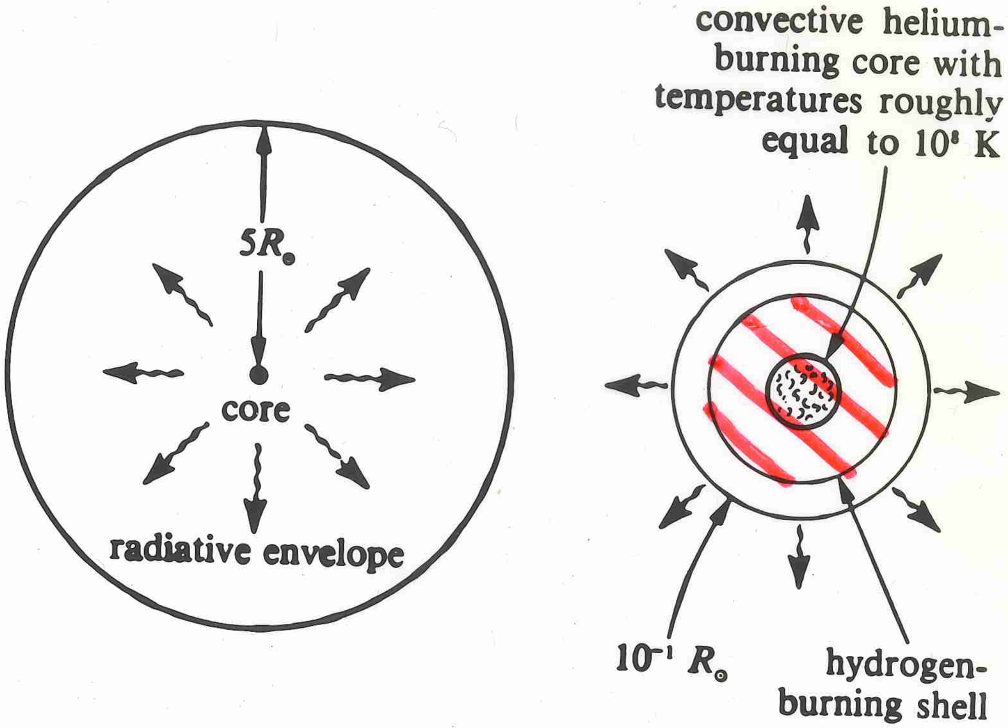


Figure 8.7. The structure of a horizontal-branch star. The left figure shows the entire star from core to photosphere. The right figure shows an enlarged picture of the region near the core.

