


**ASTR 1040: Stars & Galaxies**



**Crab Nebula**

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Lecture 16 Thur 18 Oct 2018  
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### Topics for Today

- Review: Life tracks of massive stars: late stages allow fusion like "layers of an onion"
- Massive stars end life with supernova explosion, when iron core exceeds  $1.4 M_{\text{sun}}$
- Pulsars – fast spinning neutron stars with fierce magnetic fields; gradually slow down
- Beamed pulses from synchrotron radiation

### Things to do

- Review 17.4 'Mass Exchange'
- Read Chap 18: 'Bizarre Stellar Graveyard' on white dwarfs (18.1), and neutron stars (18.2) with care
- Homework #7 due, new HW #8 available
- Mid-Term Exam 2 next Thur (Oct 25)
- Review Session next Wed by Ryan, 5pm-7pm G130 (here) Review Set 2 available

### Evolution of massive stars

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

SO WHAT IS DIFFERENT? **REMINDER**

"CLOCK" CAN RUN MUCH FASTER  
CAN BURN MORE ELEMENTS (C, O, Ne, Si...)  
FINAL FATE CONTROLLED BY HOW MUCH MASS LOST BY STRONG WINDS

- 1. MAIN SEQUENCE** H CORE BURNING, C-N-O CYCLE  
STELLAR WINDS  $M \downarrow$  (4H → He)
- 2. RED GIANT I** H SHELL BURNING  
INERT HE CORE SLOWLY CONTRACTING
- 3. HORIZONTAL BRANCH** LESS POWER, NO DEGENERACY IN HE CORE (IF  $M > 2.5 M_{\odot}$ )  
→ NO HELIUM FLASH  
SMOOTH TRANSITION TO HE CORE BURNING: TRIPLE-ALPHA (3He → 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!

**Clock runs faster, can burn heavier elements**

**First 4 steps, pretty familiar, but no helium flash**

**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... **REMINDER**

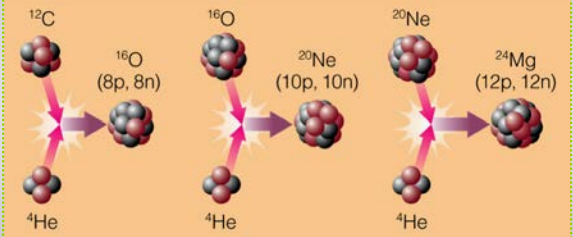
**5. CARBON FLASH** INITIATE CARBON BURNING IN DEGENERATE CORE WITH EXPLOSIVE FLASH  
"ALPHA CAPTURE"  
 $C + He \rightarrow O + \text{ENERGY}$   
A. EXPLODE AS SUPERNOVA TYPE I  
OR  
B. REMOVE DEGENERACY, EVEN QUIETLY IN STAGES TO PRODUCE IRON IN CORE

**6. HORIZONTAL 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  
Fe CORE  
Si BURNING SHELL  
O...  
Ne...  
He SHELL  
H SHELL

**REMINDER**

### Fusion by "helium-capture" (alpha-particles) burns C, O, Ne, Mg, Si .. "layers of onion"



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

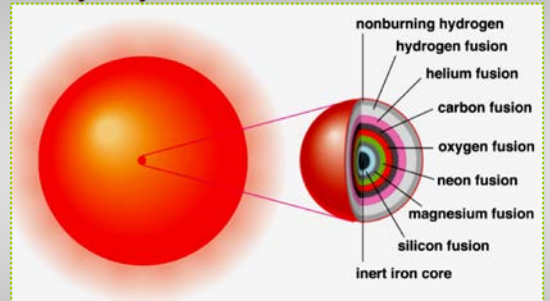
Carbon (6), Oxygen (8), Neon (10)  
Magnesium (12)....

Periodic Table of the Elements

1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	*Ac	Rf	Ha	Hs	Hs	Mt	110	111	112	113						

\* Lanthanide Series  
+ Actinide Series

**REMINDER**  
Many "layers of onion" in massive star



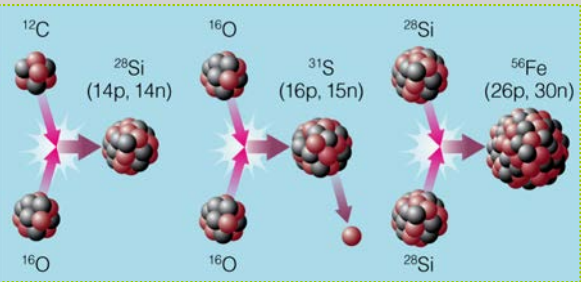
Core structure from successive burning stages:  
lesser elements on outside, heavier on inside

Clicker Question

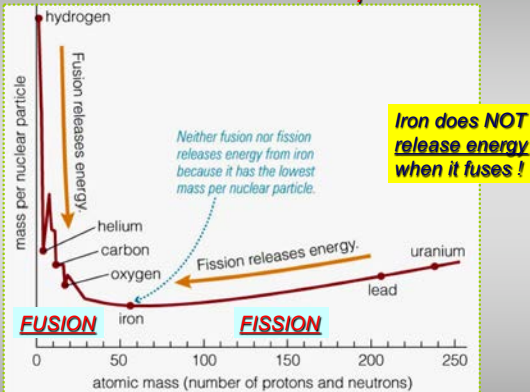
Which of these stars formed EARLIEST (in the lifetime of the Universe)?

