


**ASTR 1040: Stars & Galaxies**



**Spirograph Planetary Nebula**

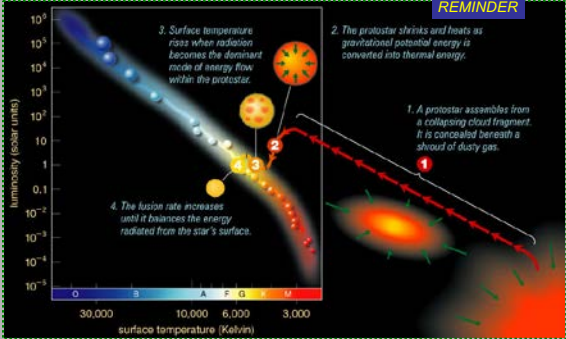
Prof. Juri Toomre TAs: Daniel Segal, Max Weiner  
Lecture 14 Thur 27 Feb 2020  
[zeus.colorado.edu/astr1040-toomre](http://zeus.colorado.edu/astr1040-toomre)

**Topics for Today**

- Revisit **birth of stars** in dark molecular clouds
- Many more **M and G** stars are made than massive **O** stars
- Next turn to **"life after the MS"**
- What happens to **solar-mass star** after it exhaust its central H fuel and **leaves the MS**
- Shell burning of H builds **red giants**
- And then **He flash, supergiants, big winds ...**
- Finally **white dwarf** emerges in the embers

**Things to do**

- Read **Chap17 'Star Stuff', with 17.2 'Life as Low-Mass Star'** covering today's lecture
- Then read **17.3 'Life as High-Mass Star'** for next class ... look over **18.3 Black Holes**
- **Homework #6** due today, new **HW #7** passed out
- **Overview on Stellar Evolution** still available
- **Next week: Observatory Night #5** on Tues, **Fiske Planetarium** on Thur



**REMINDER**

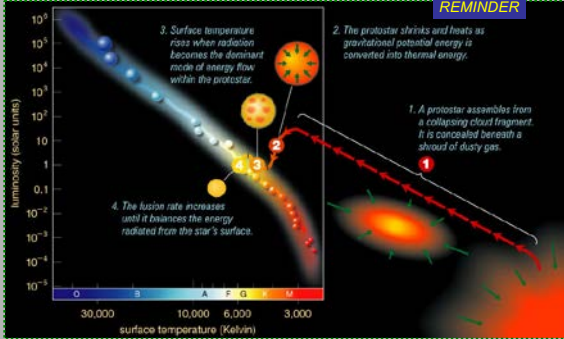
1. A protostar assembles from a collapsing cloud fragment. It is concealed beneath a shroud of dusty gas.

2. The protostar shrinks and heats as gravitational potential energy is converted into thermal energy.

3. Surface temperature rises when radiation becomes the dominant mode of energy flow within the protostar.

4. The fusion rate increases until it balances the energy radiated from the star's surface.

**1 → 2: Collapsing protostar is first shrouded by cocoon of dusty gas, but then winds and jet blast through**



**REMINDER**

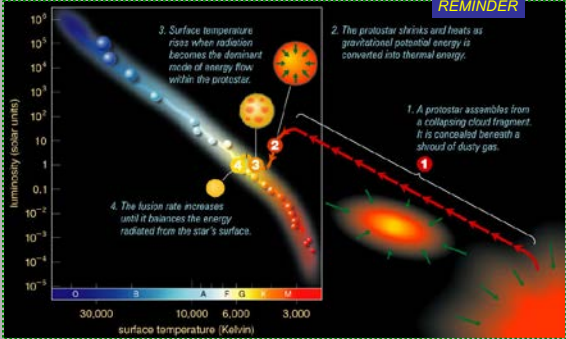
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**2: Collapse continues, temperature stabilizes as deep convection circulates energy outwards**