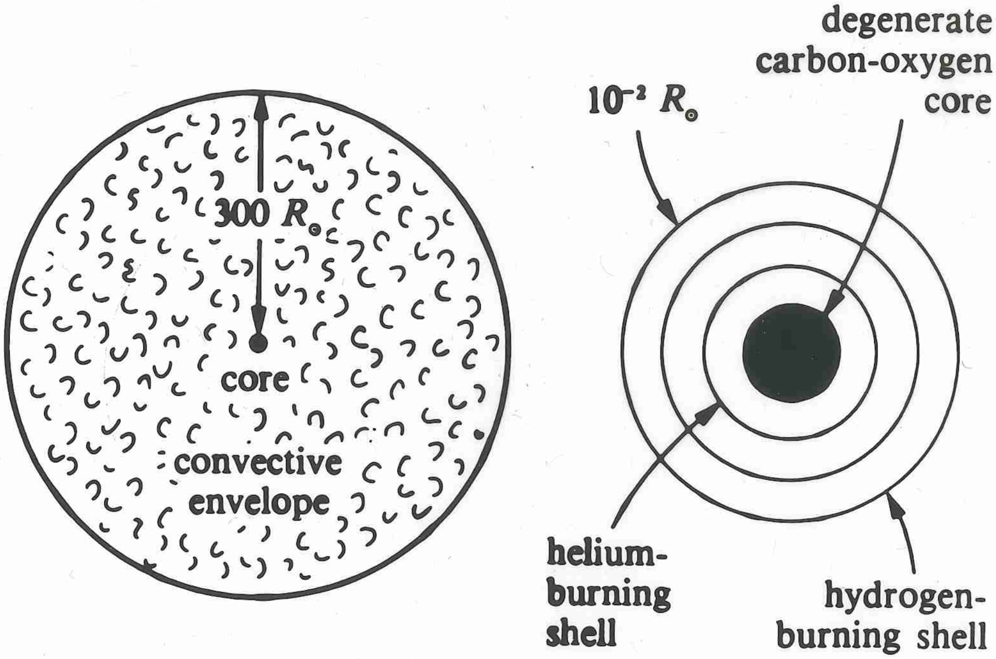
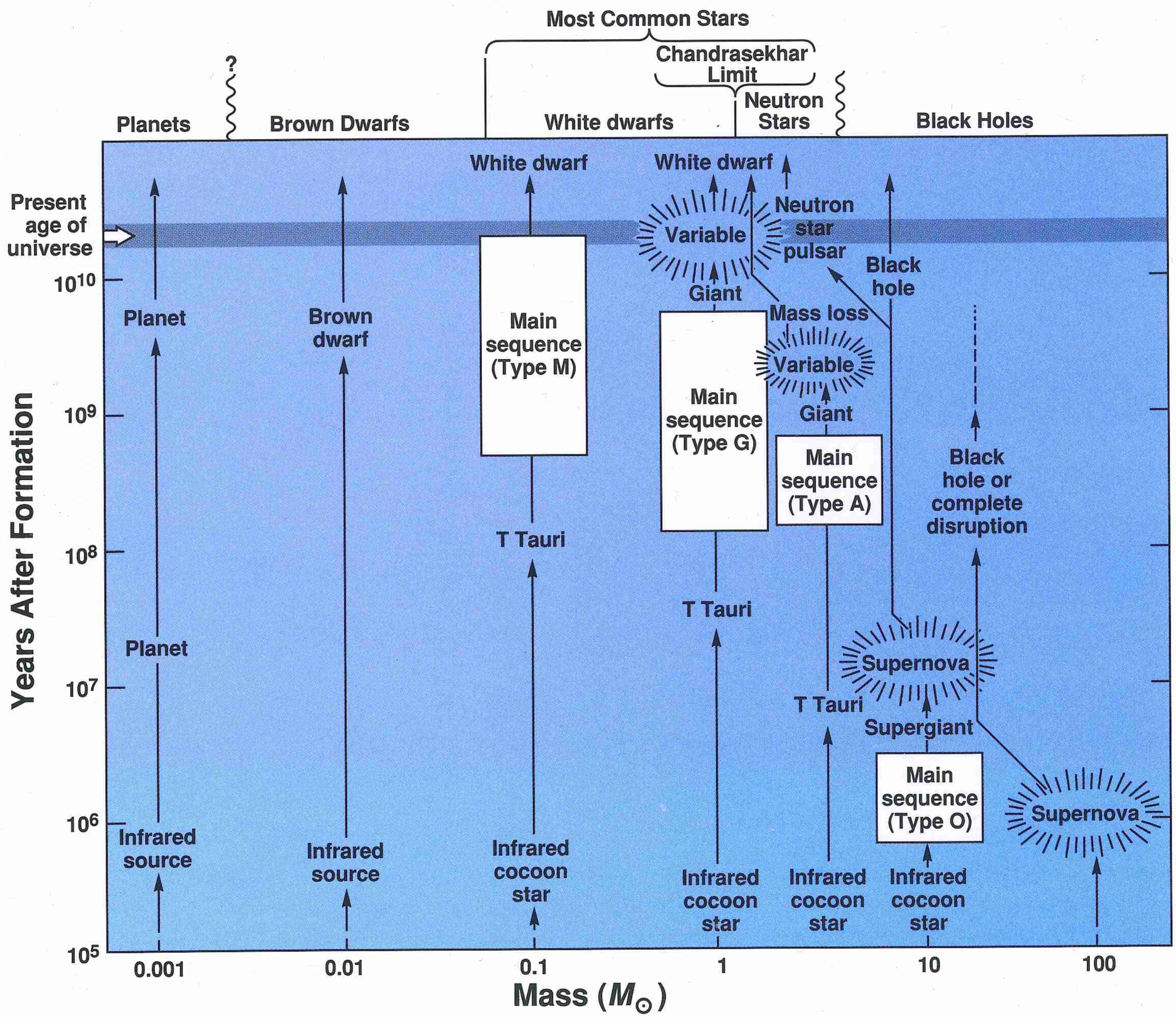


Figure 8.8. The structure of an asymptotic giant. The figure on the left shows the entire star from core to photosphere. The figure on the right shows an enlarged picture of the region near the core.



