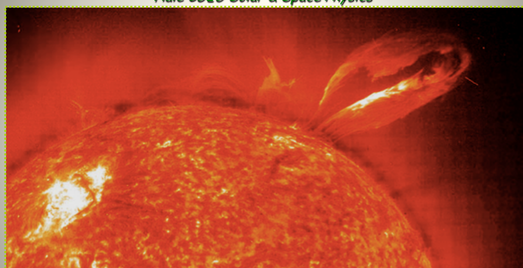
ASTR 7500: Solar & Stellar Magnetism

Hale CGEG Solar & Space Physics



Prof. Juri Toomre + HAO/NSO colleagues

Lecture 1 Tues 22 Jan 2013

zeus.colorado.edu/astr7500-toomre

Why bother with stellar magnetic fields?

- Sun is evidently a (mildly) magnetic star, with (major) impacts on our technological society
- Stars are primary builders of magnetism, by dynamo action in their convection zones
- Stellar magnetic fields likely influence winds and mass loss during evolution (recycling)
- Thus end states of stars can hinge on how much mass is left (WD vs NS vs BH vs nothing)
- But studying dynamo processes is tough, since stellar convection is highly turbulent

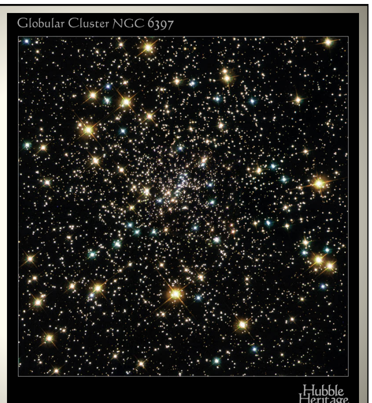
Solar & Stellar Magnetism

- *Discuss solar magnetism: its interior origins and photospheric properties. Consider magnetic activity on other stars. Focus on interplay between observations and modeling.*
- *Examine helioseismic measurements of solar interior and constraints on dynamo models.*
- *Evaluate 3-D MHD models of global-scale convection coupled to rotation, and building magnetic fields through dynamo action.*
- *Consider flux transport from the base of solar CZ into surface layers. Look at thin flux tube models and rising flux bundles.*
- *Study turbulent dynamo processes and spectro-polarimetric measurements of small-scale photospheric fields.*
- *Assess capabilities and limitations of current instrumentation and modeling efforts. Consider promise of ATST and terascale computing.*

Course Resources and Structure

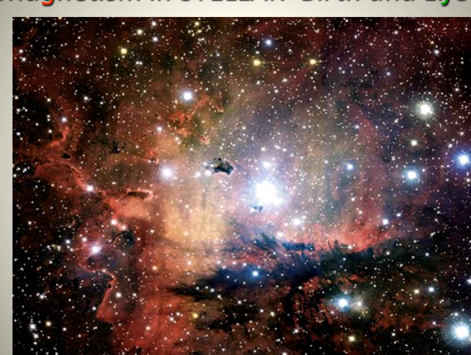
- *Lovely book:* ***Stellar Magnetism***, 2nd edition, ***Leon Mestel***, Oxford 2012
- Major review articles: ***Living Reviews in Solar Physics (on web)*** selected reviews
- ***Heliophysics summer school*** three volumes: selected articles
- Lectures will be ***recorded*** for later review, powerpoint/keynote slides ***available*** as pdf's
- Course primarily lectures and discussions, some problem sets and group projects

STARS come in very many sizes and colors

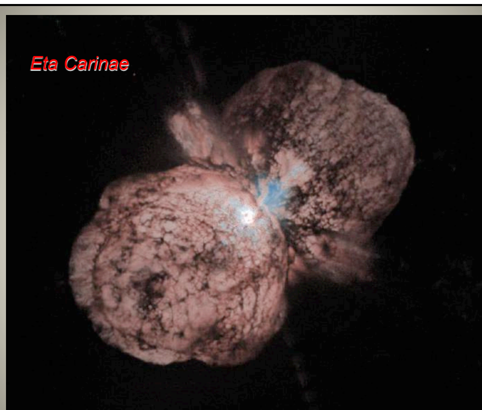


Evolution path and color / brightness depends on MASS

Magnetism in STELLAR Birth and Life



Magnetism in STAR DEATH: white dwarfs; supernovae: neutron stars and black holes



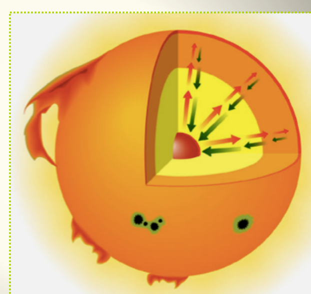
Basic truths: gravity PULL = pressure gradient PUSH

1. SPHERICAL nature of gravity: ROUND star

2. High PRESSURE needed at CENTER, achieved with high TEMPERATURE

3. NUCLEAR BURNING maintains hot center: reactions HIGH powers of TEMPERATURE

4. LUMINOSITY very sensitive to MASS



What is role of rotation or magnetism in stars?

- Either rotation or magnetism can break radial (1-D) symmetry of star assumed in stellar structure and evolution
- Rapid rotation can flatten, even leading to disk, with now preferred direction (rotation axis)
- Rotation can yield Coriolis forces, as one goes into rotating (non-inertial) coordinate system
- Magnetism can provide spatial linkages over broad range of scales, and introduce new time scales
- Lorentz forces serve to couple flows and magnetism

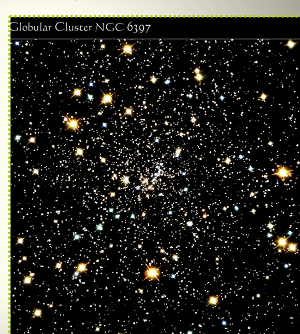
Brief stellar review: why OBAFGKM ?!?