**REMINDER**

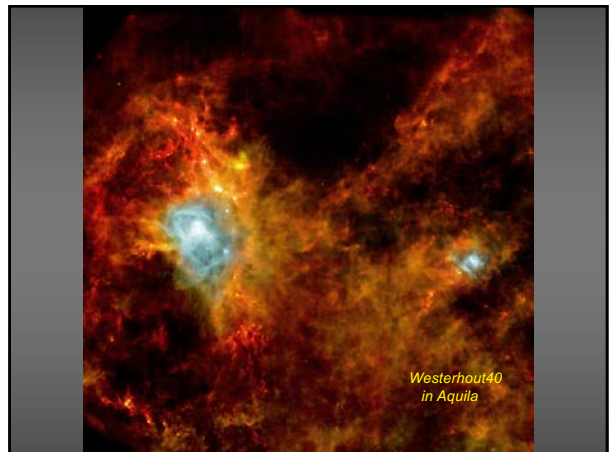
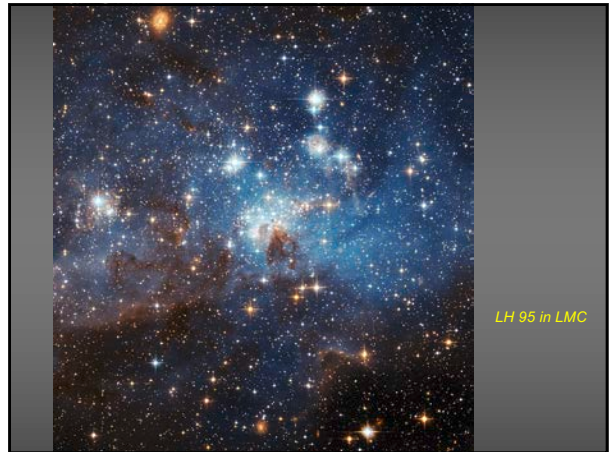
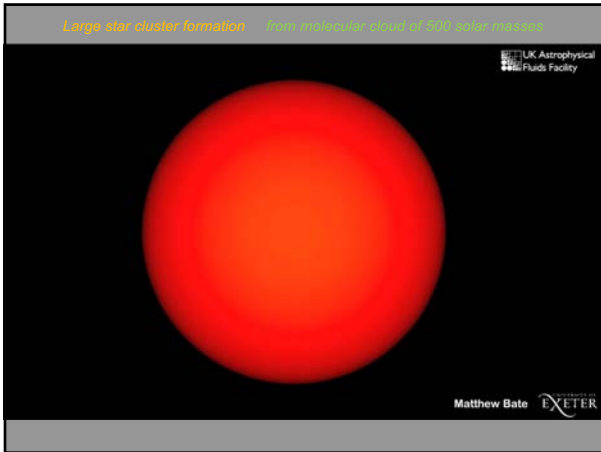
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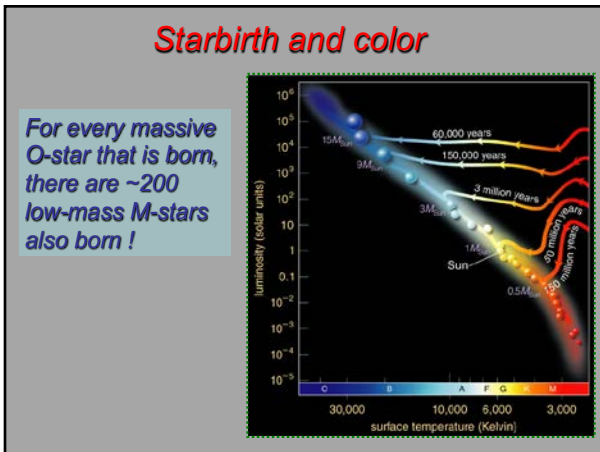
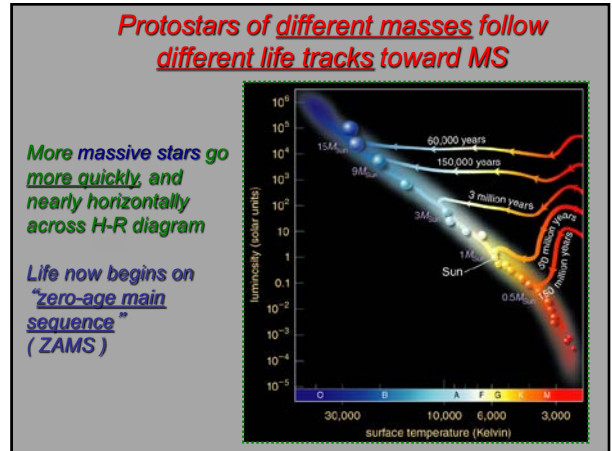
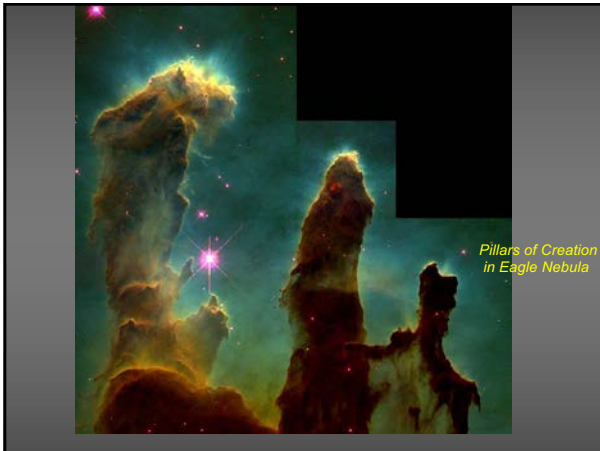
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4. The fusion rate increases until it balances the energy radiated from the star's surface.

