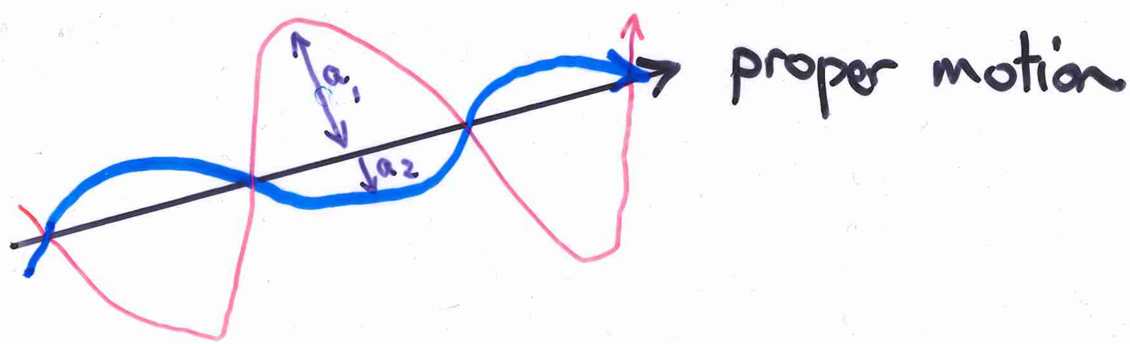
VISUAL BINARIES

- A system in which two stars are resolved by a telescope

- Stars seen to orbit each other but periods are long [WHY?]

  P ~ 10s to 1000s years

- Relative masses, m_1/m_2



STAR 2 more massive than STAR 1 [WHY?]

$$\frac{m_1}{m_2} = \frac{a_2}{a_1}$$

SIRIUS

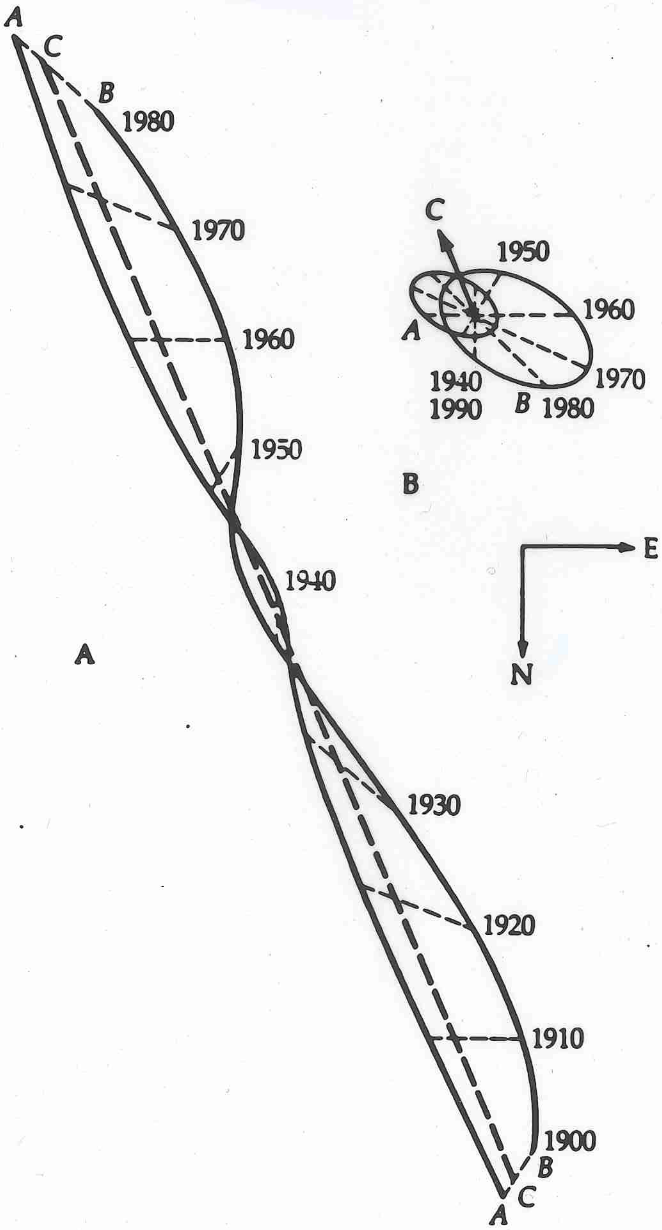
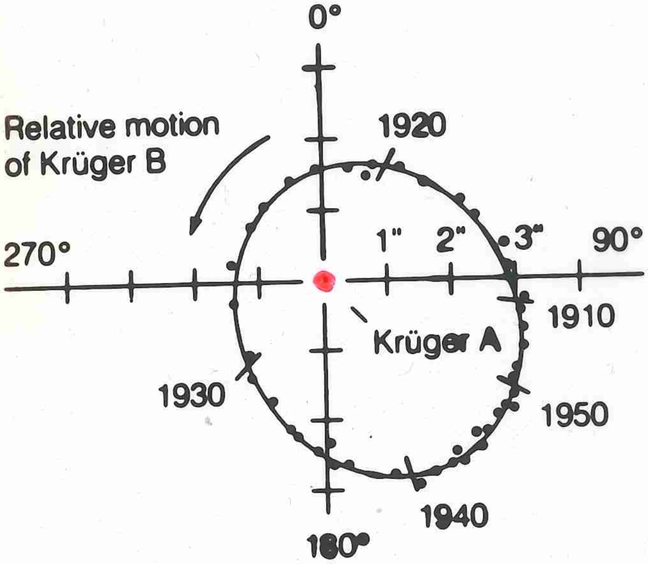
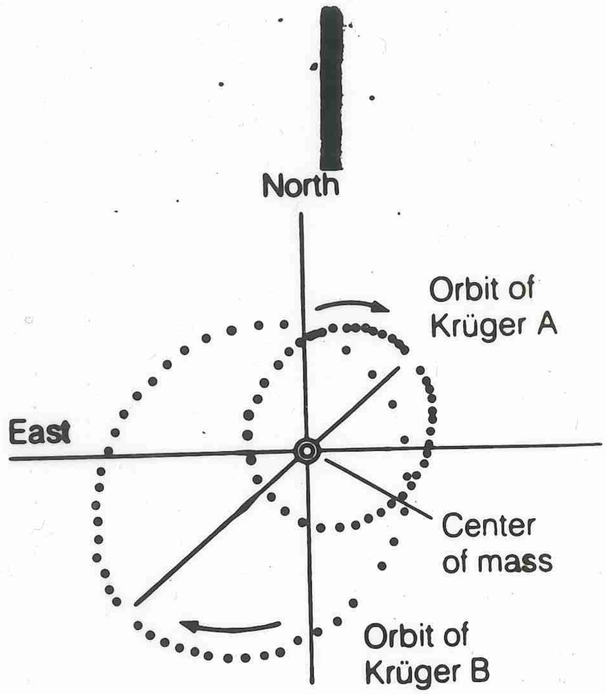


Figure 12-2

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.