- Spectral (color) classification

O = bluest, hottest

G = yellow (Sun)

M = reddest, coolest



A bit of history: Classifying Stars

World War I, Harvard College observatory

Women were hired by Pickering as "calculators" to help with a new survey of the Milky Way

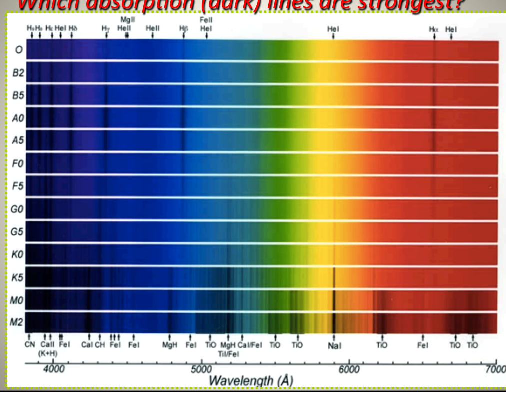
Most had studied astronomy, but were not allowed to work as scientists

Devising the odd spectral (temperature) code

- Original classification of spectra (1890) was:
  A = strongest hydrogen feature
  B = less strong hydrogen
  …C, D, etc.
- Annie Jump Cannon realized that a different sequence made more sense (~1910)

→ O B A F G K M !!

Which absorption (dark) lines are strongest?



Spectral Classification: O B A F G K M

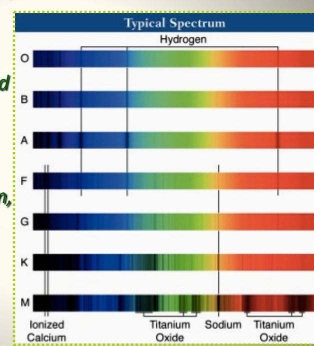
Which ABSORPTION lines are strongest

Hottest stars: O B ionized helium only

Hot stars: A F helium, hydrogen

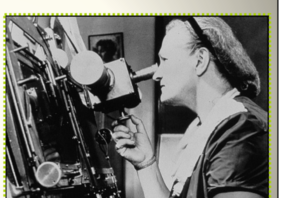
Cooler stars: G hydrogen, heavier atoms

Coolest stars: M molecules, (complex absorption bands)



WHY stellar spectra are so different: TEMPERATURE

- Cecelia P-G showed that SURFACE TEMPERATURE is the big factor (not composition)
- She used newly-devised SAHA EQUATION (1920), estimating how many electrons remain attached to atoms as temperature (avg KE of atoms in collisions) is changed (or the level of ionization)



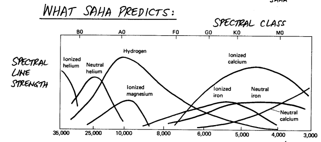
Cecelia Payne-Gaposchkin
(Harvard PhD thesis 1925)

O B A F G K M → decreasing temperature

SAHA predicts spectral line strengths with temperature

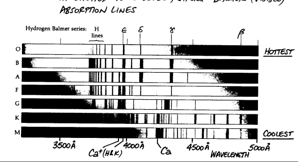
SAHA

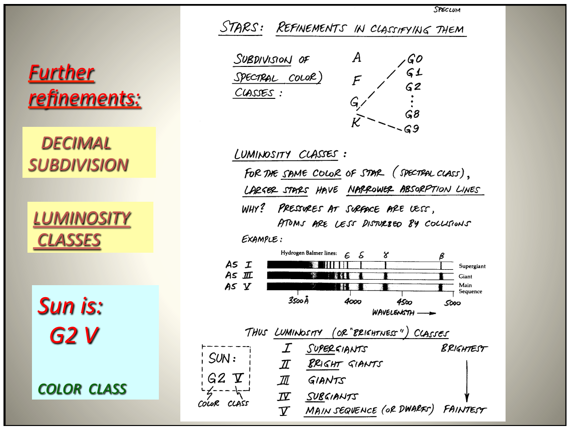
WHAT SAHA PREDICTS:

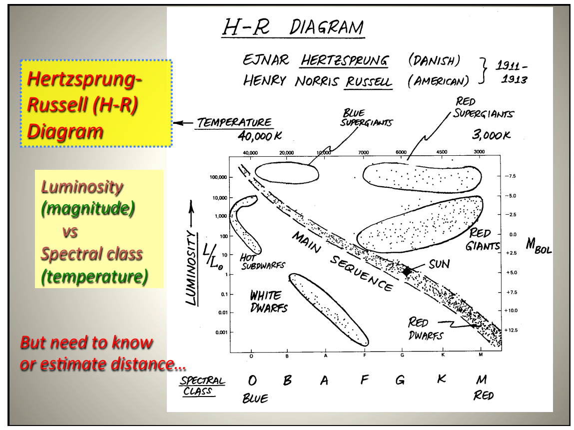


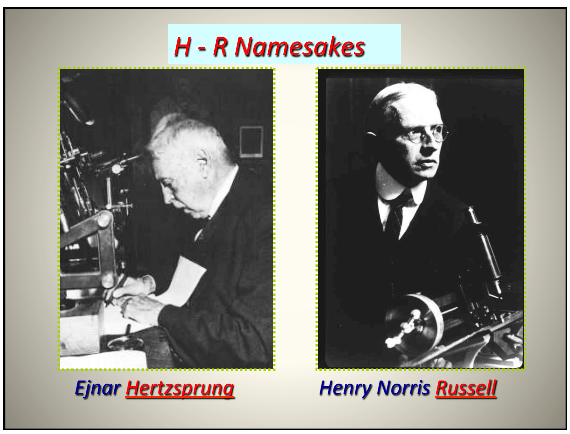
SAHA EQUATION FOR HYDROGEN:

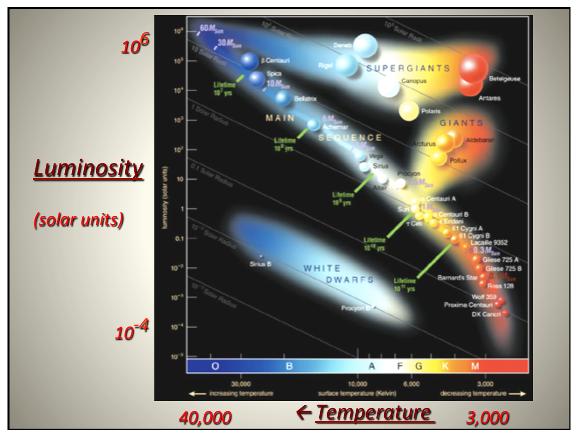
- FOR HOTTEST STARS (O, B), FULLY IONIZED CANNOT ABSORB PHOTONS
- FOR COOLEST STARS (M), MOSTLY AT GROUND LEVEL ($n = 1$), SO ABSORPTION OF UV PHOTONS (LYMAN)
- FOR A-TYPE STARS (~ 10,000 K), MANY ATOMS AT EXCITED $n = 2$ LEVEL, STRONG BALMER (VISIBLE) ABSORPTION LINES

