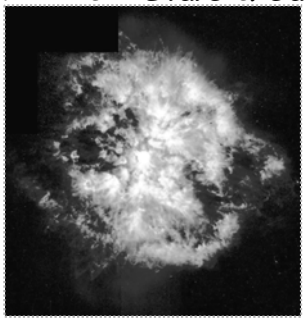
ASTR 1120: Stars & Galaxies



MID-POINT LECTURE

Stellar winds from hot star

Prof. Juri Toomre TA: Ben Brown

Lecture 22 Wed 2 Mar 05

zeus.colorado.edu/astr1120-toomre

Today's "Bizarre" Events

- Evolution of *massive stars* through *giant and supergiant phases*: fusion occurs in `successive layers of onion'
- End life as *supernova explosion*, leaving behind either *neutron star* or *black hole*
- Supernova can create *neutron stars*
- Consider *"pulsars"* – fast spinning neutron stars with fierce magnetic fields

- Read *18.4 Black Holes* with some care
- Come see us if need help with *HW # 6*
- *Homework # 5* returned graded + answer sheet

Binary Systems: The Algol Paradox

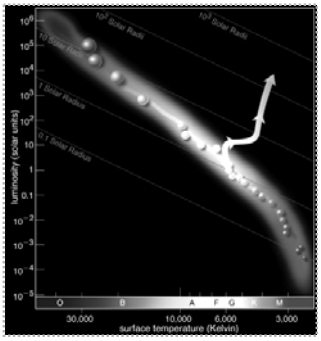
- *Algol is a binary system consisting of a 3.7 solar mass main sequence star and a 0.8 solar mass red giant. Why is this strange?*

A.

- *A.* A 3.7 star should have become a red giant before a 0.8 solar mass star
- *B.* Binary stars usually have the same mass
- *C.* 0.8 solar mass stars usually never become red giants

Clicker Puzzle: Algol Binary System

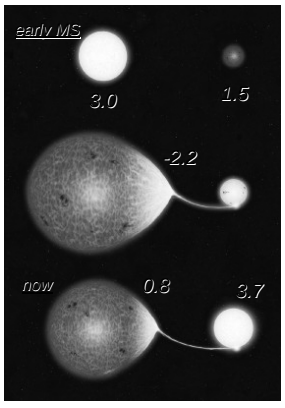
- *A. Binary stars can have different masses but usually ARE formed at the same time.*
- *More massive star should have had a shorter main sequence lifetime*



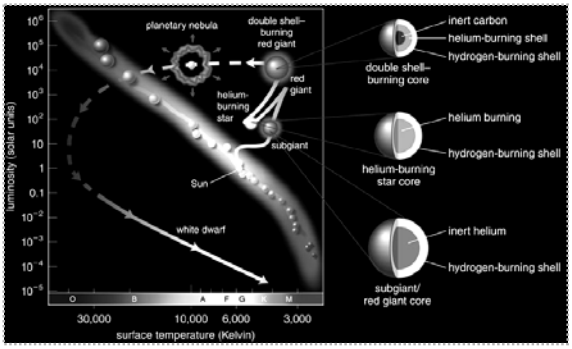
What happened?

Binary Mass Exchange

- *The 0.8 solar mass star once was more massive (3.0), with a 1.5 mass companion*
- *As it became a red giant, it swelled and poured material onto its companion (lost 2.2)*
- *The red giant (0.8) is now less massive than its companion (3.7)*
- *Future: when the other star becomes red giant, it may pour gas back…?*



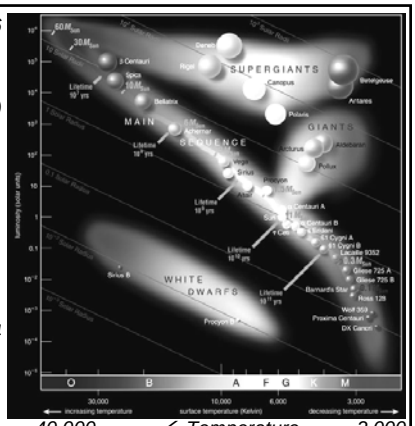
Overview reminder: Life track of low-mass star



10^6

Luminosity (solar units)

Now consider evolution of massive stars after MS



10^{-4}

40,000 ← Temperature 2,000

Evolution of massive stars

EVOLUTION OF MASSIVE STARS $M > 2M_\odot$

SO WHAT IS DIFFERENT ?

"CLOCK" CAN RUN MUCH FASTER

CAN BURN MORE ELEMENTS (C, O, Ne, Si ...)