APPARENT RELATIVE ORBIT

- INDIVIDUAL MASSES, m_1 & m_2

CORRECT OBSERVED ORBIT FOR ITS TILT RELATIVE TO LINE OF SIGHT

DETERMINE PERIOD AND SEMI-MAJOR AXIS ESTIMATE DISTANCE

APPLY KEPLER'S 3rd LAW!

$$m_1 + m_2 = \frac{a^3}{P^2}$$

TWO EQNS, TWO UNKOWNS

$\rightarrow m_1$ and m_2

$$\boxed{\text{VITAL SOURCE OF STELLAR MASSES}}$$

ECLIPSING BINARIES

- Stars experience mutual eclipses:

  ORBITS SEEN EDGE-ON

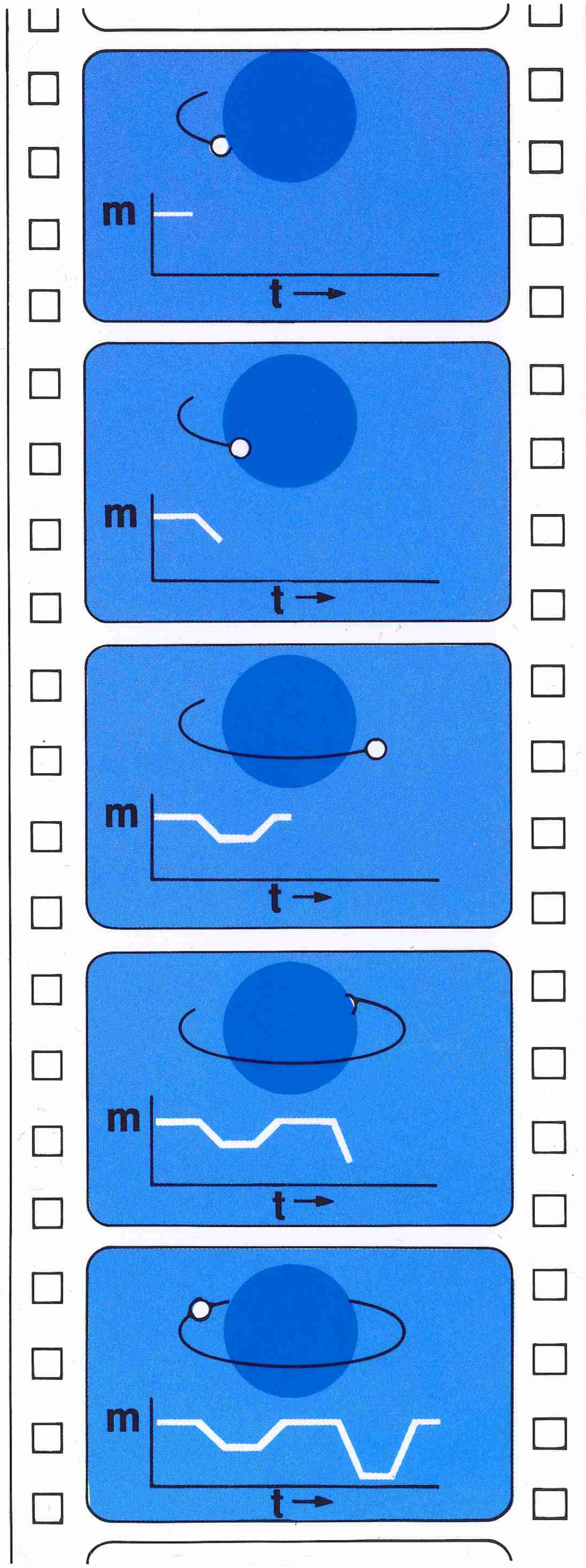
- BRIGHTNESS VARIATIONS | ECLIPSES and RADIAL VELOCITY VARIATIONS are observed

$\Longrightarrow m_1, m_2$ [KEPLER'S LAWS]

R_1, R_2 [ECLIPSE DURATION + RADIAL VELOCITY]

ORBIT DIMENSIONS

WHY ARE ECLIPSING BINARIES NOT VISUAL BINARIES?



Eclipsing binary—changes in brightness

Seeds: Horizons, 1995 ed., Fig. 8–18; Foundations of Astronomy, 1994 ed., Fig. 10–18

SPECTROSCOPIC BINARIES

- A binary system in which stars are too close to be seen as 2 stars but their presence revealed by spectroscopy [Doppler effect]

- If stars have similar luminosities, both contribute to total light.

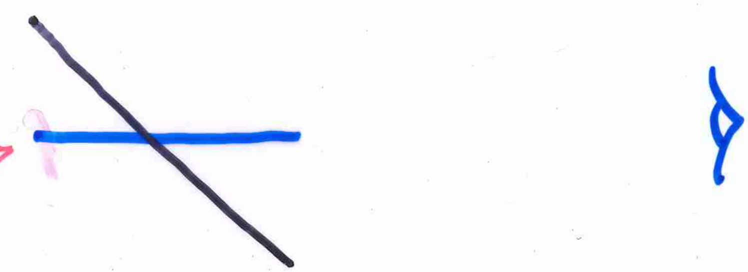
  TWO SETS OF ABSORPTION LINES SEEN : DOUBLE-LINED SB