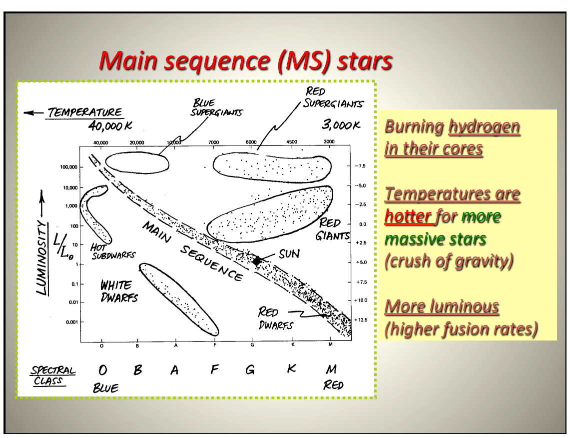


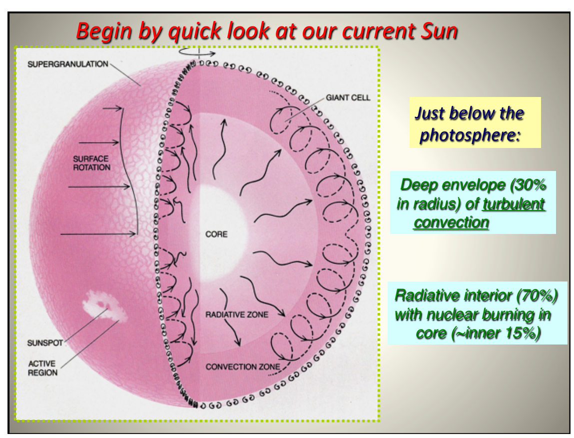

Further refinements:
DECIMAL SUBDIVISION
LUMINOSITY CLASSES
Sun is: G2 V
COLOR CLASS
STARS: REFINEMENTS IN CLASSIFYING THEM
SUBDIVISION OF SPECTRAL COLOR) CLASSES:
A F G K
G0 G1 G2 G8 G9
LUMINOSITY CLASSES:
FOR THE SAME COLOR OF STAR (SPECTRAL CLASS),
LARGER STARS HAVE NARROWER ABSORPTION LINES
WHY? PRESSURES AT SURFACE ARE LESS,
ATOMS ARE LESS DISTURBED BY COLLISIONS
EXAMPLE:
AS I
AS III
AS V
WAVELENGTH
THUS LUMINOSITY (OR "BRIGHTNESS") CLASSES
SUN: G2 V
COLOR CLASS
I SUPERGIANTS
II BRIGHT GIANTS
III GIANTS
IV SUBGIANTS
V MAIN SEQUENCE (OR DWARFS)
BRIGHTEST
FAINTEST


Hertzsprung-Russell (H-R) Diagram
Luminosity (magnitude) vs Spectral class (temperature)
But need to know or estimate distance...
H-R DIAGRAM
EJNAR HERTZSPRUNG (DANISH)
HENRY NORRIS RUSSELL (AMERICAN)
1911-1913
TEMPERATURE 40,000 K
BLUE SUPERGIANTS
RED SUPERGIANTS
3,000 K
LUMINOSITY
L/L⊙
HOT SUBDWARFS
MAIN SEQUENCE
RED GIANTS
SUN
WHITE DWARFS
RED DWARFS
M BOL
SPECTRAL CLASS O B A F G K M
BLUE RED

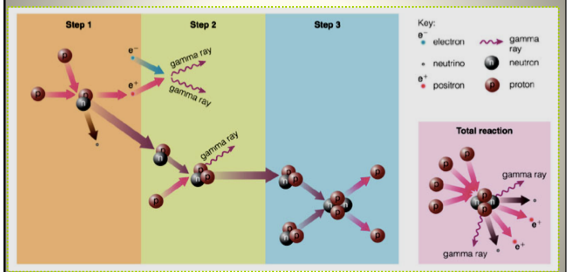

H - R Namesakes
Ejnar Hertzsprung
Henry Norris Russell


10^6
Luminosity
(solar units)
10^-4
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
O B A F G K M
40,000
← Temperature
3,000


Main sequence (MS) stars
Burning hydrogen in their cores
Temperatures are hotter for more massive stars (crush of gravity)
More luminous (higher fusion rates)
TEMPERATURE 40,000 K
BLUE SUPERGIANTS
RED SUPERGIANTS
3,000 K
LUMINOSITY
L/L⊙
HOT SUBDWARFS
MAIN SEQUENCE
RED GIANTS
SUN
WHITE DWARFS
RED DWARFS
SPECTRAL CLASS O B A F G K M
BLUE RED


Begin by quick look at our current Sun
Just below the photosphere:
Deep envelope (30% in radius) of turbulent convection
Radiative interior (70%) with nuclear burning in core (~inner 15%)
SUPERGRANULATION
GIANT CELL
SURFACE ROTATION
CORE
RADIATIVE ZONE
CONVECTION ZONE
SUNSPOT
ACTIVE REGION

Proton-Proton (P-P) Chain [Hans Bethe 1937]

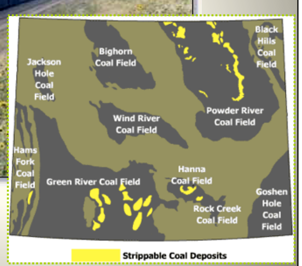


Sun burns 600 million tons of H every sec, making 596 million tons of He and '4 million tons goes into ENERGY'