Schematic summary of stellar evolution

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 19-33

DEGENERATE MATTER

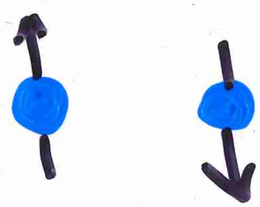
- PAULI EXCLUSION PRINCIPLE

  NO TWO ELECTRONS CAN BE IDENTICAL

  SAME MOMENTUM ($\approx$ ENERGY) (p)

  SAME PLACE (x)

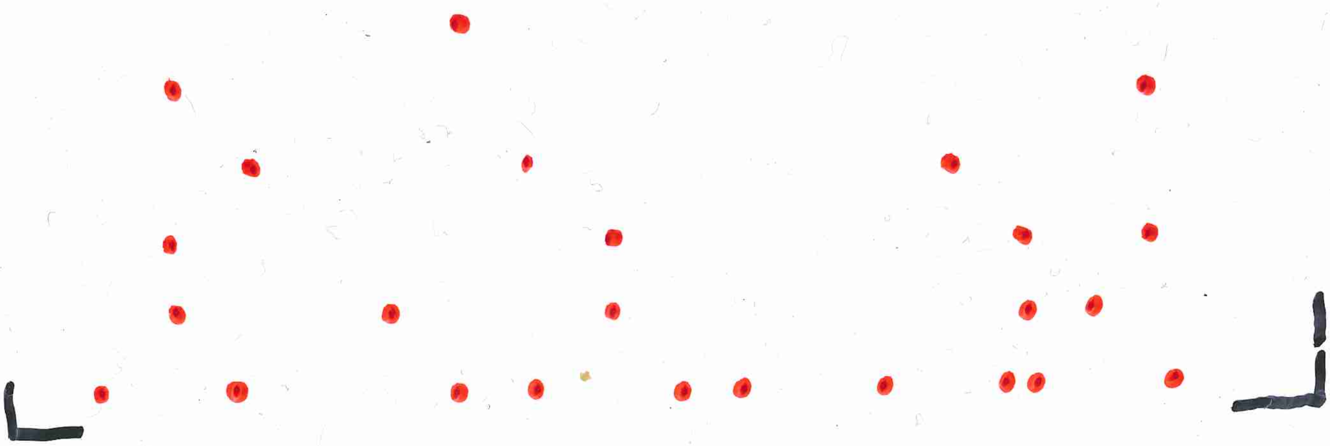
  SAME SPIN (UP or DOWN)



- HEISENBERG UNCERTAINTY PRINCIPLE

$$\Delta p \, \Delta x \sim \frac{h}{2\pi}$$

defines what constitutes different place & different momentum



NORMAL/NON-DEGENERATE GAS

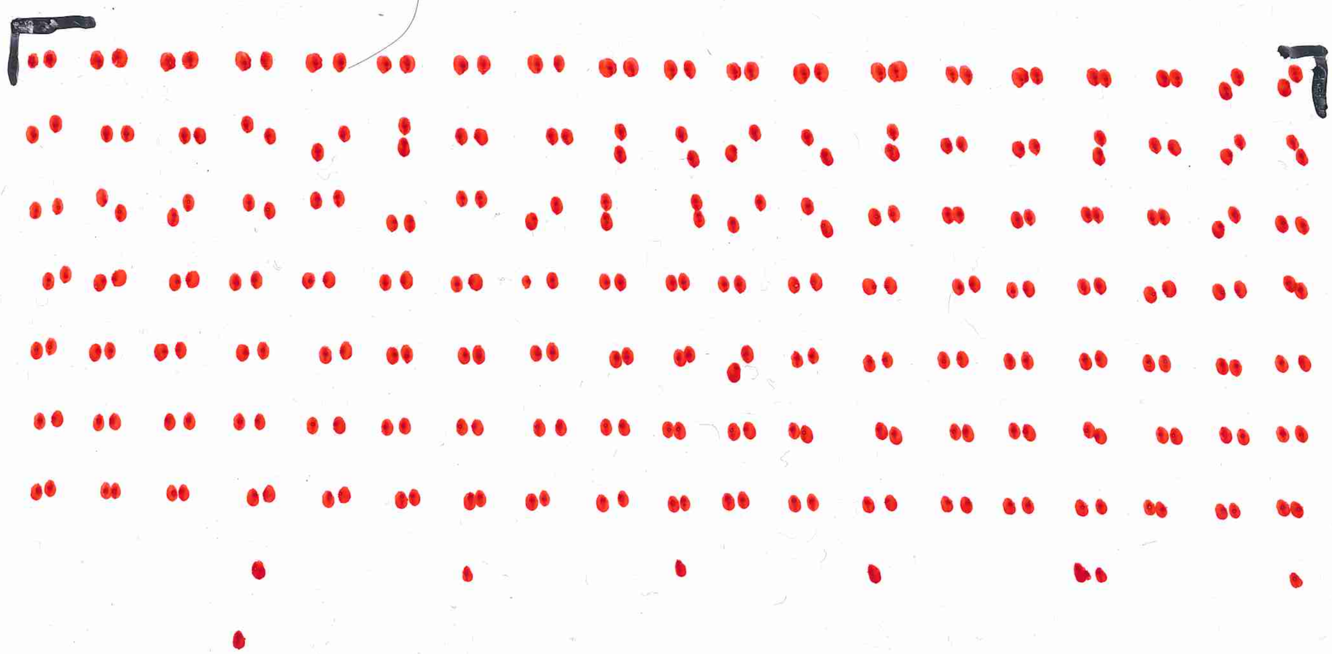
- easily compressed
- easily cooled (heated)

