ASTR 1040: Stars & Galaxies

Etched Hourglass Nebula

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Lecture 12   Thur 20 Feb 2020
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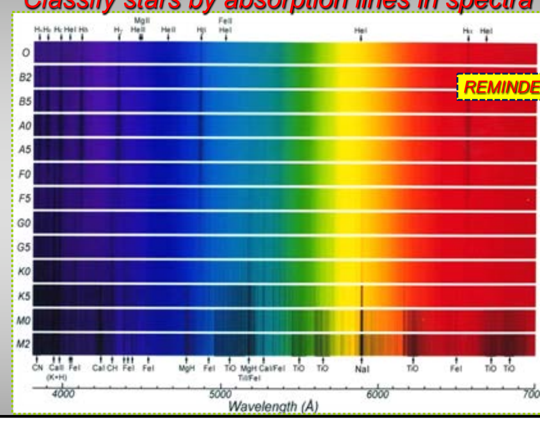
Stuff to do

- Paper shuffle: Graded HW #4 to retrieve with answers, HW #5 due, new HW #6 passed out. Graded MT-Exam 1 still available.
- Re-read 15.3 Star Clusters with care, and review all of Chap 15 "Surveying the Stars"
- Read 16.1 "Stellar Nurseries" & 16.2 "Stages of Star Birth" for Tues lecture (getting to the Main Sequence)
- Some basic comments about Homeworks and their Answers

Topics for Today

- Brief review of roadmap to the stars: Hertzsprung-Russell (H-R) diagram
- Binary stars allow us to measure MASS
- Why O and B stars are so luminous on MS?
- C-N-O cycle dominates fusion burning of H in massive stars, really pours out the energy
- Explains observed MASS-LUMINOSITY relation
- Estimate lifetime on the main sequence (MS)
- What star clusters can tell us

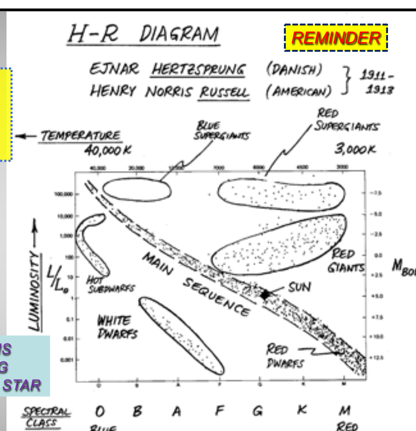
Classify stars by absorption lines in spectra



Hertzsprung-Russell (H-R) Diagram

Luminosity (magnitude) vs Spectral class (temperature)

... BUT TO MAKE THIS REQUIRES KNOWING DISTANCE TO EACH STAR



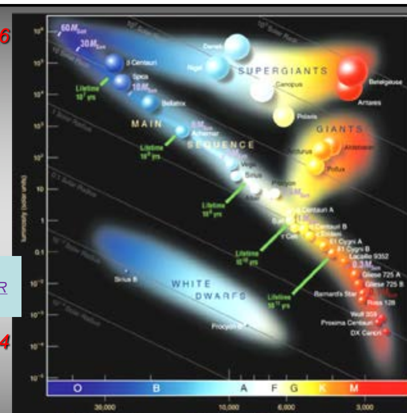
10^6

Luminosity

(solar units)

NOTE DIAGONAL LINES OF STELLAR RADII HERE

10^{-4}



40,000   ← Temperature   3,000

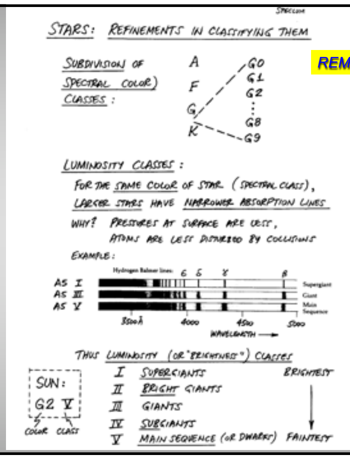
Further refinements:

DECIMAL SUBDIVISION

LUMINOSITY CLASSES

Sun is: G2 V

COLOR CLASS



REMINDER

Why do visible spectra of hottest stars (O and B types) show few absorption lines?