Nuclear vs chemical burning

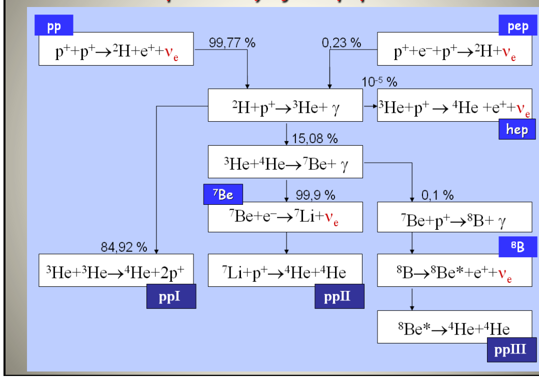
- Nuclear p-p burning :
  1 kg of H becomes 0.993 kg He
- 7 grams releases : 6.3×10^{14} joules
- Same energy released by chemically burning ~20,000 tons of coal !! (2 unit trains)
- Sun's luminosity : (vs 40 W lightbulb)
  $L \sim 3.8\ 10^{26}$ joules/sec (watts)

Wyoming "unit coal trains"



Unit train: 100-110 hopper cars, each 100 T of coal, mile long. 80/day, 26,000 trains in 2000

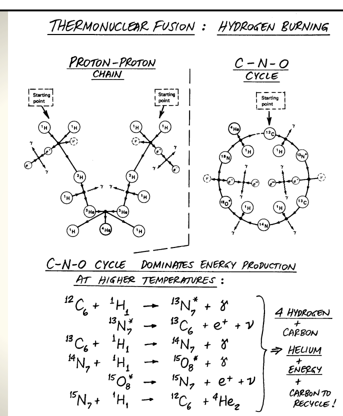
Three pathways for "p-p chain"



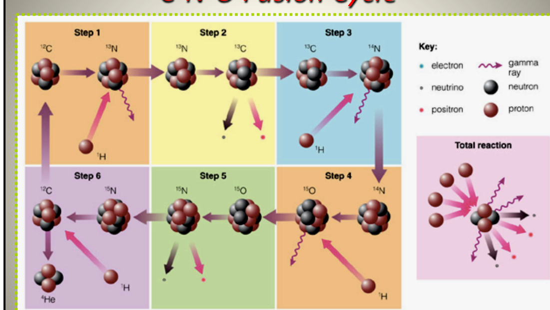
P-P Chain & C-N-O Cycle

Both fusion processes occur in parallel, but C-N-O makes far more energy at higher temperatures

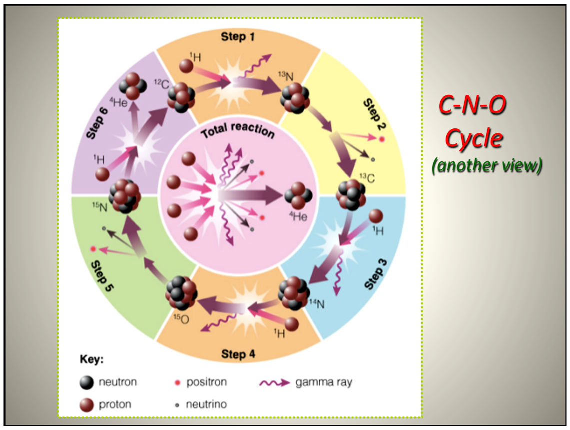
Stars hotter than F1, C-N-O wins

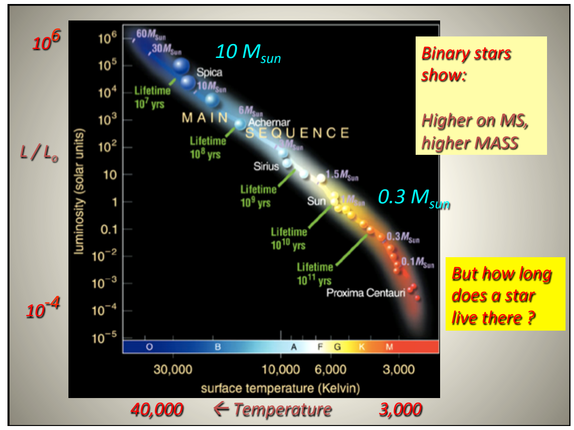


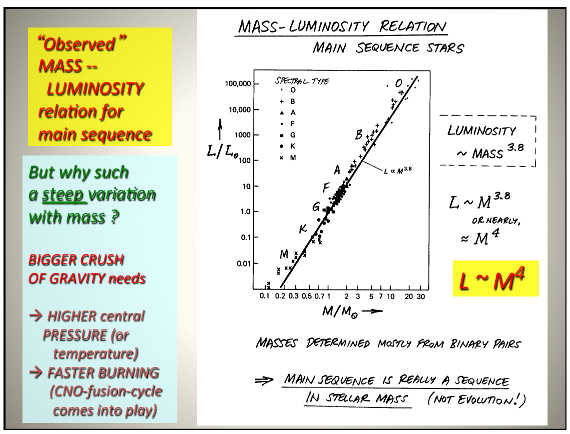
C-N-O Fusion Cycle

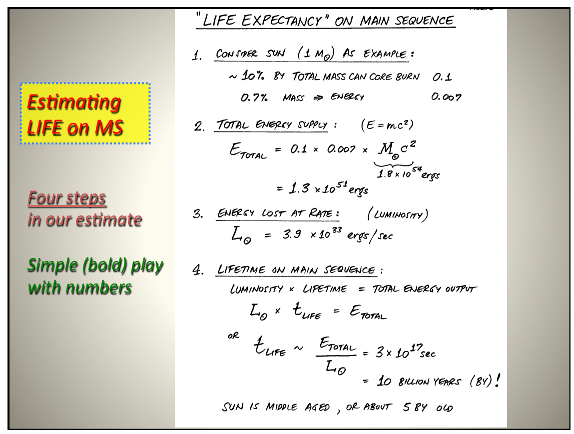


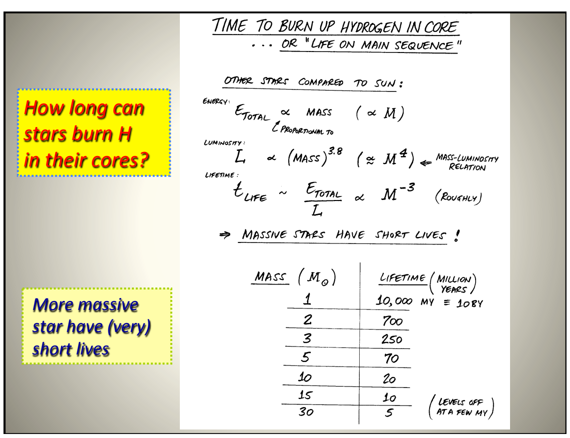
Can provide vast luminosity for massive stars on MS