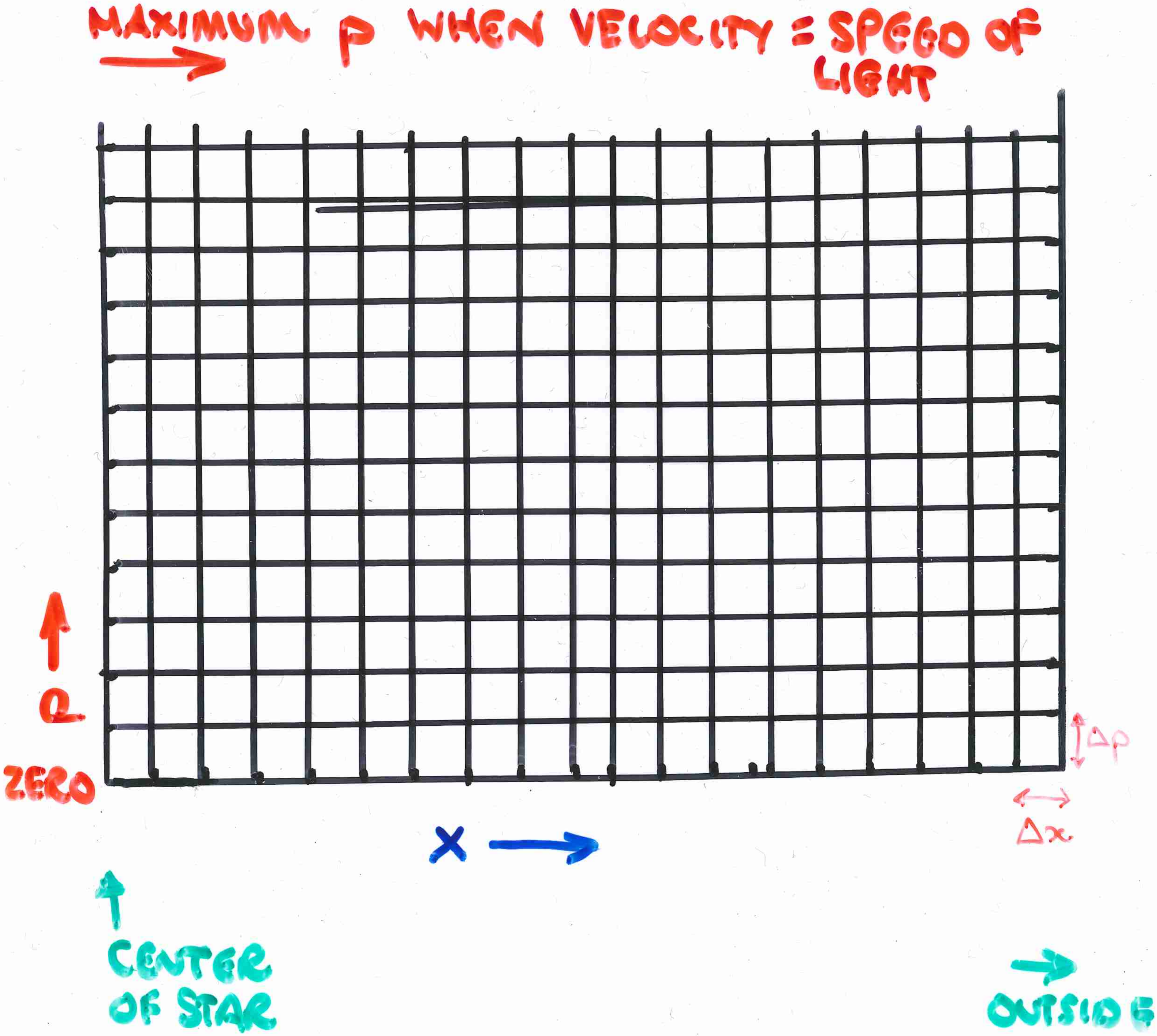
- GOOD CONDUCTOR OF HEAT

NOT TEMP. DEPENDENT

- CANNOT BE COOLED ∴ PRESSURE
- CANNOT BE EASILY COMPRESSED

DEGENERATE ELECTRON GAS




MAXIMUM p WHEN VELOCITY = SPEED OF LIGHT
p
ZERO
Δp
Δx
X
CENTER OF STAR
OUTSIDE

- MAXIMUM MASS SUPPORTABLE AGAINST GRAVITY BY DEGENERATE ELECTRONS

  SET BY VELOCITY MUST BE LESS THAN SPEED OF LIGHT

- CHANDRASEKHAR'S LIMIT

  $1.4 M_{SUN}$ for He CORE

- RADIUS OF STAR (WHITE DWARF) SUPPORTED BY DEGENERATE ELECTRONS DECREASES WITH INCREASING MASS (FIG. 14-6)