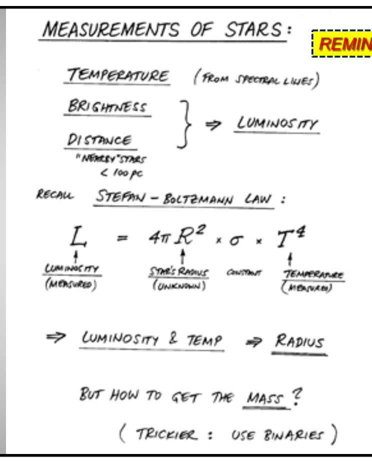
E.

- A. Many elements have been used up in these stars
- B. These stars are old and were formed before there were many elements in the galaxy
- C. Many atoms in these stars are ionized – have lost electrons – so cannot absorb
- D. Much of their absorption is in the ultraviolet
- E. C and D

Estimating the size of a star – its RADIUS

Stefan-Boltzmann

But how to measure MASS: … binary stars

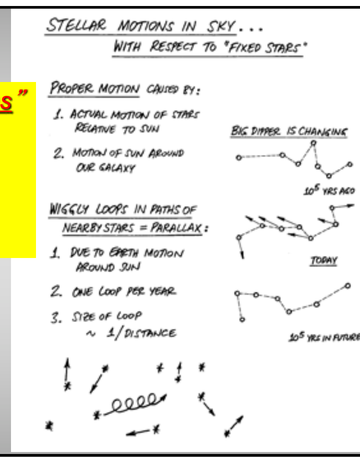


REMINDER

"Proper motions"

wiggly motions (parallax)

and binaries …

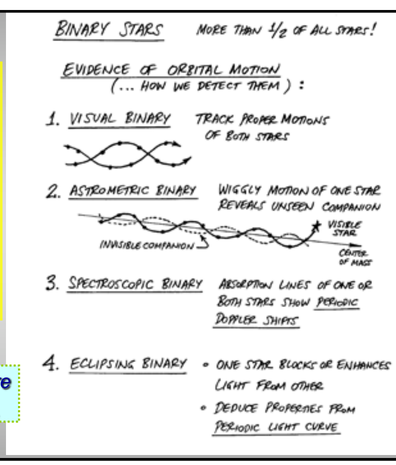


BINARY STARS

4 varieties:

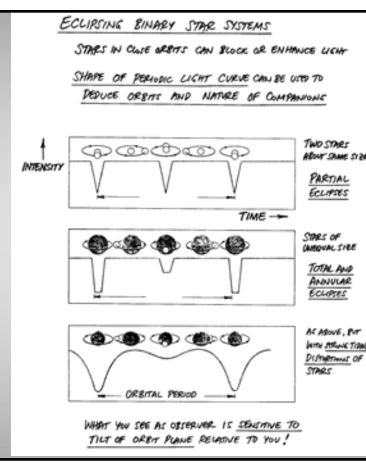
Visual
Astrometric
Spectroscopic
Eclipsing

Use to measure stellar masses

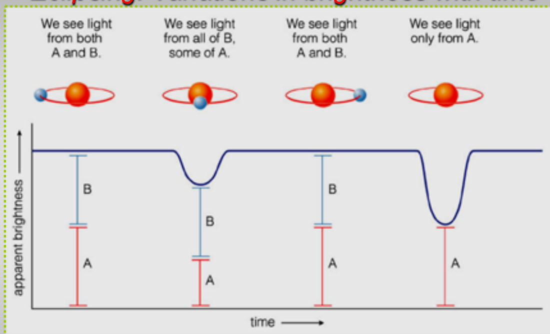


Eclipsing binaries

one star gets in front or behind other



Eclipsing: Variations in brightness with time



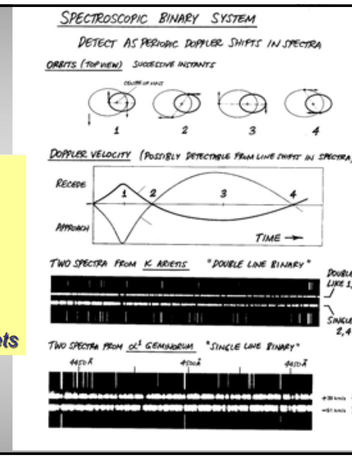
Very useful (can even infer stellar radii), but RARE … viewing angle has to be right on edge!