FINAL FATE CONTROLLED BY HOW MUCH MASS LOST BY STRONG WINDS

Clock runs faster, can burn heavier elements

First 4 steps pretty familiar, but no helium flash

1. MAIN SEQUENCE — H CORE BURNING, C-N-O CYCLE; STELLAR WINDS $\dot{M}$ ↓ ($4H \rightarrow He$)
2. RED GIANT I — H SHELL BURNING; INERT He CORE SLOWLY CONTRACTING
3. HORIZONTAL BRANCH — LESS DENSE, NO DEGENERACY IN He CORE (IF $M > 2.25 M_\odot$) ⇒ NO HELIUM FLASH; SMOOTH TRANSITION TO He CORE BURNING: TRIPLE-ALPHA ($3He \rightarrow C$)
4. RED GIANT II (SUPERGIANT) — He SHELL BURNING STARTED, H CONTINUES TO BURN IN SHELL; INERT C CORE SLOWLY CONTRACTING, MAY BECOME DEGENERATE MATTER!

Successive core & shell fusion burning of C, O, Ne, Si ..

all with "alpha capture" (or He)

stars make many shallow H-R loops

MASSIVE STARS ...

5. CARBON FLASH — INITIATE CARBON BURNING IN DEGENERATE CORE WITH EXPLOSIVE FLASH

C → (α capture) O → (α) Ne → (α) Si → (α) STOPS WITH Fe — MANY ELEMENTS

"ALPHA CAPTURE"

$C + He \rightarrow O + \text{ENERGY}$

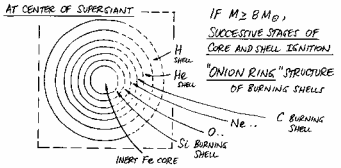
A. EXPLODE AS SUPERNOVA TYPE I OR

B. REMOVE DEGENERACY, BURN QUIETLY IN STAGES TO PRODUCE IRON IN CORE

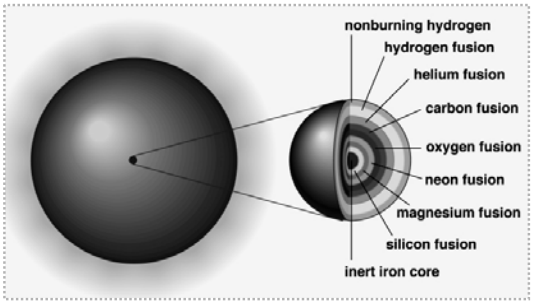
6. HORIZ BRANCHES, RED SUPERGIANTS (MANY LOOPS IN H-R DIAGRAM!)

AT CENTER OF SUPERGIANT — IF $M \geq 8 M_\odot$, SUCCESSIVE STAGES OF CORE AND SHELL IGNITION

"ONION RING" STRUCTURE OF BURNING SHELLS

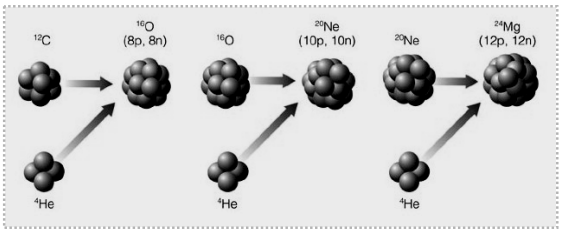


Many "layers of onion" in massive star



Core structure from successive burning stages: lesser elements on outside, heavier on inside

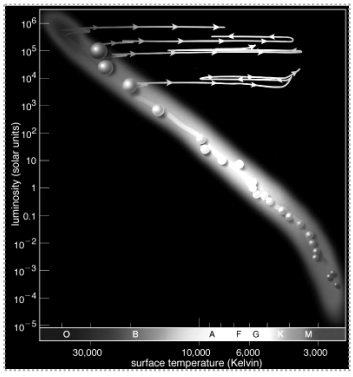
Fusion by "alpha-capture" (He nucleus) burns C, O, Ne, Mg, Si ..



- *Helium nucleus (2 protons) is absorbed, energy is released*
- *Elements are created going up periodic table in steps of 2*

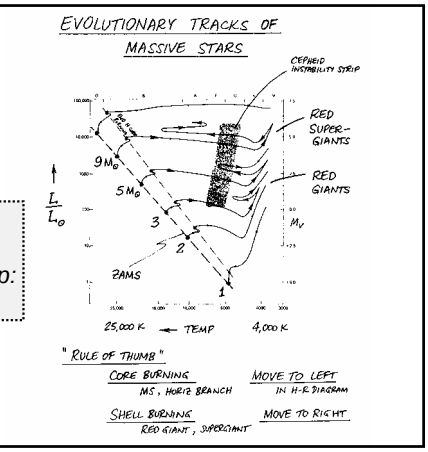
High-mass zigs and zags in H-R diagram

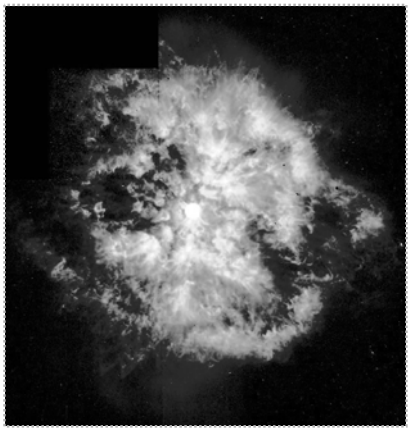
- *Elements of higher mass fusion burn successively, releasing energy to support the star against gravity.*
- *Reactions may change too fast for outer layers to respond, so last zig/zags are small*