  $\langle m_{WD} \rangle \sim 0.6 m_{\odot}$; $R \sim R_{EARTH}$

  $m_{WD} = 1.4 M_{\odot}$; $R = $ ZERO

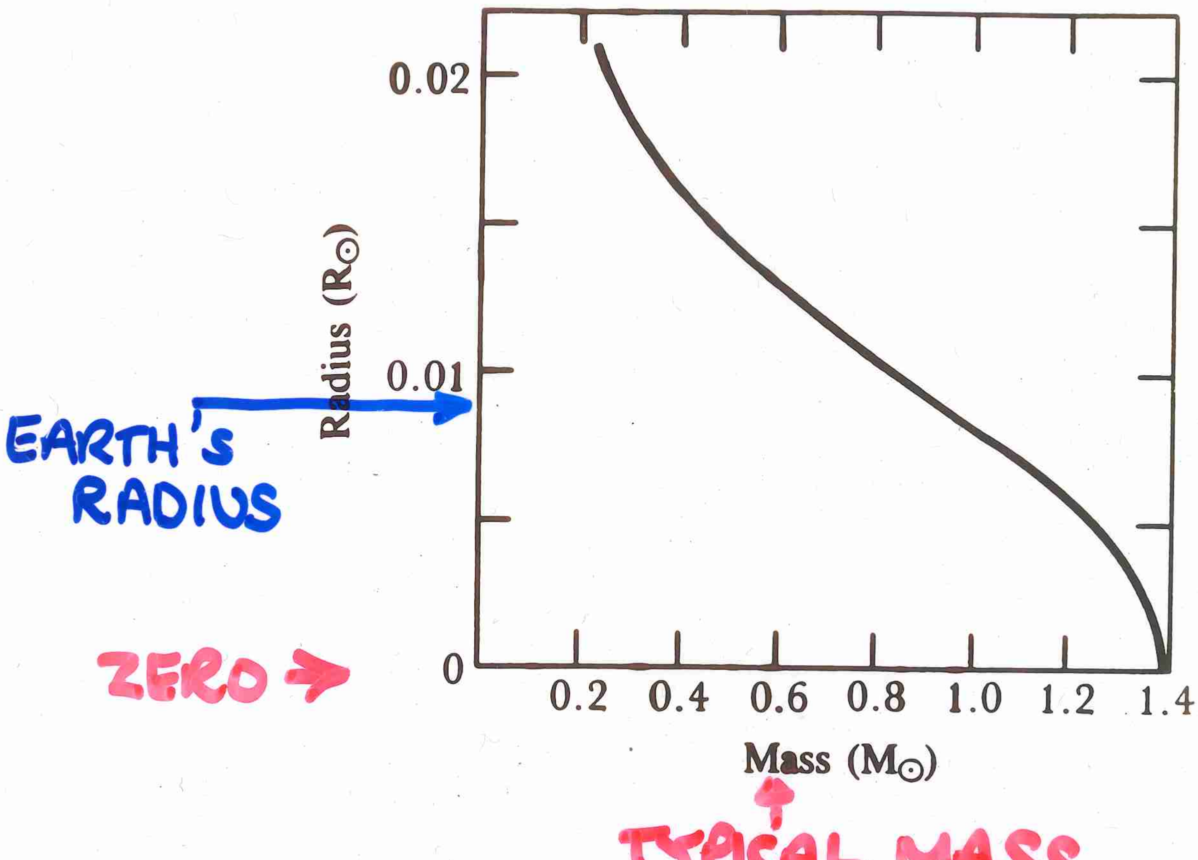


Figure 22-6 The mass–radius relationship for white dwarfs *The more massive a white dwarf is, the smaller it is. This unusual relationship between mass and radius is a result of the degenerate-electron pressure that supports the star. The maximum mass of a white dwarf, called the Chandrasekhar limit, is 1.4* $M_{\odot}$*. Incidentally, 0.01* $R_{\odot} = 6960$ *km =* $1.09\ R_{\oplus}$*, where* $R_{\oplus}$ *is the radius of the Earth.*

CAN NUCLEI BE DEGENERATE?