Spectroscopic binaries

Most common of all

Do not see stars individually
-- but see shifting absorption lines

Sometimes TWO sets


SPECTROSCOPIC BINARY SYSTEM

DETECT AS PERIODIC DOPPLER SHIFTS IN SPECTRA

ORBITS (TOP VIEW) SUCCESSIVE INSTANTS

1 2 3 4

DOPPLER VELOCITY (POSSIBLY DETECTABLE FROM LINE SHIFTS IN SPECTRA)

RECEDE

APPROACH

TIME →

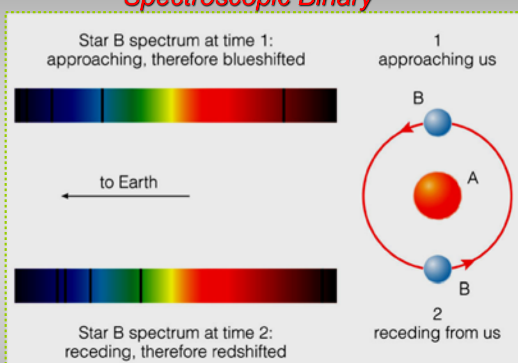
TWO SPECTRA FROM K ARIETIS "DOUBLE LINE BINARY"

DOUBLE-LINE 1,3

SINGLE 2,4

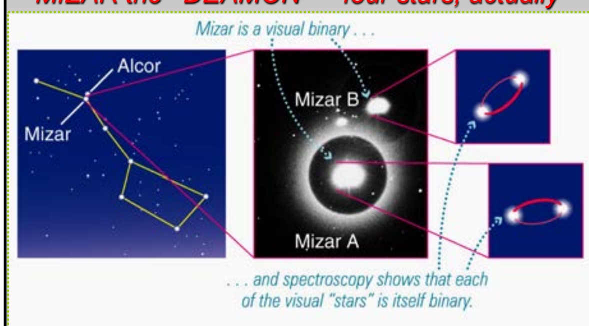
TWO SPECTRA FROM α[1] GEMINORUM "SINGLE LINE BINARY"

Spectroscopic Binary



Harder to interpret, since do not know viewing angle

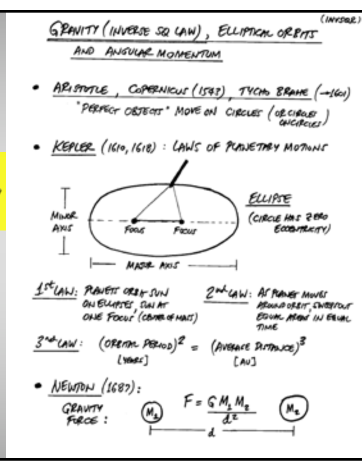
MIZAR the "DEAMON" – four stars, actually



Recall from Chap 3 :

KEPLER devised 3 laws for planetary (or stellar) motions

In 1687, NEWTON explained them as balance of gravity and centrifugal force


GRAVITY (INVERSE SQ LAW), ELLIPTICAL ORBITS AND ANGULAR MOMENTUM (INVSQR)

- ARISTOTLE, COPERNICUS (1543), TYCHO BRAHE (→1601)
  "PERFECT OBJECTS" MOVE ON CIRCLES (OR CIRCLES ON CIRCLES)
- KEPLER (1610, 1618) : LAWS OF PLANETARY MOTIONS

MINOR AXIS — FOCUS — FOCUS — MAJOR AXIS

ELLIPSE (CIRCLE HAS ZERO ECCENTRICITY)

1st LAW: PLANETS ORBIT SUN ON ELLIPSES, SUN AT ONE FOCUS (CENTER OF MASS)

2nd LAW: AS PLANET MOVES AROUND ORBIT, SWEEPS OUT EQUAL AREAS IN EQUAL TIME

3rd LAW: $(\text{ORBITAL PERIOD})^2 = (\text{AVERAGE DISTANCE})^3$
[YEARS] [AU]

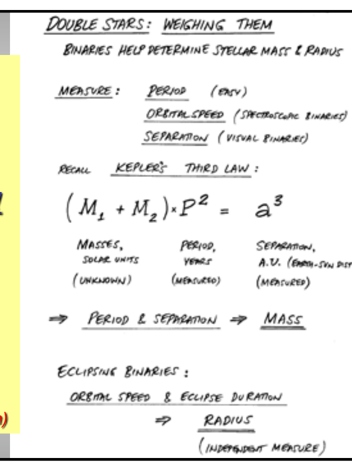
- NEWTON (1687):
  GRAVITY FORCE : $F = \frac{G M_1 M_2}{d^2}$ (M_1, M_2, separated by d)

So why all the fuss with BINARIES?