**3 → 4: As core temperatures reach millions of degrees, fusion begins and stabilizes – star joins main sequence**





## Reading Clicker -- life tracks

- What can we find out about a star from its life track on the H-R diagram?

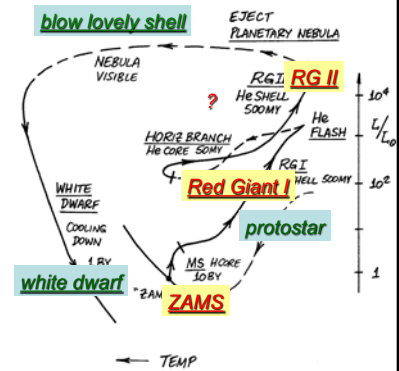
B.

- A. When the star was born
- B. The surface temperature and luminosity of the star at each stage of its life
- C. The star's current stage of life
- D. Where the star is located

### 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<sub>⊙</sub> STAR



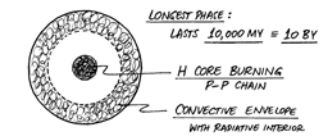
### 1: Low-Mass Star on MS

H burning in core

Longest phase: 10,000 MY = 10 BY if solar mass

#### EVOLUTION OF LOW MASS STARS $M < 2M_{\odot}$ ... CONSIDER SUN AS AN EXAMPLE

##### STEP 1. MAIN SEQUENCE PHASE HYDROGEN BURNING IN CORE



- 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

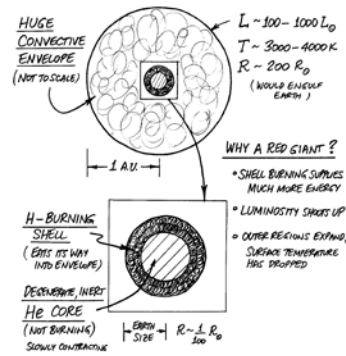
### 2: Subgiant to Red Giant (first visit)