- SAME PRINCIPLES APPLY

- Δp LIMIT SAME

  BUT p = MASS × VELOCITY

- FOR NUCLEI, PROTONS, NEUTRONS

  MASS $\gtrsim$ 2000 (MASS OF ELECTRON)

  ∴ MANY MORE Δp BOXES BETWEEN

  $v = 0$ AND v = SPEED OF LIGHT

∴ WHEN ELECTRONS ARE DEGENERATE,
NUCLEI ARE NOT

WHAT IF $m > 1.4 m_{SUN}$?

- COLLAPSE CANNOT BE PREVENTED BY DEGENERATE ELECTRONS

- IN COLLAPSE, ELECTRONS AND NUCLEI FORCED INTO CONTACT
  - NUCLEI → PROTONS AND NEUTRONS
  - $p + e^- \rightarrow n + \nu_e$

- DEGENERATE NEUTRONS OPPOSE GRAVITY AS LONG AS $m_* \lesssim (2 \text{ to } 3)\, m_{SUN}$ AT RADIUS OF A FEW KMS.

NEUTRON STAR

- AT LIMIT $m \sim (2\text{-}3) M_{SUN}$, NEUTRONS ARE BROKEN UP INTO QUARKS

  THIS OCCURS BEFORE SPEED OF LIGHT LIMIT IS REACHED

- AT $m > (2\text{-}3) M_{SUN}$, NO OPPOSITION TO GRAVITATIONAL COLLAPSE IS KNOWN.

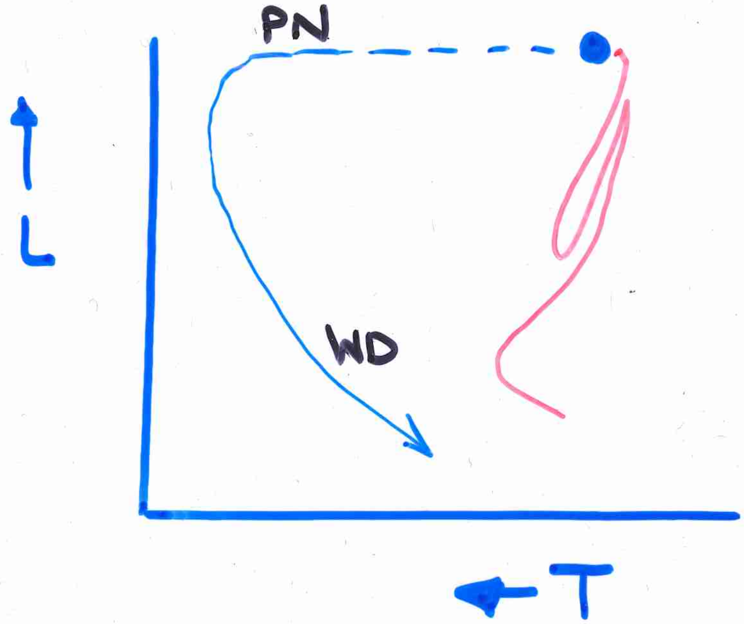
  COLLAPSE IS INEVITABLE FOR.....

BLACK HOLE

WHITE DWARFS

- FORMATION

LOW MASS RED GIANT LOSES H-RICH ENVELOPE BY A WIND. He-SHELL/C-O CORE IS EXPOSED. RAPIDLY COOLS



THE APPEARANCE OF THE ORBITS OF A + B.

THE MOTION OF SIRIUS-A IS SHOWN BY THE RED CURVE.

