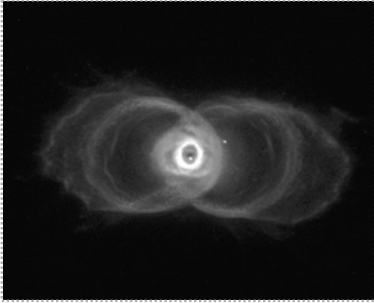


ASTR 1120: Stars & Galaxies



Etched
Hourglass
Nebula

Prof. Juri Toomre TA: Ben Brown
Lecture 19 Wed 23 Feb 05
zeus.colorado.edu/astr1120-toomre

Today

- Continue with life of a low-mass star (like the Sun) after exhausting H in core -- post MS
- Red giant (RG I) phase, with H shell burning
- Helium flash goes off in shrinking degenerate core: horizontal branch star with He core burning
- Double shell burning (H and He) yields red supergiant (RG II), blows off planetary nebula
- Discuss white dwarfs formed at end of evolution of low-mass stars
- Planetarium #2 this FRIDAY 'Birth of Stars' -- go there directly -- read 17.2 Star Birth carefully -- bring clickers
- HW Set # 4 returned + answers + Evolution OV

Reading Clicker -- life tracks

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

B.

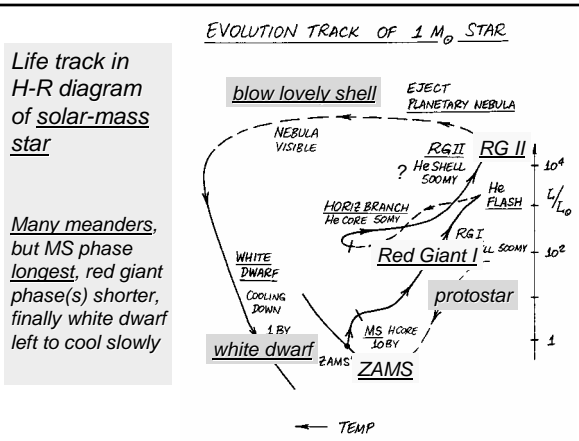
- A. When the star was born
- B. The surface temperature and luminosity of the star at each stage of its life
- C. The star's current stage of life
- D. Where the star is located

Clicker – Stellar Evolution

- Which is correct order for some stages of life in a low-mass star?

A.

- A. protostar, main-sequence star, red giant, planetary nebula, white dwarf
- B. protostar, main-sequence star, red giant, supernova, neutron star
- C. main-sequence star, white dwarf, red giant, planetary nebula, protostar
- D. protostar, main-sequence star, planetary nebula, red giant



Clusters: test lifetimes on main sequence

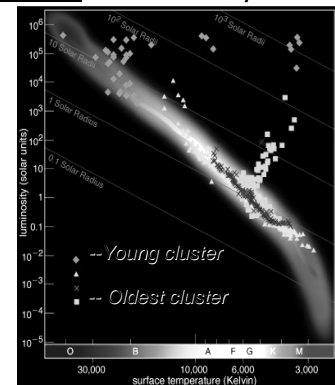
REMINDER:

All stars at about same distance

All formed at about same time

Range of different mass stars!

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



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

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

EVOLUTION TRACK OF $1 M_{\odot}$ STAR

Overview of what will happen:

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

NEBULA VISIBLE

EJECT PLANETARY NEBULA

RG II
HE SHELL
500 MY

HE FLASH

HORIZ BRANCH
HE CORE 50 MY

RG I
H SHELL 500 MY

MS
MS H CORE
10 BY

WHITE DWARF

COOLING DOWN

1 BY

* ZAMS

TEMP

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

HUGE CONVECTIVE ENVELOPE (NOT TO SCALE)

L ~ 100 - 1000 L_{\odot}

T ~ 3000 - 4000 K

R ~ 200 R_{\odot}
(WOULD ENVELOP EARTH)

1 AU

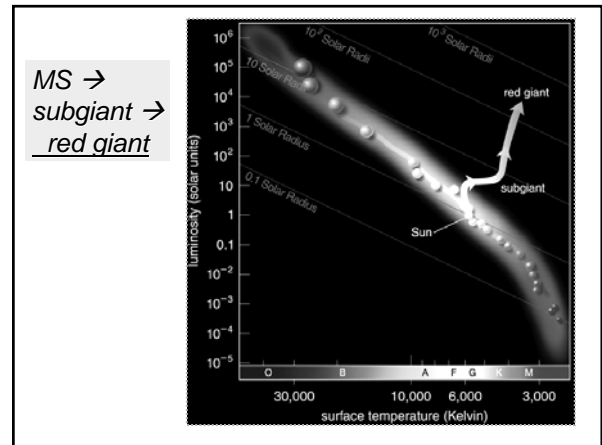
WHY A RED GIANT?

- SHELL BURNING SURFACES MUCH MORE ENERGY
- LUMINOSITY SHOTS UP
- OUTER REGIONS EXPAND, SURFACE TEMPERATURE HAS DROPPED

H-BURNING SHELL (EATS ITS WAY INTO ENVELOPE)

DEGENERATE INERT HE CORE (NOT BURNING) SLOWLY CONTRACTING

1 R_{\oplus} | $R \sim \frac{1}{200} R_{\odot}$



MS → subgiant → red giant

expanding photosphere

contracting inert helium core

photosphere

hydrogen-burning core

hydrogen-burning shell

MS

red giant

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

DEGENERACY PRESSURE

... CONTROLS STRUCTURE OF GIANTS AND WHITE DWARFS!

Complex aside:

"DEGENERACY" pressure

"PAULI EXCLUSION PRINCIPLE"

⇒ MATTER RESISTS TOO MUCH CONFINEMENT

EXAMPLES ...

1. INCOMPRESSIBILITY OF LIQUIDS, SOLIDS:
DEGENERATE ATOMS
2. CORE OF LOW-MASS ($\leq 2.25 M_{\odot}$) RED GIANT, ALSO WHITE DWARF:
DEGENERATE ELECTRONS
3. NEUTRON STAR OR PULSAR:
DEGENERATE NEUTRONS

EVOL 4

EM6

DEGENERACY AND STELLAR EVOLUTION

Oops!

Thermostat is missing in degenerate gas

Could get exciting!

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!

EM7

STEP 3. HELIUM FLASH

3: Helium Flash

He core burning -- removes electron degeneracy

→ He core burning 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 (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

EM8

STEP 4. HORIZONTAL BRANCH STAR

4: Horizontal branch star

He core burning, H shell burning

Short phase, lasts ~50 MY

Triple-alpha fusion:
 $3 \text{ He} \rightarrow \text{C}$

He CORE BURNING LASTS 50 MY (ANALOGOUS TO M.S.)

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

H SHELL BURNING

H (HE COOL TO BURN)

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

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

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

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

Helium flash → He fusion to C in core (horizontal branch)

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

Temperature (Kelvin): 10,000, 6,000, 3,000

Helium fusing into carbon in core

hydrogen-burning shell

EM9

STEP 5. RED SUPERGIANT (ASYMPTOTIC GIANT)

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

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

→ EARTH →

- SECOND VISIT TO RED GIANT STAGE ENDS WITH RAPIDLY BURNING OFF ENVELOPE ⇒ "PLANETARY NEBULA" + "NAKED DWARF"

EM10

STEP 6. PLANETARY NEBULA

6. Planetary Nebula

Outer shells of red supergiant "puffed off"

Great pictures!

"Naked" white dwarf emerges

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