BIG Evolutionary SWINGS

Cross the pulsational instability strip: Cepheids





Massive red giant or supergiant:

Fierce hot winds and pulsed ejecta

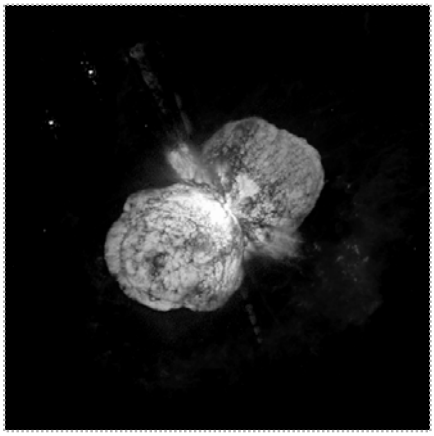
Hubble

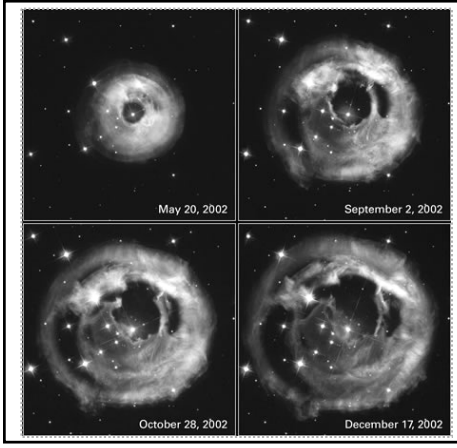
Wildest of all !

ETA CARINAE

Supermassive star (100 M_{SUN}) late in life, giant outburst 150 yr ago

Violent bipolar ejecta + disk at equator



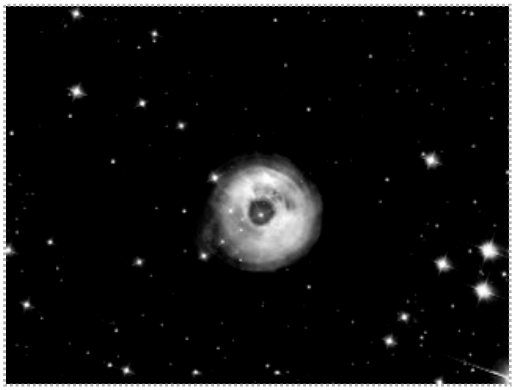


Red Giant or SG with intense brightening

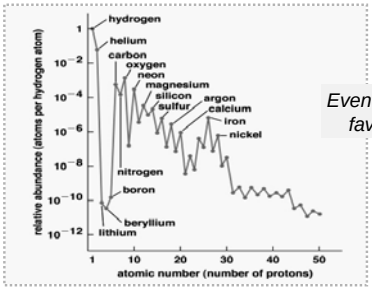
`Light Echo' from pulse

Star V838 Monocerotis HST-ACS

Evolution of V838 Light Echo (HST)



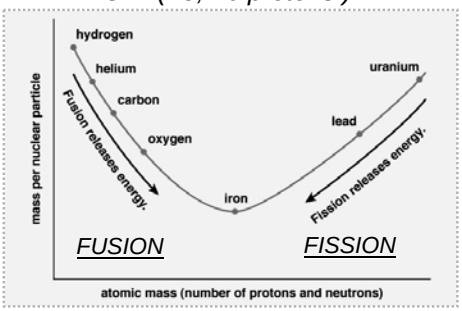
Creation of elements from He-capture ?



Even numbers favored !

- *Mixture of elements in our near universe follows the pattern of <u>He-capture fusion</u> reactions, up to iron*
- *Even <u>heavier elements</u> are made by <u>nucleosynthesis</u> during supernova explosion*

"Onion-shell fusion burning" stops with IRON (Fe, 26 protons)



Iron does NOT release energy when it fuses !

Several fates for massive star

1. Strong winds shrink star, may end as WHITE DWARF

2. Or core burns to Fe, eventually sudden CORE COLLAPSE !

⇨ *SUPERNOVA*

MEMO 4

FINAL FATE OF MASSIVE STAR

TWO POSSIBILITIES....