Can really "weigh" a star !

STELLAR MASSES can be inferred from watching orbits

(via law of gravity – Kepler and Newton)


DOUBLE STARS: WEIGHING THEM

BINARIES HELP DETERMINE STELLAR MASS & RADIUS

MEASURE : PERIOD (EASY)
ORBITAL SPEED (SPECTROSCOPIC BINARIES)
SEPARATION (VISUAL BINARIES)

RECALL KEPLER'S THIRD LAW :

$$(M_1 + M_2) \times P^2 = a^3$$

MASSES, SOLAR UNITS (UNKNOWN)
PERIOD, YEARS (MEASURED)
SEPARATION, A.U. (EARTH-SUN DIST) (MEASURED)

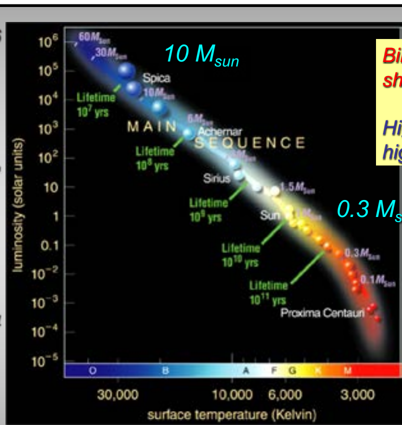
⇒ PERIOD & SEPARATION ⇒ MASS

ECLIPSING BINARIES :
ORBITAL SPEED & ECLIPSE DURATION
⇒ RADIUS
(INDEPENDENT MEASURE)

10^6

L / L_o

10^{-4}



10 M_{sun}

0.3 M_{sun}

40,000 ← Temperature 3,000

Binary stars show:

Higher on MS, higher MASS

But how long does a star live there ?

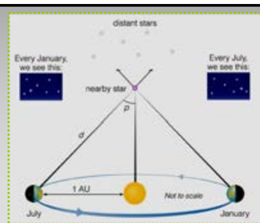
Brightness / Distance Clicker Q

B.

- *Leonardo and Guinevere are two stars that have the same apparent brightness. Leonardo has a larger parallax angle than Guinevere. Which star is more luminous?*

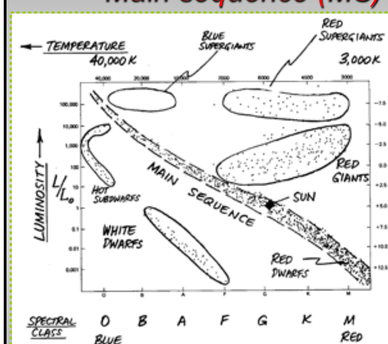
- *A.* Leonardo
- *B.* Guinevere
- *C.* Cannot determine from data given

Brightness vs Distance



- *Leonardo has a larger parallax angle -- thus he is closer to us*
- *They both have the same APPARENT brightness, but Leo is closer*
- ***B.*** *Guinevere must be more luminous*

Main sequence (MS) stars



Burning hydrogen in their cores

Central temperatures are hotter for more massive stars (crush of gravity)

More luminous (higher fusion rates)

Lifetimes on Main Sequence (MS)