- If luminosities are dissimilar, one dominates light

  ONE SET OF ABSORPTION LINES: SINGLE-LINED SPECTROSCOPIC BINARY

- RADIAL VELOCITIES measured

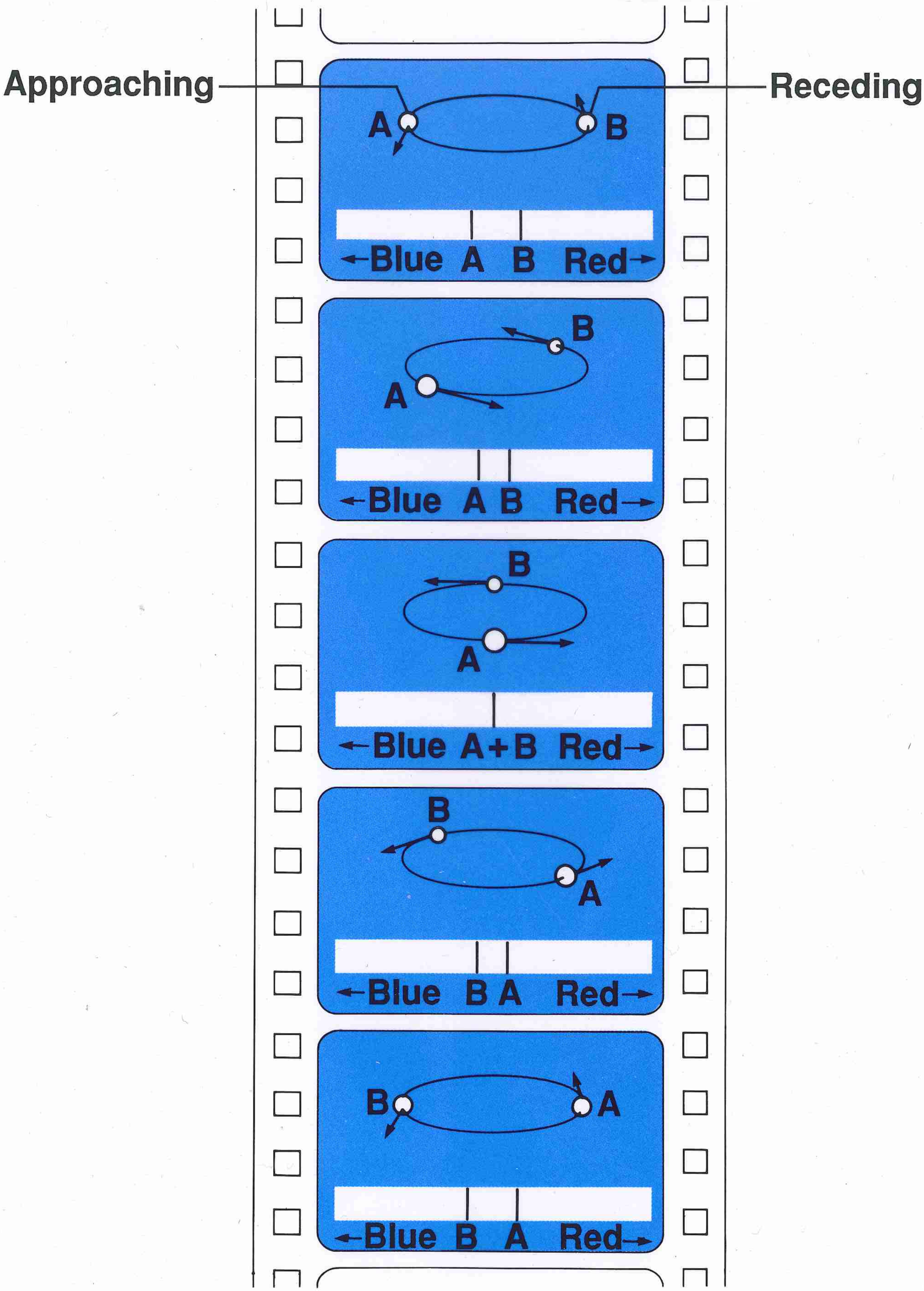
CANNOT DETERMINE TRUE SIZE OF ORBITS : TILT TO LINE OF SIGHT IS INDETERMINATE



RADIAL VELOCITIES TELL US THIS PROJECTED SIZE

SB2 $\Rightarrow \dfrac{m_1}{m_2}$ from the amplitudes of the radial velocity swings

SB1 $\Rightarrow$ LOWER LIMIT to $(m_1 + m_2)$



Spectroscopic binary—Doppler shifts

Seeds: Horizons, 1995 ed., Fig. 8–14; Foundations of Astronomy, 1994 ed., Fig. 10–12