1. LOSES ENOUGH MASS IN WIND / PLANETARY NEBULA
   $< 1.4\ M_\odot$ LEFT ⇒ WHITE DWARF
   (W.D. COMPOSED OF HEAVIEST ELEMENTS PRODUCED)
2. ENTIRE CORE BURNS TO IRON
   NO MORE NUCLEAR ENERGY CAN BE RELEASED!
   AND $> 1.4\ M_\odot$ LEFT
   COLLAPSE CANNOT BE STOPPED BY ELECTRON DEGENERACY PRESSURE
   ⇒ NEUTRON STAR OR BLACK HOLE

"Core collapse" SUPERNOVA

"Rapid disassembly" of elements in core
→ neutrons
+ neutrinos

Neutron degeneracy pressure stiffens collapsing core ---
+ push of neutrinos

→envelope `bounces' !
→SHELL BLOWS OFF

STELLAR COLLAPSE (VERY RAPID)

GRAVITY MAKES IT GO ... BUT IRON CANNOT BURN, SO NO RESISTANCE

1. ELEMENTS DISMANTLED
   Fe → .. Si → ... O → Ne → C → He → H
   ⇒ NEUTRONS
2. "INVERSE BETA DECAY"
   PROTONS + ELECTRONS --- JAMMED TOGETHER ⇒ NEUTRONS + NEUTRINOS
3. NEUTRINOS TRY TO ESCAPE
   ⇒ PUSH AGAINST INFALLING GAS
   ENVELOPES "BOUNCES" AGAINST CORE
   ⇒ EXPLOSION — SUPERNOVA TYPE II
   "DEBRIS" FLIES INTO SPACE

WHAT'S LEFT ?
1. NOTHING !
2. NEUTRON STAR (PULSAR)
3. BLACK HOLE

Only supernova explosion creates elements heavier than iron:

magic of nucleosynthesis

SN shells, and what is left at center ?

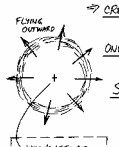
MEMO 5-SN

SUPERNOVA

AFTER "CORE BOUNCE", OUTER REGIONS OF STAR BLOWN OFF EXPLOSIVELY !

HIGH-ENERGY RADIATION & PARTICLES, NEUTRONS AND NEUTRINOS COME FLOODING OUT

NUCLEOSYNTHESIS: NEUTRONS + VARIOUS NUCLEI
⇒ CREATE HEAVY ELEMENTS BEYOND IRON (LIKE SILVER, GOLD, MERCURY ...)
ONLY PLACE IN UNIVERSE TO MAKE THIS STUFF!



SUPERNOVA SHELLS (OR REMNANT):
DO NOT LAST LONG BEFORE DISPERSING
FIRST ~ 1000 YEARS
SEEN IN VISIBLE, X-RAY
AFTER ~ 10,000 YEARS
SNOWPLOW MATERIAL AHEAD
⇒ RELATIVELY COOL ⇒ RADIO EMISSION

WHAT'S LEFT AT CENTER ?
1. NOTHING
2. PULSAR
3. BLACK HOLE

SN REMNANT BECOMES UNDETECTABLE AFTER ABOUT 1 MILLION YEARS

"Core Collapse SUPERNOVA"

- *Exploding remnant of massive star disperses heavy elements through the galaxy*
- *Inside may be a neutron star – a remnant core of pure neutrons!*

Crab Nebula (M1), first seen as SUPERNOVA on 4 July 1054 from China -- visible in daytime

Was Crab SN recorded in Chaco?
….and nothing recorded in Europe!

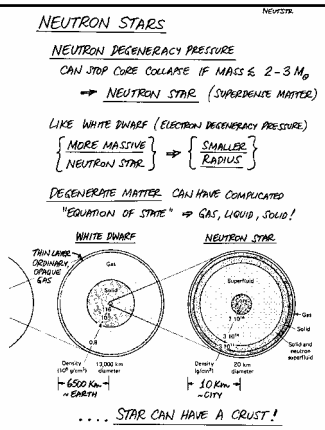
- *Petroglyph from Chaco Canyon:*
- *Correct position relative to new moon for Crab Supernova*
- *Check this on your SkyGazer software*

Neutron stars

More massive, smaller in size!

Star with a crystal crust !

Idea of neutron stars first suggested in 1930s (Landau, Zwicki, Baade, Oppenheimer) … but seemed like dreaming



Favorite Postcard: Size of Neutron Stars

- *Structure determined by gravity vs. neutron degeneracy pressure*
- *Size ~ 10 km. More massive, smaller !!*
- *Crushing gravity at its surface, so not a nice neighbor …or place to visit …. as tourist – try Big Apple instead.*

Neutron star over NYC !