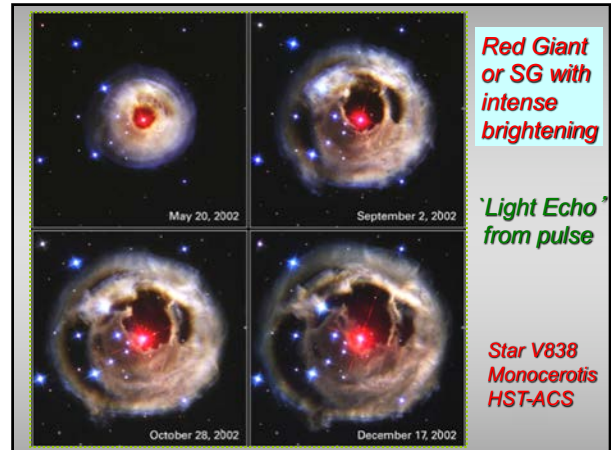
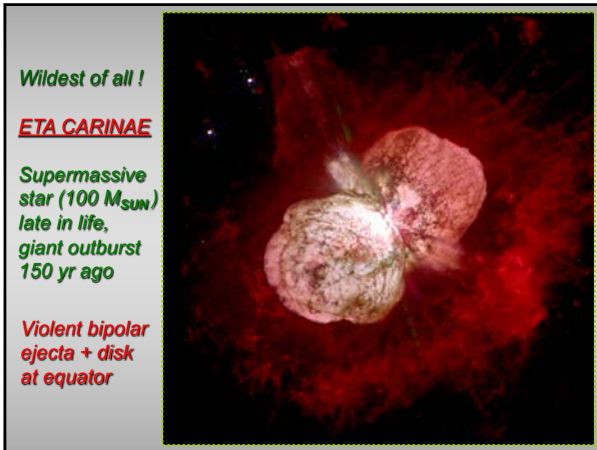
- A. Star A: 70% H, 28% He, 2% other
- B. Star B: 75% H, 25% He, 0% other
- C. Star C: 72% H, 27% He, 1% other
- D. Star D: 90% H, 10% He, 0% other
- E. It depends on their masses

**REMINDER**  
A few of many other fusion reactions also feasible in high-mass stars



Actual "mass / nuclear particle"





Reading Ahead Clicker Question

After a "core-collapse" supernova event, what is left behind?

A. A white dwarf  
 B. A neutron star  
 C. A black hole  
 D. A white dwarf or a black hole  
 E. A neutron star or a black hole

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**

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"**

- 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



**"Core collapse" (massive star) 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 → JAMMED TOGETHER → NEUTRONS  
ELECTRONS → NEUTRINOS

3. NEUTRINOS TRY TO ESCAPE  
→ PUSH AGAINST INFALLING GAS  
ENVELOPE "BOUNCES" AGAINST CORE  
→ EXPLOSION SUPERNOVA TYPE II  
"DEBRIS" FLIES INTO SPACE

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

**SUPERNOVA**

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

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

**NUCLEOSYNTHESIS**: NEUTRONS + VARIOUS NUCLES  
→ 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  
SNOWFLOW MATERIAL AHEAD  
→ RELATIVELY COOL → RADIO EMISSION

SN REMNANT BECOMES UNDETECTABLE  
AFTER ABOUT 3 MILLION YEARS

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

**Supernova explosion creates elements heavier than iron:**

**magic of nucleosynthesis**

**SN shells, and what is left at center?**



**SNR: Crab Nebula M1**

4 July 1054

**Observing Supernovae**

- About 1 per century per galaxy (none in Milky Way since 1604 - Kepler) [1572 - Brahe; 1054 - Crab; 1004 - brightest]
- Bright explosion visible for weeks/months - some visible in daytime!
- Remnant visible for 10,000+ years as huge bubbles and "veils" - longer in radio



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

- Petroglyph from Chaco Canyon:
- Correct position relative to new moon for Crab Supernova, but some doubt
- 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, Zwicky, Baade, Oppenheimer) ... but seemed like wild dreaming

**NEUTRON STARS**

NEUTRON DEGENERACY PRESSURE  
CAN STOP CORE COLLAPSE IF MASS ≤ 2-3 M<sub>☉</sub>  
→ NEUTRON STAR (SUPERDENSE MATTER)

LIKE WHITE DWARF (ELECTRON DEGENERACY PRESSURE)  
{ MORE MASSIVE } → { SMALLER RADIUS }

DEGENERATE MATTER CAN HAVE COMPLICATED "EQUATION OF STATE" → GAS, LIQUID, SOLID!