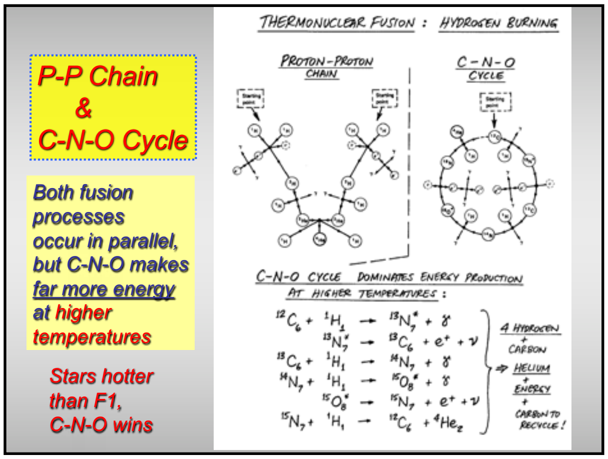
- *Stars spend 90% of their lives on MS*
- *Lifetime on MS = amount of time star burns hydrogen (gradually) in its core*

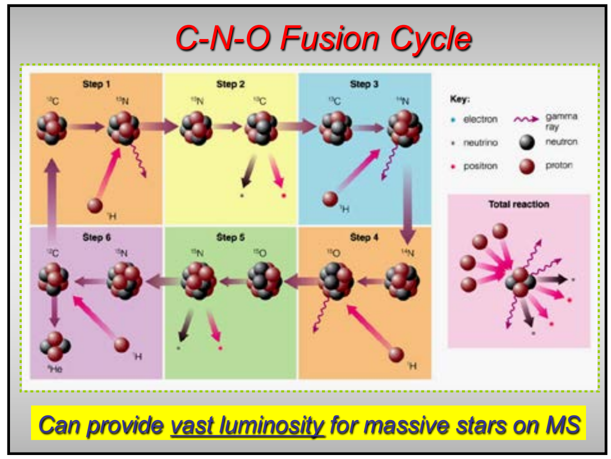
- *For Sun, this is about 10 billion years*
- *For more massive stars (OBAF), lifetime is (much) shorter*
- *For less massive stars (KM), lifetime is longer*
- *But how do we get these numbers?*

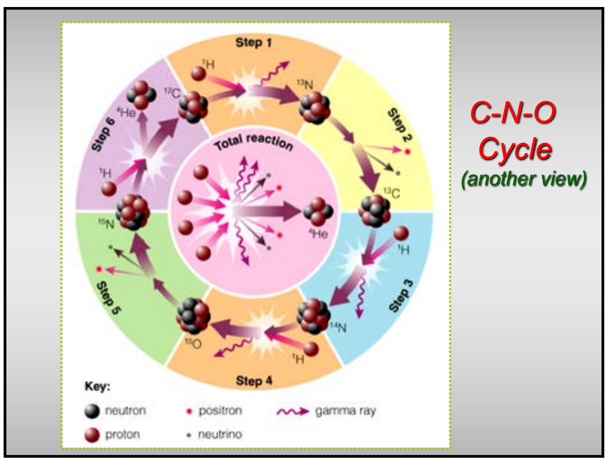
Look at broad sample, to figure out any lifespan

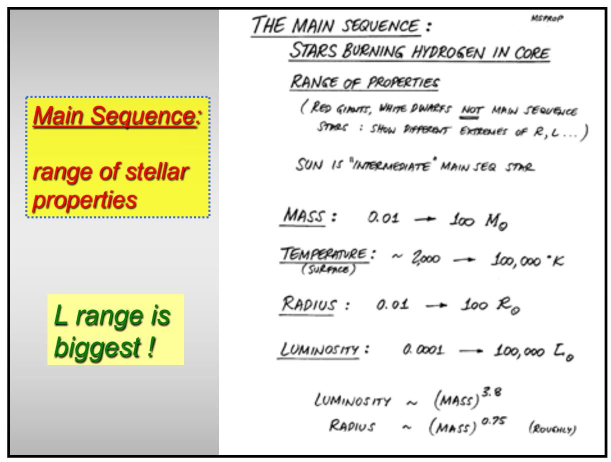
- *Stars take millions to billions of years to go through their life stages - we rarely see a single star change*