H burning in shell, makes much more energy

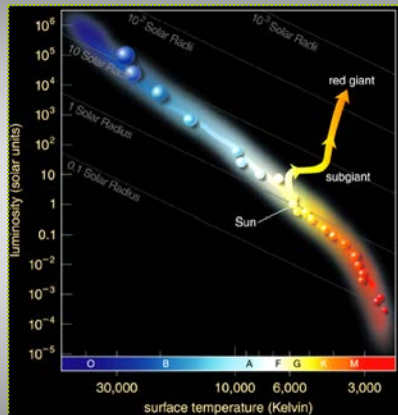
Vast expansion, RG phase lasts ~ 500 MY

Huge convective envelope

#### STEP 2. RED GIANT STAR (FIRST VISIT) H SHELL BURNING LASTS 500 MY



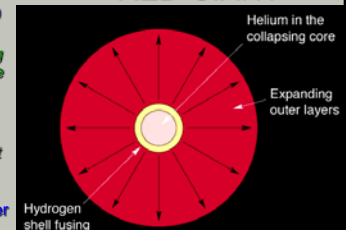
MS → subgiant → red giant



### Without Fusion, the Core Starts to Contract

- Helium has built up in the core
  - Temperatures not hot enough to fuse helium (100 million K needed).
- With fusion no longer occurring in the core, gravity causes core contraction (collapse)
  - Core temperature starts to heat up
- Layer just above the core must contract also (and heat up)
  - Now hot enough for hydrogen fusion in that layer
    - Hydrogen "shell fusing" pushes outer layers of the star out

### RED GIANT



## Red Giants

- **Thermostat is broken**  
– No more fusion in the core!
- As core contracts, **hydrogen SHELL fuses faster and faster** – more energy created
- Star becomes larger, cooler, but **brighter!**
- All the while, the core is continuing to shrink and is heating up

## MS → subgiant → red giant

**MS**                      **red giant**

Contracting core in red giant gradually becomes "electron degenerate" -- what does that mean?

### DEGENERACY AND STELLAR EVOLUTION EM 6

**Oops!**

**Thermostat is missing in degenerate gas**

**HEAT NORMAL GAS (TEMP ↑)**

- ⇒ PRESSURE ↑ ⇒ GAS EXPANDS
- ⇒ COOLS DOWN "THERMOSTAT WORKS"

**HEAT DEGENERATE GAS (TEMP ↑)**

- ⇒ PRESSURE UNCHANGED
- ⇒ NO THERMOSTAT

IF NUCLEAR FUSION STARTS IN CORE ...

**NORMAL GAS:** STABLE, LIKE M.S. STAR

**DEGENERATE GAS:** "THERMAL RUNAWAY"

... BURNING ⇒ HIGHER TEMP ⇒ FASTER BURNING ⇒ EVEN HIGHER TEMP ⇒ **EXPLOSIVE!**

Could get exciting!

### STEP 3. HELIUM FLASH EM 7

#### 3: Helium Flash

He core burning -- removes electron degeneracy

- He core burning now with thermostat!
- "horizontal branch star"

**AS INERT, DEGENERATE HE CORE OF RED GIANT CONTRACTS, CORE GETS HOTTER & DENSER UNTIL AT ~100 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 (UNCOMMON)
- 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 fusing into carbon in core

hydrogen-burning shell

### EVOLUTION TRACK OF 1 M<sub>⊙</sub> STAR

Overview of what will happen:

**MS → Red Giant I → Horiz Branch → Red Giant II (or Supergiant)**

NEBULA VISIBLE

EJECT PLANETARY NEBULA

RG II

RG I

MS HORE 10 BY

MS

WHITE DWARF

COOLING DOWN

1 BY

"ZAMS"

TEMP

**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 TOO COOL TO BURN

He CORE BURNING  
 $3 \text{ He} \rightarrow \text{C}$   
(TEMP ~  $2 \times 10^8 \text{ K}$ )

H SHELL BURNING

H (NOT BURNING)

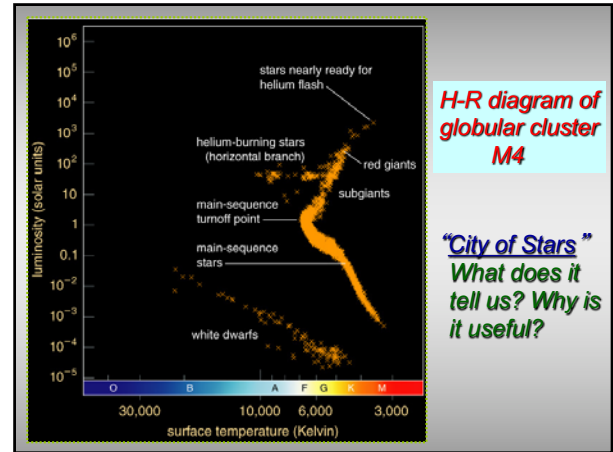
$L \sim 100 - 1000 L_{\odot}$   
 $T \sim 5000 \text{ K}$