WHITE DWARF vs NEUTRON STAR

THIN LAYER (20% OF MASS) OPACQUE GAS

Core  
Envelope  
Outer atmosphere

Density: 10<sup>9</sup> kg/m<sup>3</sup> → 10,000 km diameter  
→ 6000 Km → EARTH

Density: 10<sup>17</sup> kg/m<sup>3</sup> → 20 km diameter  
→ 10 km → CITY

... STAR CAN HAVE A CRUST!

### 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 !

### Observing the 'First' Pulsar: BIG discovery

- Jocelyn Bell (Burnell):** Cambridge (UK) graduate student in 1967 (+ **Anthony Hewish**) discovered pulsars by accident
- Little Green Men (LGM) ? Just WHAT could cause signal?**

### "Pulsar" = rotating neutron star

**Fierce magnetic fields + sizzling electrons + fast rotation → finest "lighthouse"**

Thomas Gold 1968

**PULSARS :**  
 INGREDIENTS .... NEUTRON STAR WITH  
 1. RAPID SPIN } DIRECT RESULT OF COLLAPSE  
 2. FIERCE MAGNETIC FIELD }  
 MAGNETIC FIELD NOT ALIGNED WITH SPIN (OR ROTATION) AXIS  
 STRONG BEAMS OF LIGHT (VISIBLE, X-RAY...) BY RADIATION CONE

**SYNCHROTRON RADIATION**

### Pulsars and Neutron Stars

**Pulsars are lighthouses in our Galaxy!**

### Bowling Ball Demo seeking to be a **PULSAR**

### Synchrotron radiation

beaming from **neutron star** ... and many other energetic places (quasars)

**"scream from electrons" spiralling along magnetic fields – like in particle accelerators**

**SYNCHROTRON RADIATION "NON-THERMAL"**  
 ... DIFFERENT THAN THERMAL (BLACK-BODY) RADIATION IN HOW INTENSITY VARIES WITH WAVELENGTH

RADIATION CAN BE IN VISIBLE AND/OR RADIO PORTIONS OF SPECTRUM  
 DEPENDS ON ELECTRON ENERGY & MAGNETIC FIELD STRENGTH (FASTER SPIRALING, HIGHER FREQUENCIES)

### Synchrotron Radiation

- Fast electrons in strong magnetic fields → neutron stars, black holes
- Different shape from thermal radiation: emits at all wavelengths, strongest in radio

### Why pulsars spin so fast: Vast shrinking conserves angular momentum

- Collapse to a neutron star increases both rotation and magnetic fields
- Newly collapsed neutron stars can rotate hundreds to thousands of times per second!

**Mystery resolved when pulsar discovered in Crab Nebula (known to be supernova remnant) -- Messier 1 or M1!**

The Crab pulsar also pulses in visual light

### Crab's pulse patterns

**CRAB PULSAR: FROM SUPERNOVA IN 1054**

- ROTATION PERIOD ~ 0.033 SEC (33 MILLISEC) (ABOUT 30 PULSES EACH SECOND)
- PULSES DETECTED IN VISIBLE, IR, X-RAY, Y-RAY, RADIO

**CRAB NEBULA SUPERNOVA REMNANT**

**PULSE PATTERNS:**

- PULSAR DISCOVERED IN 1967 FOUND TO BE VERY GRADUALLY SLOWING DOWN IN SPIN (PULS RATE)
- PULSAR "ON" FOR SMALL FRACTION OF EACH CYCLE
- PULSE SHAPES IN PULSARS CAN BE INTRICATE

### Pulsars and Neutron Stars

**Neutron Stars on the Web**

### Listening to Pulsars

- PSR **B0329+54** typical, normal pulsar: period 0.714 sec (~1.40 rotations/sec)
- PSR **B0933-45 VELA** pulsar: period 89 millisecond (0.089 sec) (~11 rot/sec) in SNR ~10,000 yrs ago
- PSR **B0531+21 CRAB** pulsar: ~30 rot/sec youngest known
- PSR **J0437-4715 "millisec"** pulsar, ~174 rot/sec
- PSR **B1937+21 fastest** pulsar, ~642 rot/sec surface of star moving at 1/7 c!