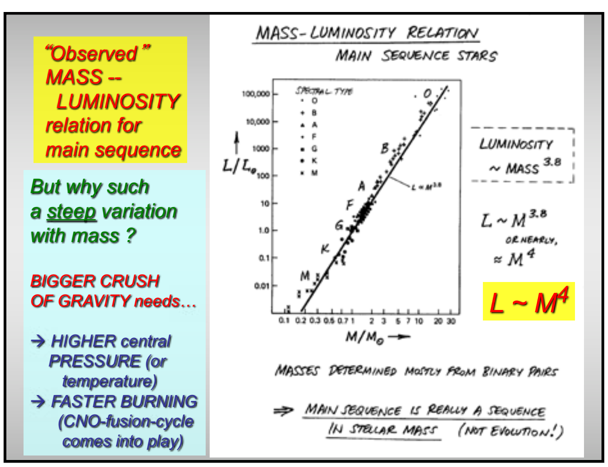
- *Observing many different stars lets us figure out the sequence of a single star's life*

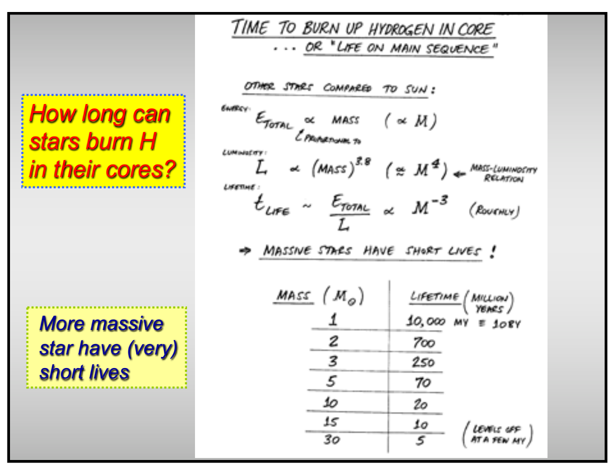

P-P Chain
&
C-N-O Cycle
Both fusion processes occur in parallel, but C-N-O makes far more energy at higher temperatures
Stars hotter than F1, C-N-O wins
THERMONUCLEAR FUSION : HYDROGEN BURNING
PROTON-PROTON CHAIN
C-N-O CYCLE
C-N-O CYCLE DOMINATES ENERGY PRODUCTION AT HIGHER TEMPERATURES :
$^{12}C_6 + {}^1H_1 \rightarrow {}^{13}N_7^* + \gamma$
$^{13}N_7^* \rightarrow {}^{13}C_6 + e^+ + \nu$
$^{13}C_6 + {}^1H_1 \rightarrow {}^{14}N_7 + \gamma$
$^{14}N_7 + {}^1H_1 \rightarrow {}^{15}O_8^* + \gamma$
$^{15}O_8^* \rightarrow {}^{15}N_7 + e^+ + \nu$
$^{15}N_7 + {}^1H_1 \rightarrow {}^{12}C_6 + {}^4He_2$
4 HYDROGEN + CARBON ⇒ HELIUM + ENERGY + CARBON TO RECYCLE !

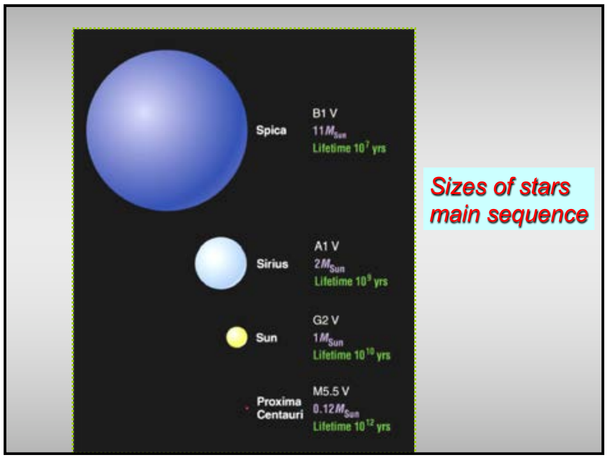

C-N-O Fusion Cycle
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Key:
electron
gamma ray
neutrino
neutron
positron
proton
Total reaction
Can provide vast luminosity for massive stars on MS