**TRIPLE-ALPHA REACTION ( $3 \text{ He} \rightarrow \text{C}$ )**

$4 \text{ He}_2 (2p, 2n) + 4 \text{ He}_2 \rightarrow {}^8 \text{ Be}_4 (4p, 4n)$   
BERYLLIUM

${}^8 \text{ Be}_4 + 4 \text{ He}_2 \rightarrow {}^{12} \text{ C}_6 (6p, 6n) + 8 \text{ H}^+$   
CARBON + ENERGY

- RADIUS & LUMINOSITY DECREASE SLOWLY
- QUITTY BURNING HE IN CORE, H IN SHELL
- CENTRAL CORE CONVERTED TO CARBON



**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 (NOT TO SCALE)

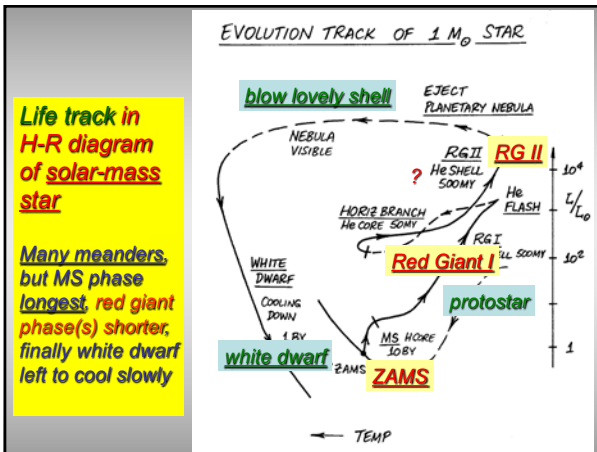
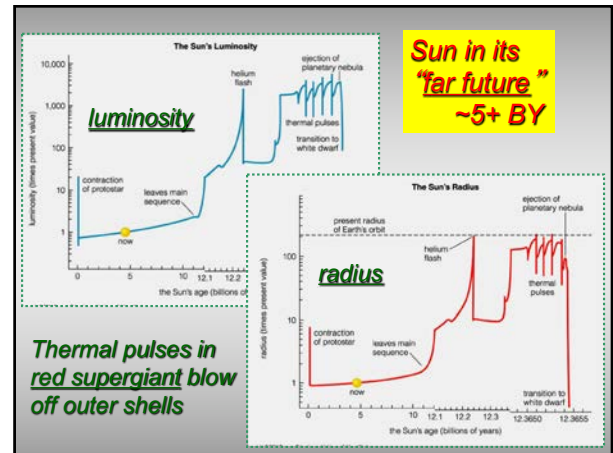
$L \sim 1000 - 10^4 L_{\odot}$   
 $T \sim 3000 - 4000 \text{ K}$   
 $R \sim 100 - 500 R_{\odot}$

DEGENERATE INERT CARBON CORE

He BURNING SHELL

H BURNING SHELL

- SECOND VISIT TO RED GIANT STAGE ENDS WITH RAPID BLOWING OFF ENVELOPE
- "PLANETARY NEBULA" + "NAKED DWARF"



**6. Planetary Nebula**

Outer shells of red supergiant "puffed off"

Great pictures!

"Naked" white dwarf emerges

**STEP 6. PLANETARY NEBULA**

RED SUPERGIANT EJECTS ENVELOPE IN SERIES OF "GENTLE PUFFS"