MASS - LUMINOSITY RELATION

- MAIN SEQUENCE STARS

$$L \propto m^4$$

- WHITE DWARFS

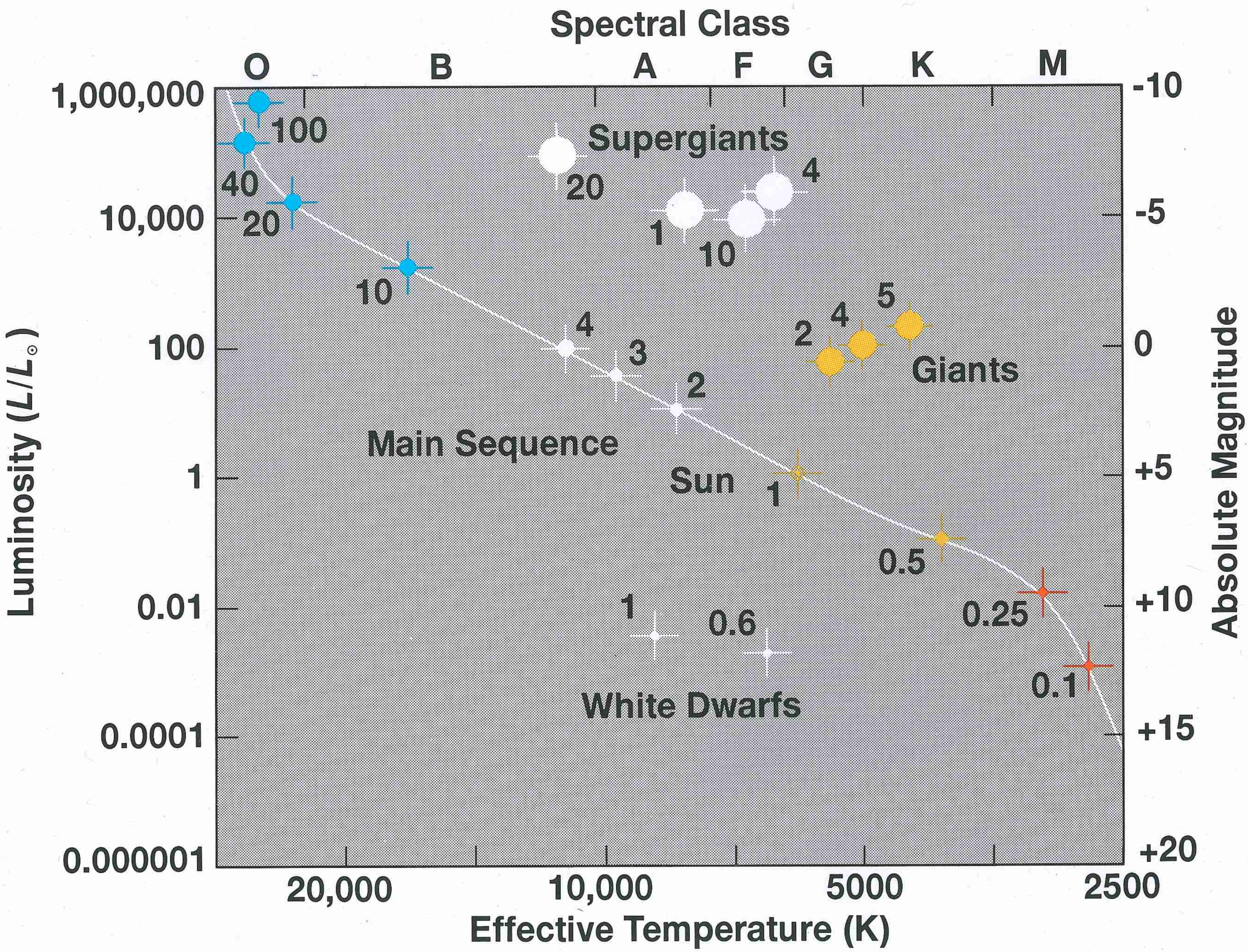
$$m \sim 0.6 m_\odot$$

L varies with age

- RED GIANTS

COMPLEX : L-m RELATION

(SEE LATER)



H-R diagram—measured masses of stars

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 17-8

STELLAR EVOLUTION

- DIRECTED FROM BIRTH BY GRAVITY (STELLAR MASS)

- POSSIBLE CONCLUSIONS

  1. GRAVITY WINS: $* \longrightarrow$ BLACK HOLE

  2. GRAVITY PERMANENTY THWARTED:

     GRAVITY OPPOSED BY A NON-THERMAL PRESSURE

     $* \longrightarrow$ STABLE COLD REMNANT

     WHITE DWARF

     NEUTRON STAR

③ GRAVITY 'LOSES':

STAR EXPLODES, LEAVES NO REMNANT.

- MASS OF REMNANT IS LESS THAN INITIAL MASS OF STAR
  - VERY LITTLE MASS (<1%) CONVERTED TO ENERGY
  - A LOT OF MASS SHED FROM STAR DURING ITS EVOLUTION AND AT ITS DEATH

- EVOLUTION OF STARS IN A BINARY CAN DIFFER GREATLY FROM SIMILAR SINGLE STARS (MASS TRANSFERRED BETWEEN STARS)

MAIN SEQUENCE LIFETIMES

$$\text{LIFETIME} = \frac{\text{FUEL SUPPLY}}{\text{RATE OF CONSUMPTION}}$$

SIMPLE ASSUMPTIONS →

$$t \propto \frac{\text{MASS OF STAR}}{\text{LUMINOSITY OF STAR}} = \frac{m}{L}$$

BUT $L \propto m^4$ FOR MAIN SEQ. STARS

$$t \propto \frac{m}{m^4} = \frac{1}{m^3}$$

$$\boxed{\frac{t_*}{t_{SUN}} = \left(\frac{m_{SUN}}{m_*}\right)^3}$$

DIFFERENT L-M

MASS ($M_\odot$)	$\frac{L}{L_\odot}$	$\frac{t}{t_\odot}$	t(yrs)
0.1	1/200	20	200 Billion
0.5	1/16	8	80 Billion
1	1	1	10 Billion
5	625	1/125	80 Million
10	10,000	1/1000	10 Million
50	6,250,000	1/125,000	80,000
100	100 Million	1/1,000,000	10,000