C IS THE NET MOTION OF THE SYSTEM

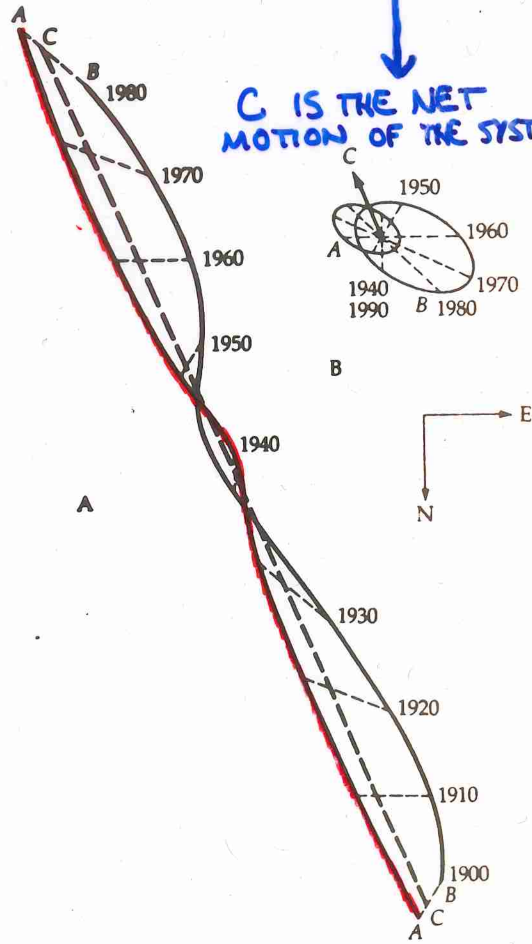


Figure 12–2

Motions of Sirius A and B. (A) The apparent motions relative to background stars of Sirius *(A)*, its companion *(B)*, and the center of mass of the system *(C)*. (B) Orbital motions of Sirius A and B relative to the system's center of mass.

NOTE THE EXTREME FAINTNESS OF SIRIUS-B RELATIVE TO SIRIUS-A.

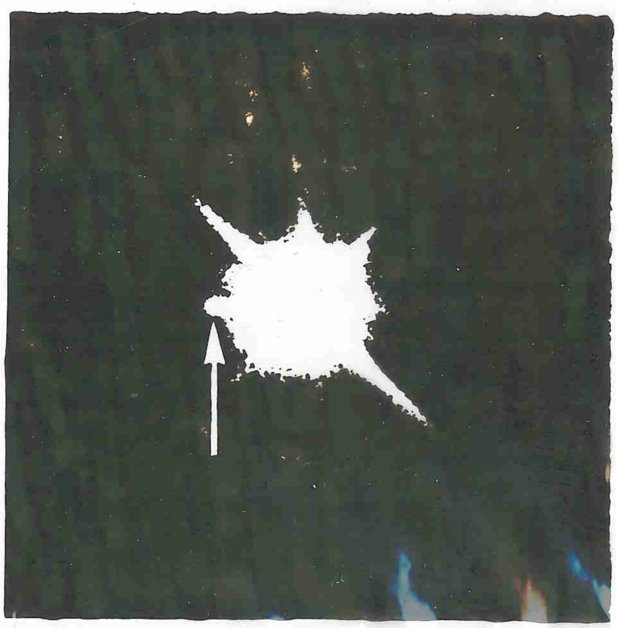


Figure 17–2

A white dwarf. Sirius B (arrow), the companion to Sirius A. *(Lick Observatory)*

DISCOVERY

SIRIUS B → V. SMALL V DENSE

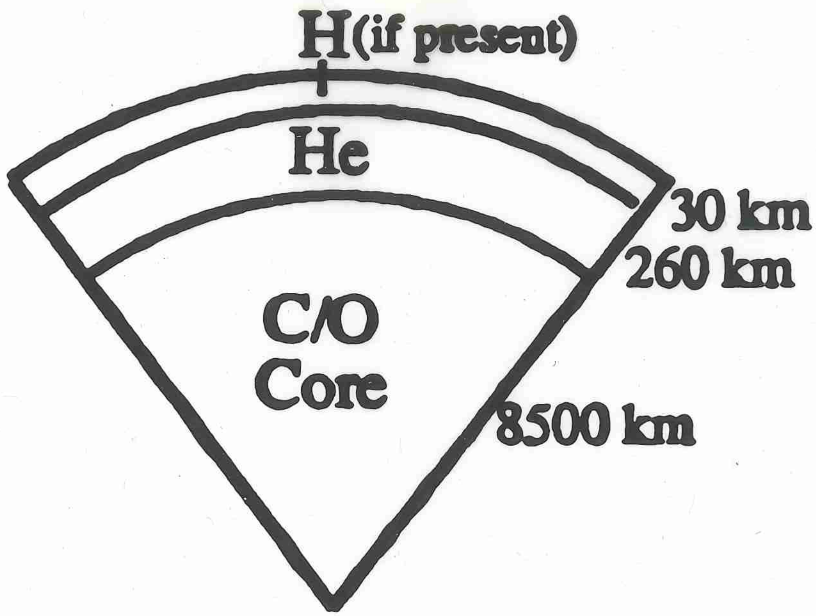
$1 M_\odot$ STAR

OBSERVATION preceded THEORY

"The message of the companion of Sirius when decoded, ran: "I am composed of material 3000 times denser than anything you've ever come across. A ton of my material would be a little nugget you could put in a matchbox" What reply could one make to something like that? Well, the reply most of us made in 1914 was, "Shut up, don't talk nonsense""

A.S. Eddington

• STRUCTURE



Cross Section of a Typical White Dwarf

RADIUS depends on MASS

R decreases as M increases up to $M = 1.4 M_\odot$

DENSITY $\sim 10^6$ gm/cm^3

$\sim$ METRIC TON/cm^3

$\sim 10^6 \times$ WATER

DENSE$^+$!