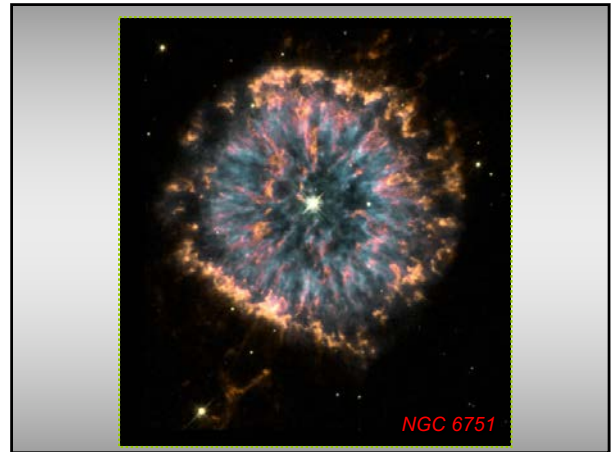
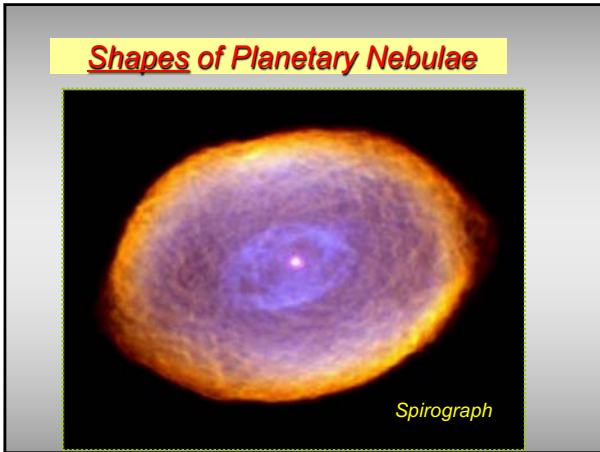
EJECTION NOT EXPLOSIVE, TAKES YEARS LASTS 0.1 MY

EXPANDING NEBULA SHELL

HOT CENTRAL STAR ILLUMINATES NEBULA

HOT "NAKED" DWARF LEFT BEHIND SLOWLY COOLS DOWN

⇒ WHITE DWARF



**7. White Dwarf**

Inert C core, He & H shells

electron degeneracy pressure holds it up

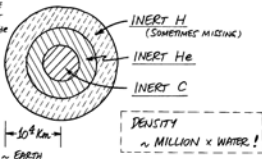
Very dense, size of Earth

max mass of 1.4 M<sub>SUN</sub>

**STEP 7. WHITE DWARF**

FOR 1 M<sub>☉</sub> STAR, CARBON CORE NEVER HOT ENOUGH TO BURN  
 ⇒ HOT DWARF SITS & COOLS VISIBLE ~ 1 BY

LESS INERTIVE STAR MAY NOT BURN BEYOND HE



INERT H (SOMETIMES MIXING)  
 INERT He  
 INERT C

DENSITY ~ MILLION X WATER!

~ 10<sup>4</sup> km  
 ~ EARTH RADIUS

HYDROSTATIC EQUILIBRIUM:  
 ELECTRON DEGENERACY PRESSURE VS. GRAVITY

ENERGY SOURCE:  
 NONE REQUIRED

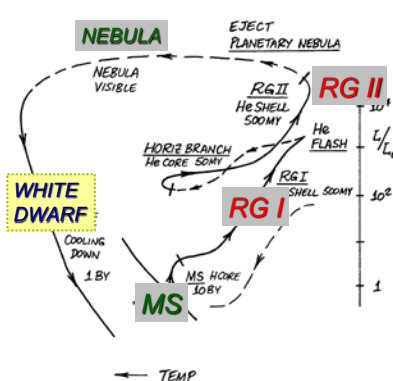
MAY NOT EXCEED 1.4 M<sub>☉</sub> "CHANDRASEKHAR LIMIT"  
 ... OR ELSE COLLAPSES FURTHER

**Final stage:**

Cooling white dwarf --- snooze ...

But if WD has binary companion, much fun can begin!

**EVOLUTION TRACK OF 1 M<sub>☉</sub> STAR**



NEBULA  
 NEBULA VISIBLE  
 EJECT PLANETARY NEBULA

RG II He SHELL SOONY  
 He FLASH  
 RG I SHELL SOONY

MS MS HORIZ BRANCH  
 MS HORIZ BRANCH He CORE SOONY

COOLING DOWN 1 BY  
 WHITE DWARF

TEMP