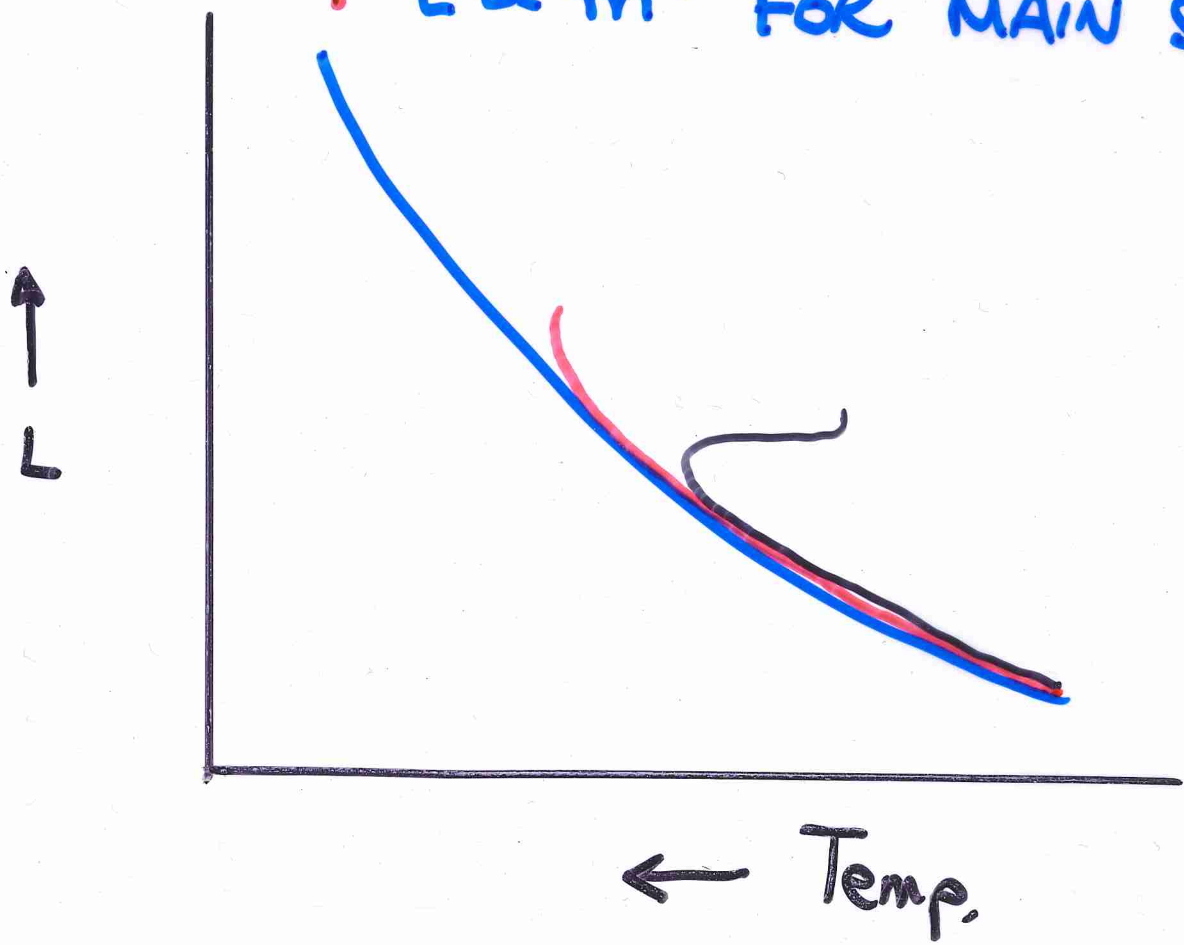
$$L \propto m^4$$

$$t \propto \frac{m}{L} = \frac{m}{m^4} = \frac{1}{m^3}$$

NOTE: ENORMOUS RANGE

CLUSTER AGES

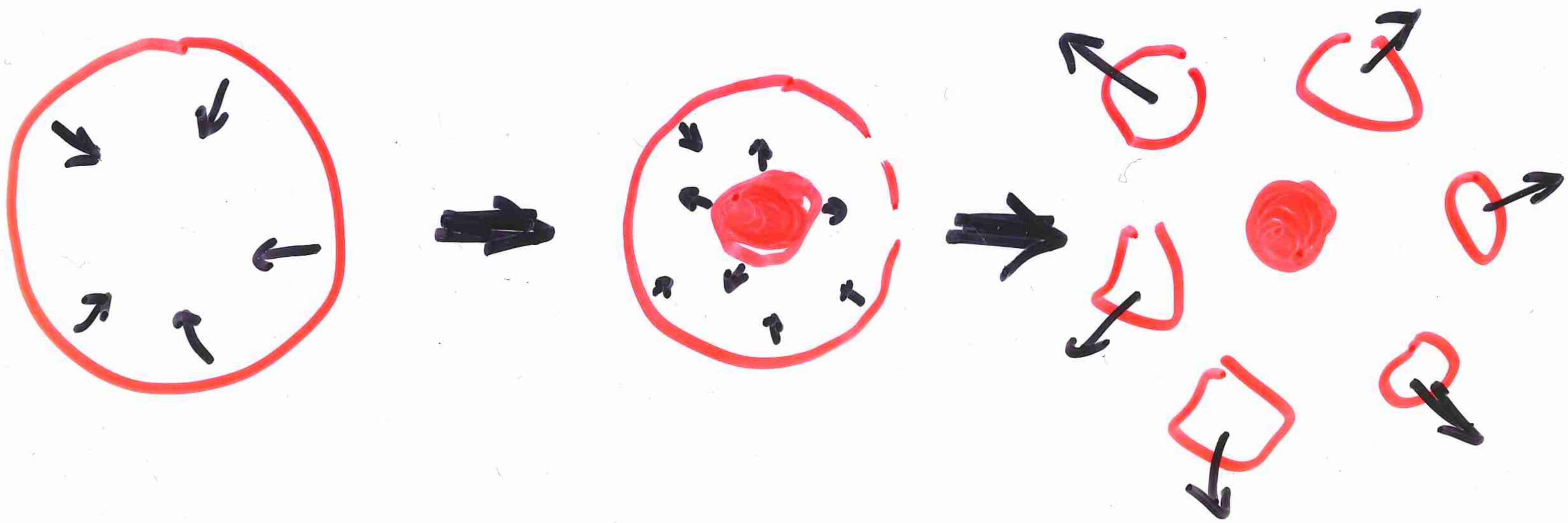
• KEY POINT: MASSIVE STARS HAVE SHORTER LIFETIMES THAN LESS MASSIVE STARS ($t \propto 1/m^3$)
: $L \propto m^4$ FOR MAIN SEQUENCE



YOUNGEST ?
OLDEST ?

RANGE OF STELLAR MASSES

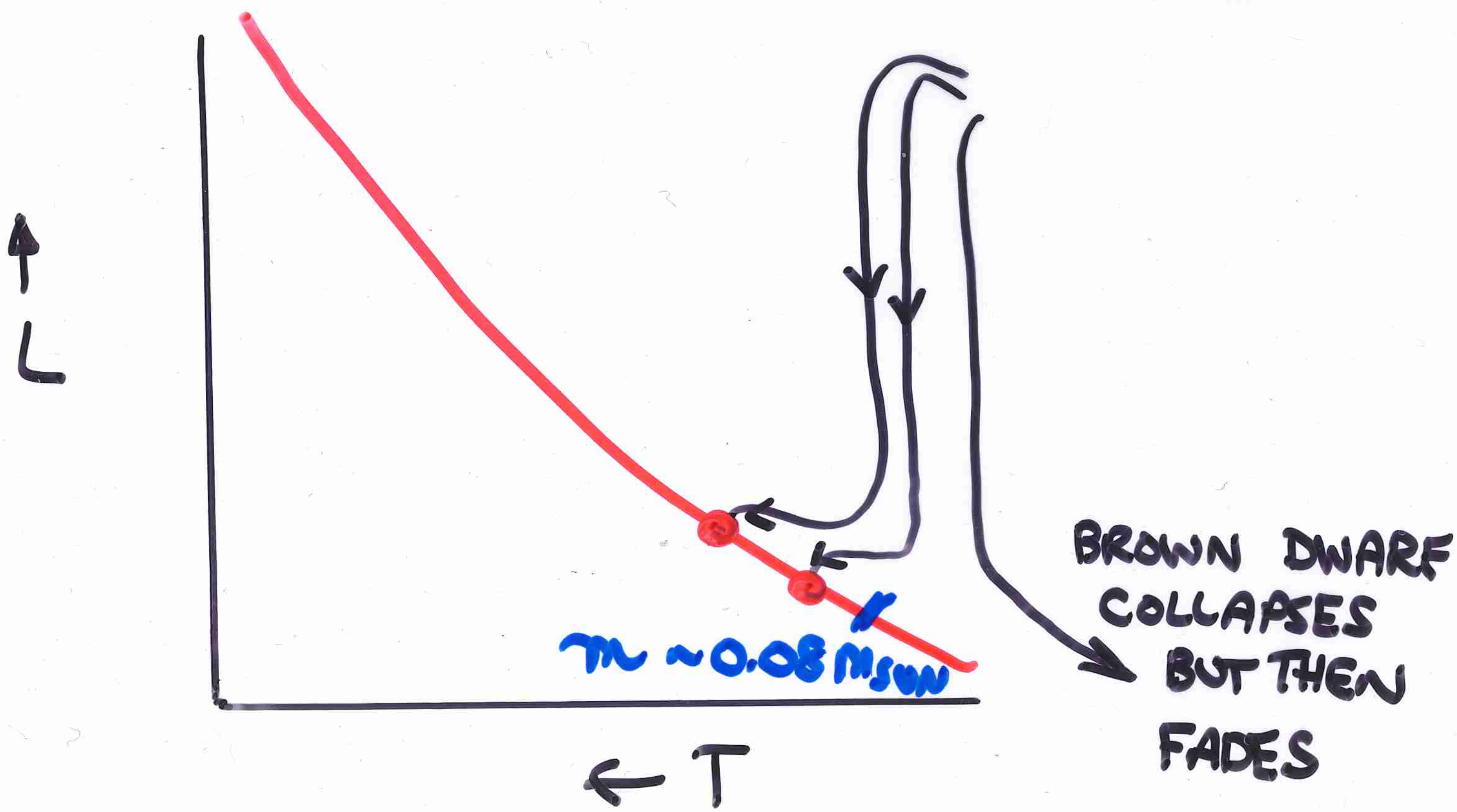
- MAXIMUM $\sim 100 M_{SUN}$
  - IF A PROTOSTAR $> 100 M_{SUN}$ FORMS, CORE COLLAPSES QUICKLY AND HEATS UP TO BLOW OFF OUTER LAYERS. SLIMMED PROTOSTAR $\approx 100 M_{SUN}$



• MINIMUM $\sim 0.08\, M_{SUN}$ SEMANTICS!