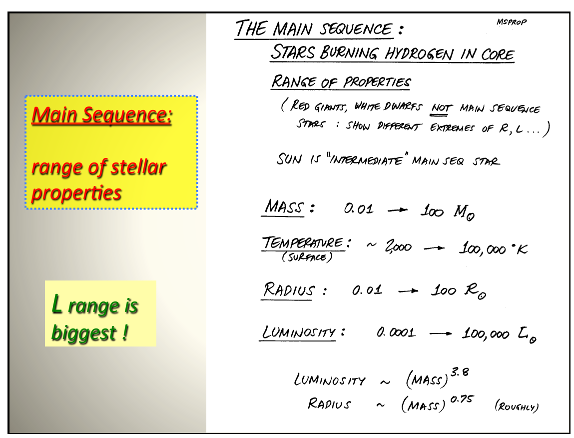

C-N-O Cycle
(another view)
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Total reaction
Key:
neutron
positron
gamma ray
proton
neutrino


10^6
L / L☉
10^{-4}
10 M sun
0.3 M sun
MAIN SEQUENCE
Spica
Achernar
Sirius
Sun
Proxima Centauri
luminosity (solar units)
surface temperature (Kelvin)
Binary stars show:
Higher on MS, higher MASS
But how long does a star live there ?
40,000
← Temperature
3,000

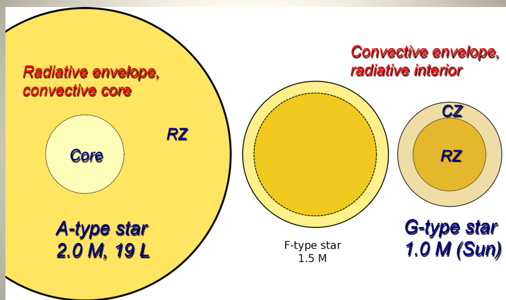

"Observed" MASS -- LUMINOSITY relation for main sequence
But why such a steep variation with mass ?
BIGGER CRUSH OF GRAVITY needs
→ HIGHER central PRESSURE (or temperature)
→ FASTER BURNING (CNO-fusion-cycle comes into play)
MASS-LUMINOSITY RELATION
MAIN SEQUENCE STARS
LUMINOSITY ~ MASS 3.8
L ~ M 3.8
OR NEARLY, ≈ M 4
L ~ M4
M/M☉
MASSES DETERMINED MOSTLY FROM BINARY PAIRS
⇒ MAIN SEQUENCE IS REALLY A SEQUENCE IN STELLAR MASS (NOT EVOLUTION!)


Estimating LIFE on MS
Four steps in our estimate
Simple (bold) play with numbers
"LIFE EXPECTANCY" ON MAIN SEQUENCE
1. CONSIDER SUN (1 M☉) AS EXAMPLE:
~ 10% BY TOTAL MASS CAN CORE BURN 0.1
0.7% MASS ⇒ ENERGY 0.007
2. TOTAL ENERGY SUPPLY: (E = mc²)
E TOTAL = 0.1 × 0.007 × M☉ c²
= 1.3 × 10^51 ergs
3. ENERGY LOST AT RATE: (LUMINOSITY)
L☉ = 3.9 × 10^33 ergs/sec
4. LIFETIME ON MAIN SEQUENCE:
LUMINOSITY × LIFETIME = TOTAL ENERGY OUTPUT
L☉ × t LIFE = E TOTAL
OR t LIFE ~ E TOTAL / L☉ = 3 × 10^17 sec
= 10 BILLION YEARS (BY)!
SUN IS MIDDLE AGED, OR ABOUT 5 BY OLD


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:
E TOTAL ∝ MASS (∝ M)
L ∝ (MASS)^3.8 (≈ M^4) ← MASS-LUMINOSITY RELATION
t LIFE ~ E TOTAL / L ∝ M^-3 (ROUGHLY)
⇒ MASSIVE STARS HAVE SHORT LIVES !
MASS (M☉) | 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)


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☉
TEMPERATURE (SURFACE): ~ 2,000 → 100,000 °K
RADIUS: 0.01 → 100 R☉
LUMINOSITY: 0.0001 → 100,000 L☉
LUMINOSITY ~ (MASS)^3.8
RADIUS ~ (MASS)^0.75 (ROUGHLY)

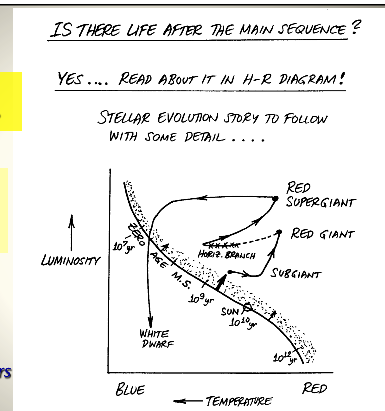
Differences between Sun and massive stars



Life AFTER main sequence

Stars evolve off MS, not along it !

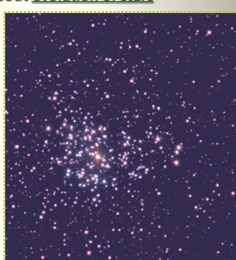
Now let us test such ideas with star clusters



STAR CLUSTERS – two varieties

both are groups of star that have evolved together --
great for testing ideas about evolution of stars

Globular cluster
old, millions of stars



Open cluster
young, thousands of stars

Globular clusters -- much older, bigger

- generally much older -- up to 13 BILLION years
- made up of millions of stars, very densely packed

Open star cluster: Pleiades

- "Open cluster" only about 100 MY old – involves several thousand stars
- Unlike Sun's age of 4.6 BY

SUBARU

Bright B-type stars, O stars now missing

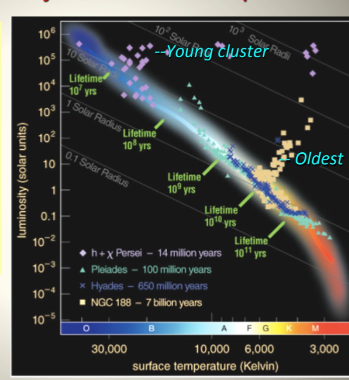
Clusters can test lifetimes on main sequence