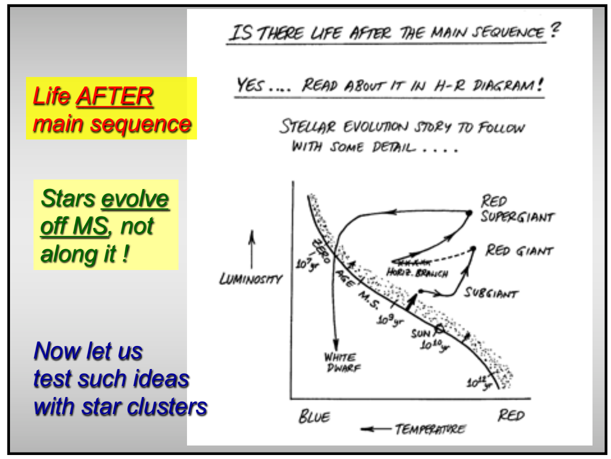

Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Total reaction
Key:
neutron
positron
gamma ray
proton
neutrino
C-N-O Cycle
(another view)


Main Sequence:
range of stellar properties
L range is biggest !
THE MAIN SEQUENCE :
STARS BURNING HYDROGEN IN CORE
RANGE OF PROPERTIES
(RED GIANTS, WHITE DWARFS NOT MAIN SEQUENCE STARS : SHOW DIFFERENT EXTREMES OF R, L ...)
SUN IS "INTERMEDIATE" MAIN SEQ STAR
MASS : 0.01 → 100 $M_\odot$
TEMPERATURE (SURFACE) : ~ 2,000 → 100,000 °K
RADIUS : 0.01 → 100 $R_\odot$
LUMINOSITY : 0.0001 → 100,000 $L_\odot$
LUMINOSITY ~ $(MASS)^{3.8}$
RADIUS ~ $(MASS)^{0.75}$ (ROUGHLY)


"Observed" MASS -- LUMINOSITY relation for main sequence
But why such a steep variation with mass ?
BIGGER CRUSH OF GRAVITY needs…
→ HIGHER central PRESSURE (or temperature)
→ FASTER BURNING (CNO-fusion-cycle comes into play)
MASS-LUMINOSITY RELATION
MAIN SEQUENCE STARS
SPECTRAL TYPE
$L/L_\odot$
$M/M_\odot$
LUMINOSITY ~ $MASS^{3.8}$
$L \sim M^{3.8}$
OR NEARLY, $\approx M^4$
$L \sim M^4$
MASSES DETERMINED MOSTLY FROM BINARY PAIRS
⇒ MAIN SEQUENCE IS REALLY A SEQUENCE IN STELLAR MASS (NOT EVOLUTION!)


How long can stars burn H in their cores?
More massive star have (very) short lives
TIME TO BURN UP HYDROGEN IN CORE
... OR "LIFE ON MAIN SEQUENCE"
OTHER STARS COMPARED TO SUN :
ENERGY: $E_{TOTAL} \propto MASS \; (\propto M)$
PROPORTIONAL TO
LUMINOSITY: $L \propto (MASS)^{3.8} \; (\approx M^4)$ ← MASS-LUMINOSITY RELATION
LIFETIME: $t_{LIFE} \sim \frac{E_{TOTAL}}{L} \propto M^{-3}$ (ROUGHLY)
⇒ MASSIVE STARS HAVE SHORT LIVES !
MASS ($M_\odot$) | LIFETIME (MILLION YEARS)
1 | 10,000 MY ≡ 10 BY
2 | 700
3 | 250
5 | 70
10 | 20
15 | 10
30 | 5
(LEVELS OFF AT A FEW MY)


Spica
B1 V
11M_{Sun}
Lifetime 10^7 yrs
Sirius
A1 V
2M_{Sun}
Lifetime 10^9 yrs
Sun
G2 V
1M_{Sun}
Lifetime 10^{10} yrs
Proxima Centauri
M5.5 V
0.12M_{Sun}
Lifetime 10^{12} yrs
Sizes of stars main sequence


Life AFTER main sequence
Stars evolve off MS, not along it !
Now let us test such ideas with star clusters
IS THERE LIFE AFTER THE MAIN SEQUENCE?
YES .... READ ABOUT IT IN H-R DIAGRAM!
STELLAR EVOLUTION STORY TO FOLLOW WITH SOME DETAIL ....
RED SUPERGIANT
RED GIANT
HORIZ. BRANCH
SUBGIANT
LUMINOSITY
ZERO AGE M.S.
10^7yr
10^9yr
SUN 10^{10}yr
10^{11}yr
WHITE DWARF
BLUE
RED
TEMPERATURE