A STAR BURNS $4H \rightarrow He$. FOR $M < 0.08\, M_{SUN}$, CORE TEMPERATURE TOO LOW TO BURN H

SUCH OBJECTS ARE CALLED <u>BROWN DWARFS</u>



STAR FORMATION [SEEDS 12-1]

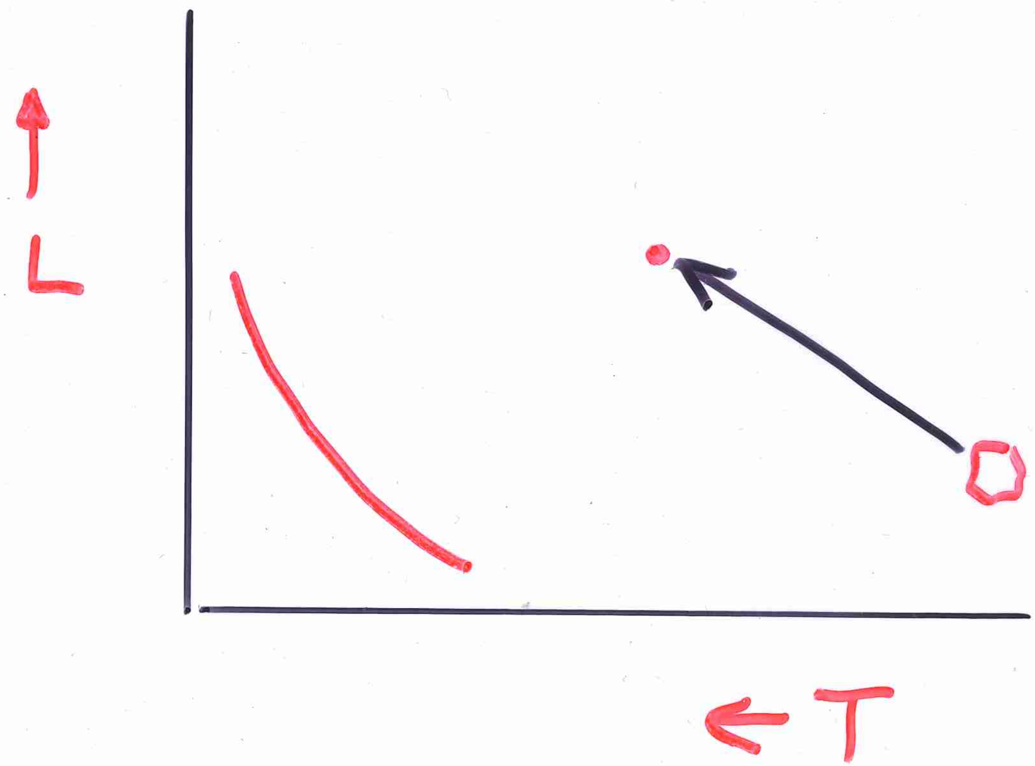
- OCCURS IN COLD DENSE CLOUDS OF GAS
- DIRECTED BY GRAVITY

  IF THERMAL PRESSURE IN CLOUD IS TOO LOW TO RESIST GRAVITY, CLOUD BEGINS TO COLLAPSE.

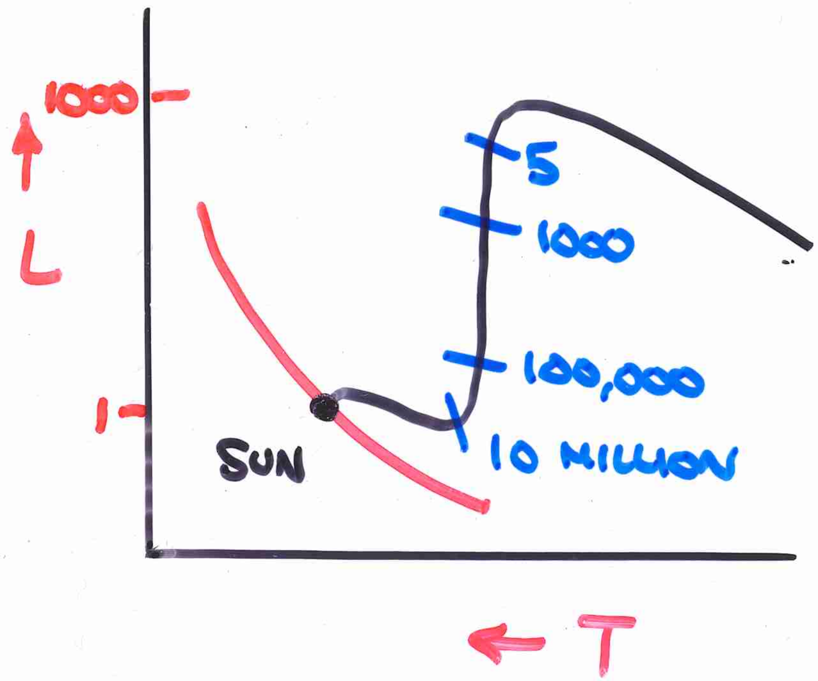
  LARGE CLOUDS ($1000^+ M_{SUN}$) COLLAPSE AND FRAGMENT INTO SMALLER CLOUDS

  → STARS

- EARLY COLLAPSE
  - GRAVITATIONAL ENERGY → HEAT
  - SOME HEAT TRAPPED, SOME ESCAPES
  - CENTRAL TEMPERATURE RISES
    → THERMAL PRESSURE RISE