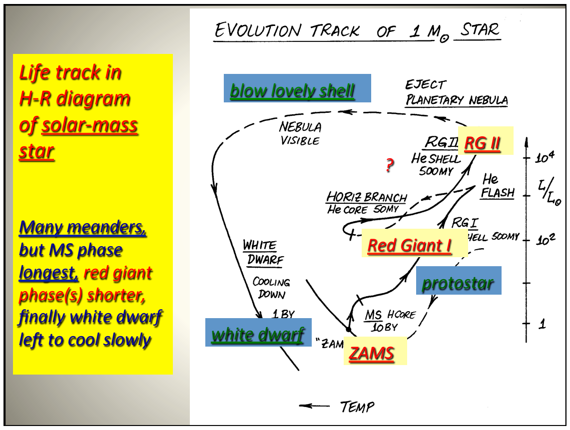
Great advantages:
All stars at about same distance (apparent brightness tracks luminosity)

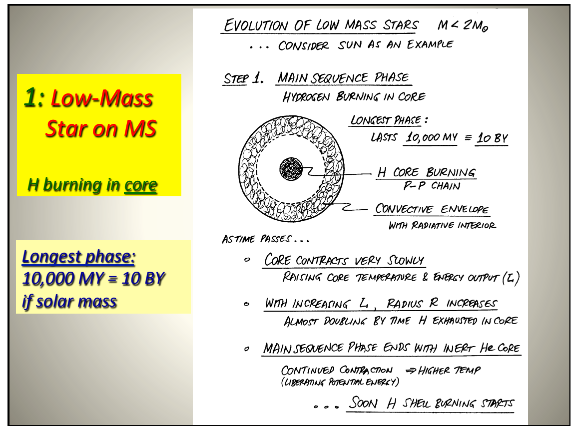
All formed at about same time

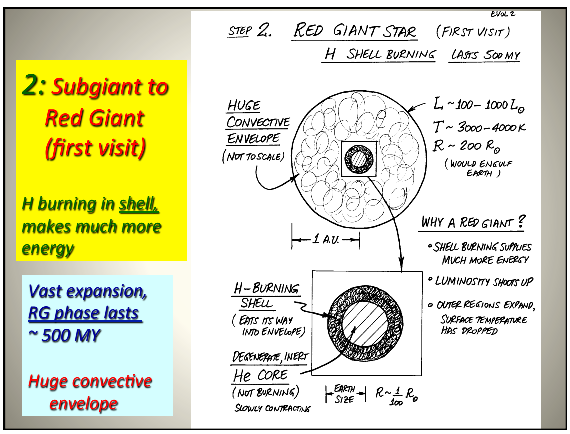
Range of different mass stars !

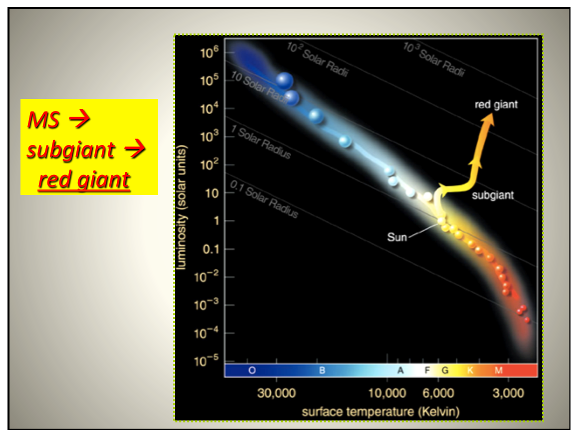
Stars "peel off" MS as core H exhausted
→ red giants

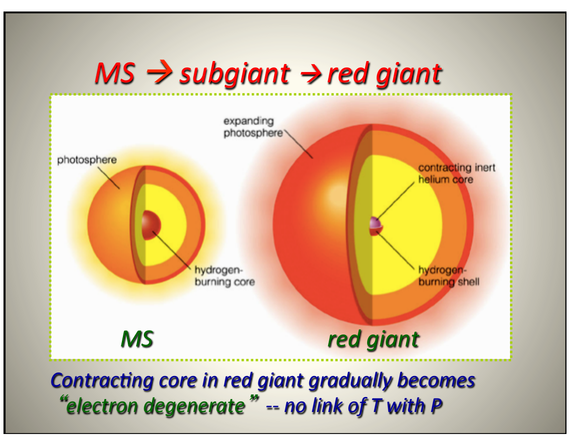


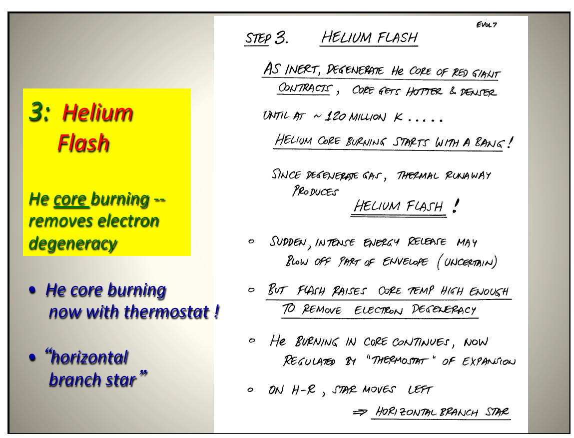

Life track in H-R diagram of solar-mass star
Many meanders, but MS phase longest, red giant phase(s) shorter, finally white dwarf left to cool slowly
EVOLUTION TRACK OF 1 M⊙ STAR
blow lovely shell
EJECT PLANETARY NEBULA
NEBULA VISIBLE
RG II
RG II
He SHELL 500 MY
?
He FLASH
HORIZ BRANCH He CORE 50 MY
RG I SHELL 500 MY
Red Giant I
WHITE DWARF
COOLING DOWN
protostar
1 BY
MS H CORE 10 BY
white dwarf
"ZAM
ZAMS
TEMP
10⁴
L/L⊙
10²
1