SURFACE GRAVITY

$\sim$ 100,000 OURS

WHITE DWARFS ARE FOREVER?

- ISOLATED WDS

  YES but......

- WDS IN A BINARY

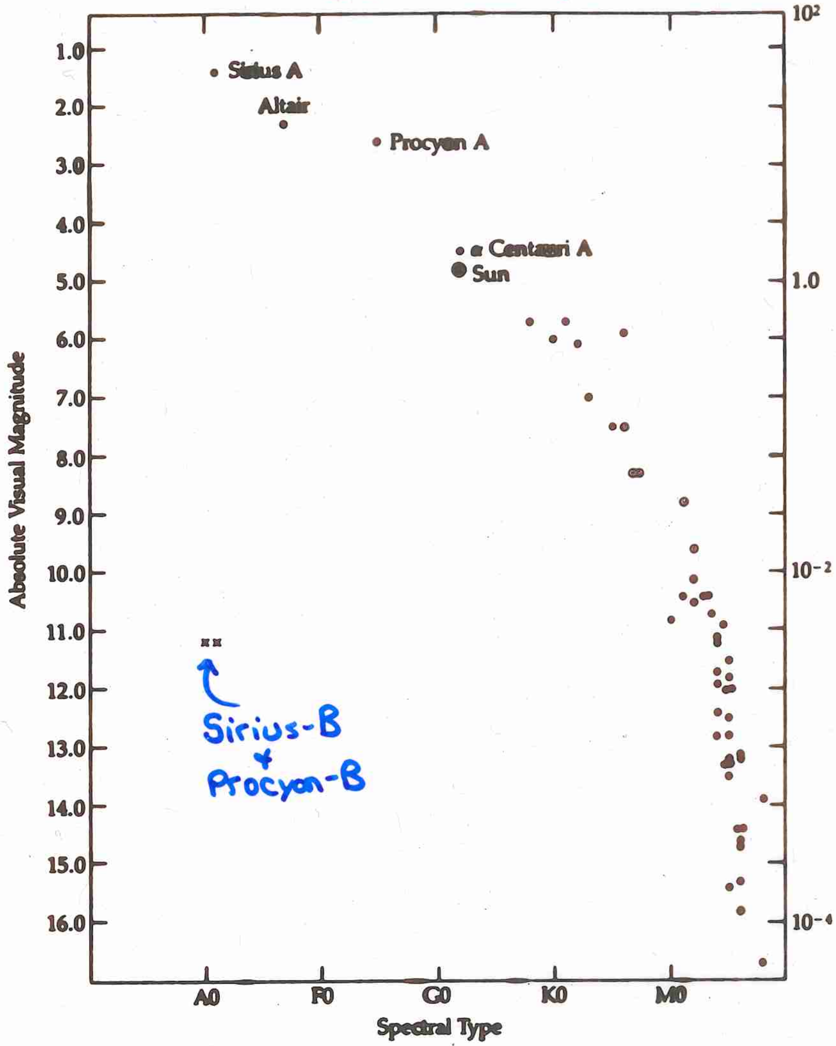
  IF COMPANION TRANSFER MASS TO WD, ITS MASS MAY BE INCREASED TO CHANDRASEKHAR'S LIMIT, THEN BANG → SN Ia

  or

  NOVA

HOW COMMON ARE WHITE DWARFS?

COMMON!



THESE ARE ALL STARS WITHIN 5 pc OF THE SUN.

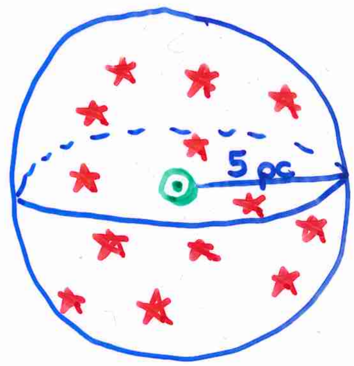


Figure 13-7

Hertzsprung-Russell diagram for stars within 5 pc of the Sun.

WHERE DO THESE WHITE DWARFS COME FROM?

WHY IS A WD A FINAL FORM ?

WD IS SUPPORTED AGAINST GRAVITY BY DEGENERATE ELECTRON PRESSURE

THIS PRESSURE IS TEMPERATURE DEPENDENT

WD COOLS : NUCLEI LOSE ENERGY : BUT DOES NOT SHRINK