• LATER COLLAPSE

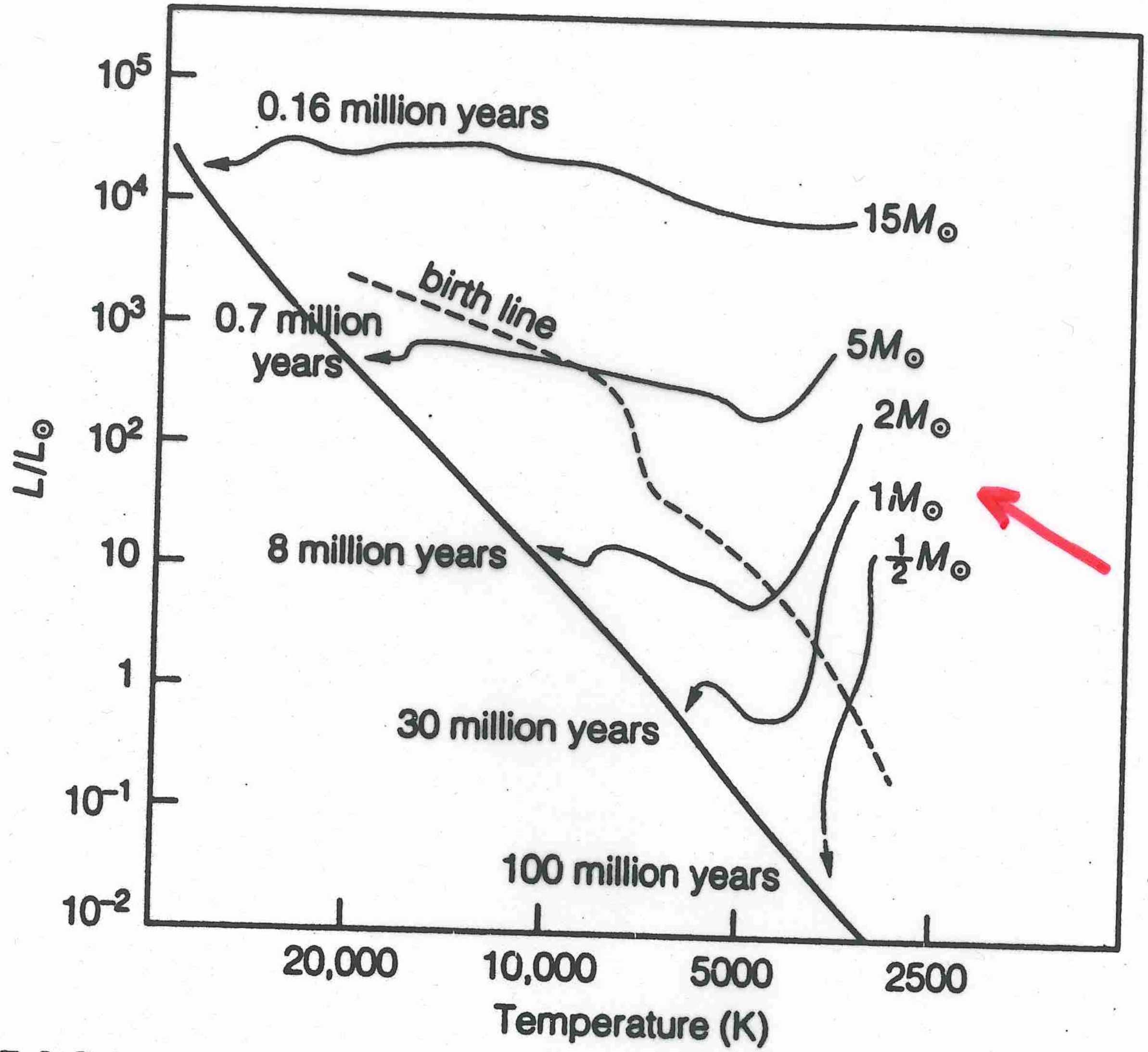


• HAYASHI TRACK RAPID DROP IN L AT ~ CONSTANT T

• ENERGY REMOVED FROM CORE EFFICIENTLY BY CONVECTION

• ENERGY USED TO BREAK UP H_2 MOLECULES

• CONVECTION CEASES AT BASE, STAR BEGINS SLOW K-H CONTRACTION TO MAIN SEQ.



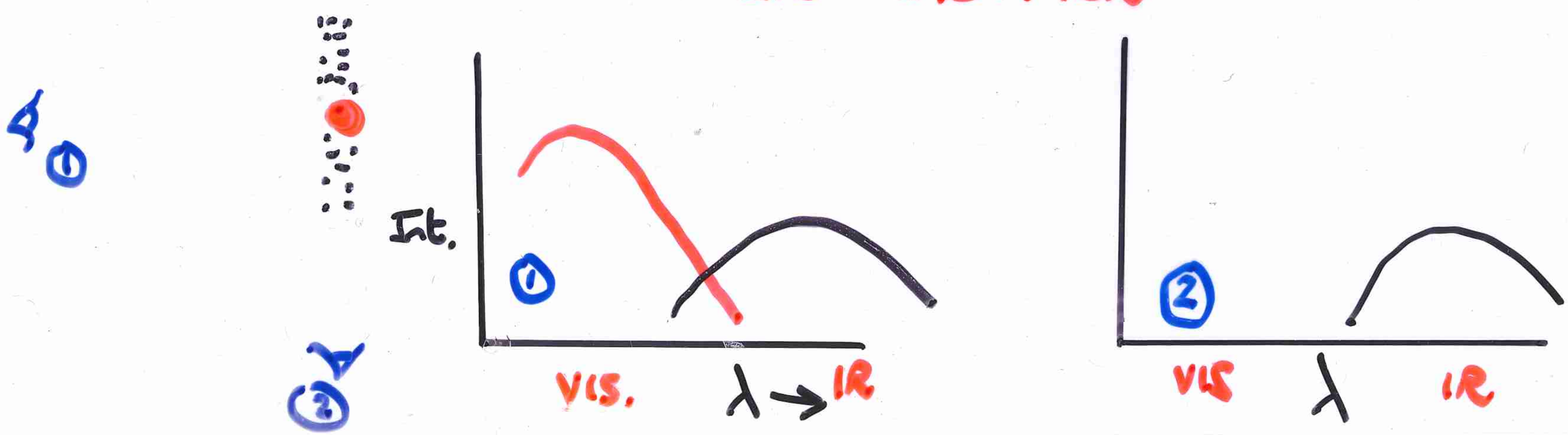
"KELVIN
- HELMHOLTZ"

FIGURE 12-5

The more massive a protostar is, the faster it contracts. A 1 $M_\odot$ star requires 30 million years to reach the main sequence. The dashed line is the birth line, where contracting stars first become visible. (Illustration design by author)

PROTOSTARS (≡ pre-MAIN SEQUENCE STARS)

- SURROUNDED BY DUST, OFTEN IN A DISK
- DISK OF DUST MAY OBSCURE STAR
- PLANETS MAY FORM IN DISK
- DUST DISPERSED EVENTUALLY
- DUST REVEALED BY IR RADIATION



STELLAR EVOLUTION

INITIAL MASS	REMNANT
LESS THAN $8\,M_{SUN}$	WHITE DWARF $m_{WD} \lesssim 1.4\,M_{SUN}$ $\sim 0.6\,M_{SUN}$ typically
GREATER THAN $8\,M_{SUN}$	NEUTRON STAR $m_{NS} \lesssim 3\,M_{SUN}$ OR BLACK HOLE $m > m_{NS}, m_{WD}$ $\gtrsim 3\,M_{SUN}$

WHAT'S THE NEXT STEP FOR He-RICH MAIN-SEQUENCE STARS?