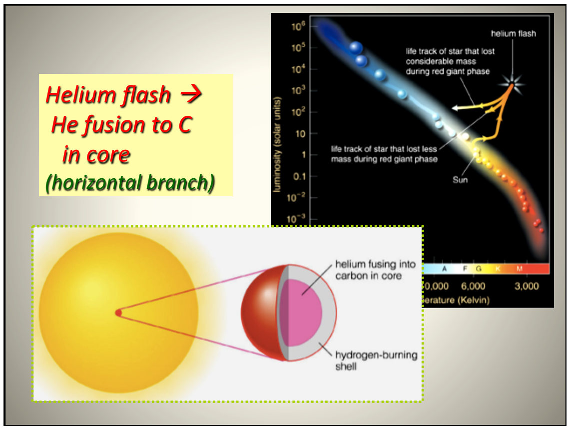

1: Low-Mass Star on MS
H burning in core
Longest phase: 10,000 MY = 10 BY if solar mass
EVOLUTION OF LOW MASS STARS M < 2M⊙
. . . CONSIDER SUN AS AN EXAMPLE
STEP 1. MAIN SEQUENCE PHASE
HYDROGEN BURNING IN CORE
LONGEST PHASE :
LASTS 10,000 MY ≡ 10 BY
H CORE BURNING
P-P CHAIN
CONVECTIVE ENVELOPE
WITH RADIATIVE INTERIOR
AS TIME PASSES . . .
∘ CORE CONTRACTS VERY SLOWLY
RAISING CORE TEMPERATURE & ENERGY OUTPUT (L)
∘ WITH INCREASING L, RADIUS R INCREASES
ALMOST DOUBLING BY TIME H EXHAUSTED IN CORE
∘ MAIN SEQUENCE PHASE ENDS WITH INERT He CORE
CONTINUED CONTRACTION ⇒ HIGHER TEMP
(LIBERATING POTENTIAL ENERGY)
. . . SOON H SHELL BURNING STARTS

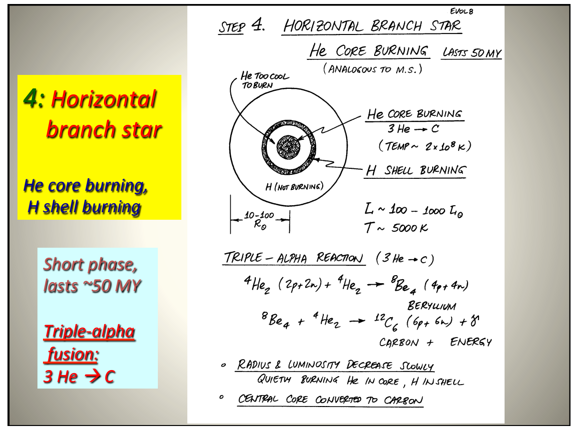

2: Subgiant to Red Giant (first visit)
H burning in shell, makes much more energy
Vast expansion, RG phase lasts ~ 500 MY
Huge convective envelope
EVOL 2
STEP 2. RED GIANT STAR (FIRST VISIT)
H SHELL BURNING LASTS 500 MY
HUGE CONVECTIVE ENVELOPE
(NOT TO SCALE)
L ~ 100 – 1000 L⊙
T ~ 3000 – 4000 K
R ~ 200 R⊙
(WOULD ENGULF EARTH)
1 A.U.
WHY A RED GIANT ?
∘ SHELL BURNING SUPPLIES MUCH MORE ENERGY
∘ LUMINOSITY SHOOTS UP
∘ OUTER REGIONS EXPAND, SURFACE TEMPERATURE HAS DROPPED
H-BURNING SHELL
(EATS ITS WAY INTO ENVELOPE)
DEGENERATE, INERT
He CORE
(NOT BURNING)
SLOWLY CONTRACTING
EARTH SIZE
R ~ 1/100 R⊙

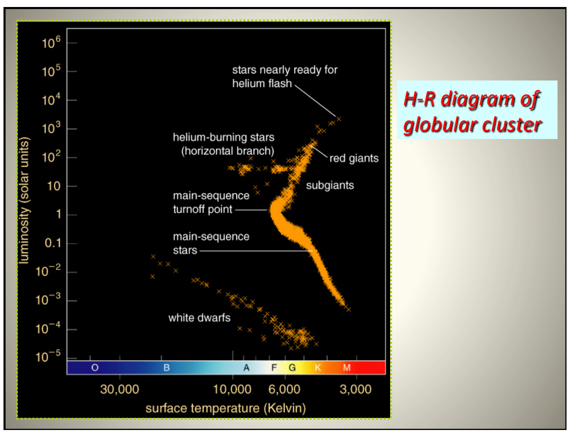

MS → subgiant → red giant
10² Solar Radii
10³ Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
red giant
subgiant
Sun
luminosity (solar units)
10⁶
10⁵
10⁴
10³
10²
10
1
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
O B A F G K M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

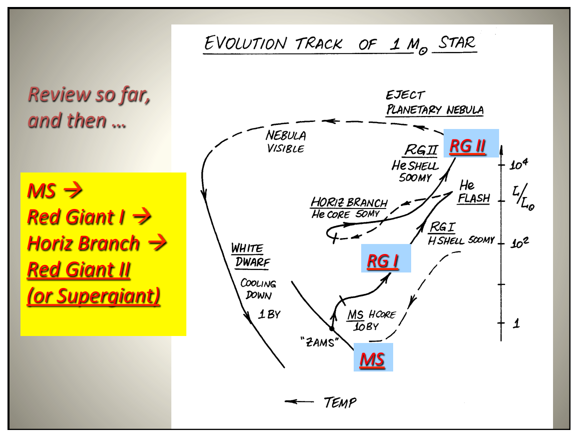

MS → subgiant → red giant
expanding photosphere
photosphere
contracting inert helium core
hydrogen-burning core
hydrogen-burning shell
MS
red giant
Contracting core in red giant gradually becomes "electron degenerate" -- no link of T with P