- AS H SUPPLY IN CORE DECLINES, ENERGY SUPPLIED BY $4H \rightarrow He$ DECLINES TOO
- CORE MUST COLLAPSE : GRAVITY IN THE ASCENDANT TEMPORARILY : H CONTINUES TO BURN IN SHELL AROUND CORE
- COLLAPSE $\rightarrow$ HEATING (KELVIN - HELMHOLTZ "We told you") WITH TEMPERATURE RISING TO 200 MILLION KELVIN
- HOT CORE CAUSES OUTER LAYERS TO SWELL : STAR APPEARS AS RED GIANT / SUPERGIANT
- AT $T \sim 200$ MILLION K, HE BURNS : GRAVITY "FRUSTRATED" AGAIN.

$\boxed{\text{He- BURNING}}$

- $^4He + {}^4He \rightarrow {}^8Be + \gamma$

  BUT ^8Be FLYS APART INTO 2 ^4He IN 10^{-16} seconds

- $^4He + {}^8Be \rightarrow {}^{12}C + \gamma$

  ^{12}C IS STABLE

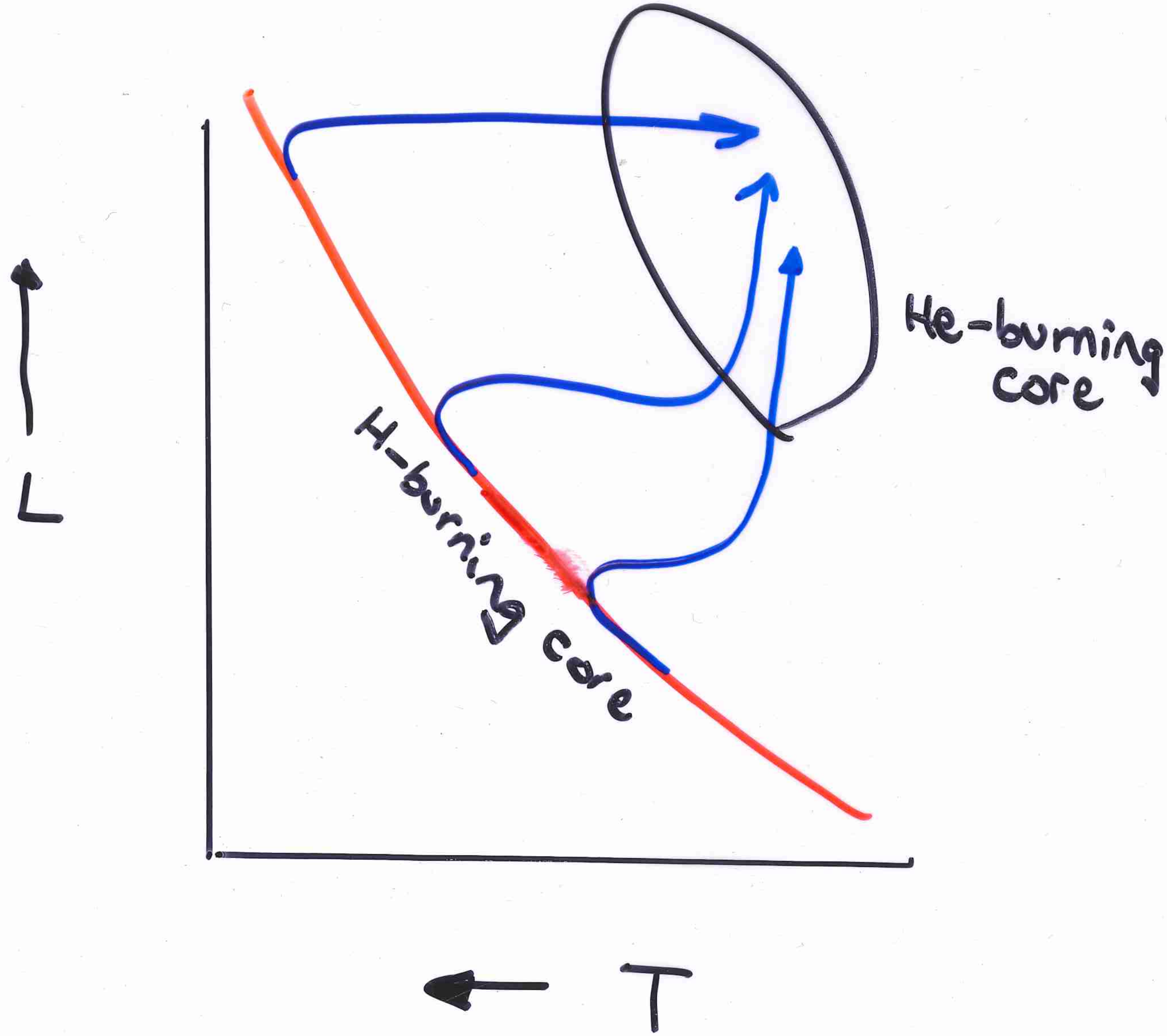
$\therefore$ THE PROCESS RUNS BY A TRIPLE COLLISION

$$\boxed{3\,{}^4He \rightarrow {}^{12}C + \gamma}$$

"TRIPLE α PROCESS"

- AT HIGH TEMPERATURES, ALSO

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



He-burning
core
H-burning core
L
T

- He-BURNING OCCURS AT HIGHER TEMPERATURES & HIGHER DENSITIES THAN H-BURNING

- He-BURNING IS LESS EFFICIENT (10 TIMES) THAN H-BURNING

SUN : $\begin{cases} 10^{10} \text{ years for H-burning} \\ 200 \times 10^{6} \text{ years for He-burning} \end{cases}$

- ALL STARS EXPERIENCE He-BURNING

- $\begin{cases} \text{HIGH MASS STARS BURN C AND O} \\ \text{LOW MASS STARS DO NOT} \end{cases}$