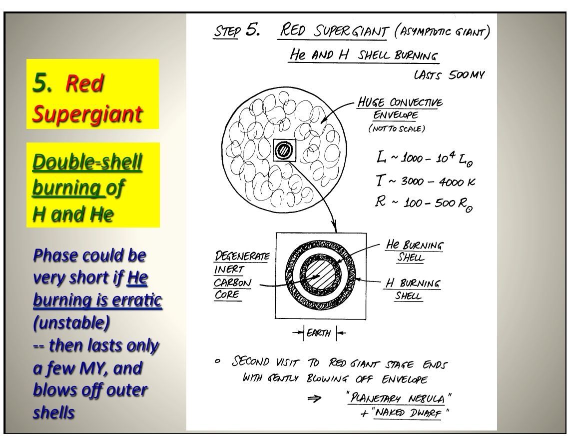

3: Helium Flash
He core burning -- removes electron degeneracy
• He core burning now with thermostat !
• "horizontal branch star"
EVOL 7
STEP 3. HELIUM FLASH
AS INERT, DEGENERATE He CORE OF RED GIANT CONTRACTS, CORE GETS HOTTER & DENSER
UNTIL AT ~ 120 MILLION K . . . . .
HELIUM CORE BURNING STARTS WITH A BANG !
SINCE DEGENERATE GAS, THERMAL RUNAWAY PRODUCES
HELIUM FLASH !
∘ SUDDEN, INTENSE ENERGY RELEASE MAY BLOW OFF PART OF ENVELOPE (UNCERTAIN)
∘ BUT FLASH RAISES CORE TEMP HIGH ENOUGH TO REMOVE ELECTRON DEGENERACY
∘ He BURNING IN CORE CONTINUES, NOW REGULATED BY "THERMOSTAT" OF EXPANSION
∘ ON H-R, STAR MOVES LEFT
⇒ HORIZONTAL BRANCH STAR

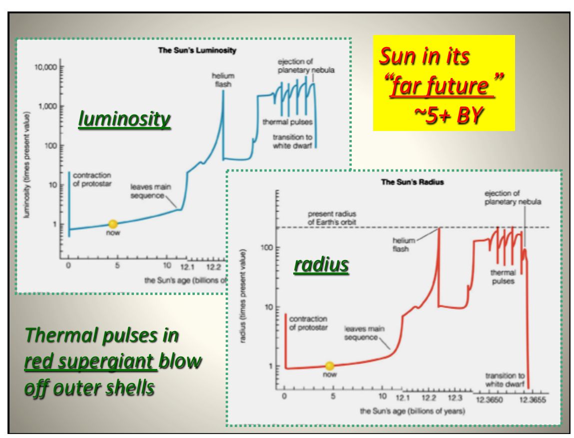

Helium flash → He fusion to C in core (horizontal branch)
helium flash
life track of star that lost considerable mass during red giant phase
life track of star that lost less mass during red giant phase
Sun
helium fusing into carbon in core
hydrogen-burning shell
luminosity (solar units)
temperature (Kelvin)

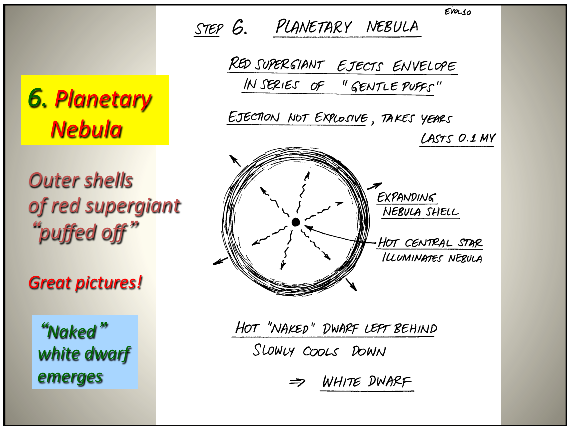

4: Horizontal branch star
He core burning, H shell burning
Short phase, lasts ~50 MY
Triple-alpha fusion: 3 He → C
STEP 4. HORIZONTAL BRANCH STAR
He CORE BURNING LASTS 50 MY
(ANALOGOUS TO M.S.)
He CORE BURNING 3 He → C
H SHELL BURNING
TRIPLE – ALPHA REACTION (3 He → C)
BERYLLIUM
CARBON + ENERGY
RADIUS & LUMINOSITY DECREASE SLOWLY
CENTRAL CORE CONVERTED TO CARBON


H-R diagram of globular cluster
stars nearly ready for helium flash
helium-burning stars (horizontal branch)
red giants
subgiants
main-sequence turnoff point
main-sequence stars
white dwarfs
luminosity (solar units)
surface temperature (Kelvin)
30,000
10,000
6,000
3,000


Review so far, and then ...
MS → Red Giant I → Horiz Branch → Red Giant II (or Supergiant)
EVOLUTION TRACK OF 1 M⊙ STAR
EJECT PLANETARY NEBULA
NEBULA VISIBLE
RG II
RG I
MS
He FLASH
HORIZ BRANCH
WHITE DWARF
COOLING DOWN
"ZAMS"
TEMP


5. Red Supergiant
Double-shell burning of H and He
Phase could be very short if He burning is erratic (unstable) -- then lasts only a few MY, and blows off outer shells
STEP 5. RED SUPERGIANT (ASYMPTOTIC GIANT)
He AND H SHELL BURNING
LASTS 500 MY
HUGE CONVECTIVE ENVELOPE
DEGENERATE INERT CARBON CORE
He BURNING SHELL
H BURNING SHELL
EARTH
SECOND VISIT TO RED GIANT STAGE ENDS WITH GENTLY BLOWING OFF ENVELOPE
"PLANETARY NEBULA" + "NAKED DWARF"


Sun in its "far future" ~5+ BY
The Sun's Luminosity
luminosity
The Sun's Radius
radius
helium flash
ejection of planetary nebula
thermal pulses
leaves main sequence
now
Thermal pulses in red supergiant blow off outer shells


6. Planetary Nebula
Outer shells of red supergiant "puffed off"
Great pictures!
"Naked" white dwarf emerges
EVOL10
STEP 6. PLANETARY NEBULA
RED SUPERGIANT EJECTS ENVELOPE
IN SERIES OF "GENTLE PUFFS"
EJECTION NOT EXPLOSIVE, TAKES YEARS
LASTS 0.1 MY
EXPANDING NEBULA SHELL
HOT CENTRAL STAR ILLUMINATES NEBULA
HOT "NAKED" DWARF LEFT BEHIND
SLOWLY COOLS DOWN
⇒ WHITE DWARF