


ASTR 1040: Stars & Galaxies



Crab Nebula

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Lecture 16 Thur 8 Mar 2018
zeus.colorado.edu/astr1040-toomre

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
- Observatory Night #5, **Mon March 12**, signup
- Homework #7 due, new HW #8 available
- **Mid-Term Exam 2** next Thur (March 15)
- **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 $M \downarrow$ ($4M \rightarrow 1M$)
- 2. RED GIANT I** H SHELL BURNING
INERT HE CORE SLOWLY CONTRACTING
- 3. HORIZONTAL BRANCH** LESS POWER, NO DEGENERACY IN HE CORE (IF $M > 2.5M_{\odot}$)
 \rightarrow NO HELIUM FLASH
SMOOTH TRANSITION TO HE CORE BURNING: TRIPLE-ALPHA ($3\text{He} \rightarrow \text{C}$)
- 4. RED GIANT II (SUPERGIANT)** HE SHELL BURNING STALLED, 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

MASSIVE STARS... **REMINDER**

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

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

AT CENTER OF SUPERGIANT: IF $M \geq 8M_{\odot}$, SUCCESSIVE STAGES OF CORE AND SHELL IGNITION
"ONION RING" STRUCTURE OF BURNING SHELLS
H SHELL, HE SHELL, O... C BURNING SHELL, SI BURNING SHELL
INERT FE CORE

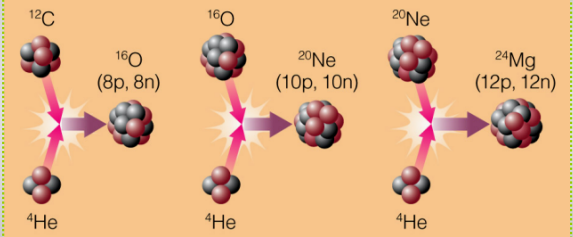
Successive core & shell fusion burning of C, O, Ne, Si ..

all with "alpha capture" (or He)

stars make many shallow H-R loops

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

REMINDER



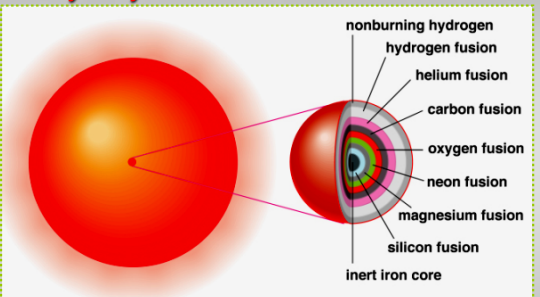
- Helium nucleus (2 protons) is **absorbed**, energy is released
- Elements are created going up periodic table in **steps of 2**

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

Periodic Table of the Elements

1	IA																IIA																IIIB										IVB										VB										VIB										VIIB										VII										IIB										IIIA										IVA										VA										VIA										VIIA										VIIIA										IIA										IA																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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REMINDER
Many "layers of onion" in massive star



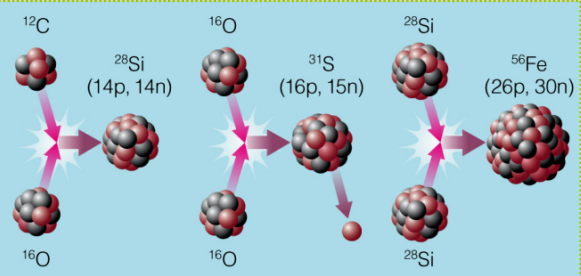
Core structure from successive burning stages:
lesser elements on outside, heavier on inside

Clicker Question

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

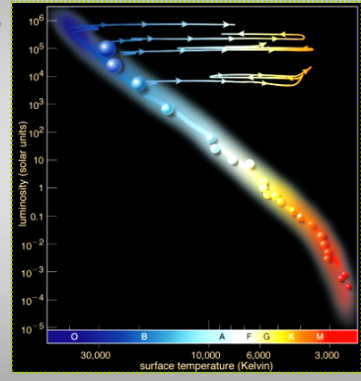
- A. Star A: 70% H, 28% He, 2% other
- B. Star B: 75% H, 25% He, 0% other
- C. Star C: 72% H, 27% He, 1% other
- D. Star D: 90% H, 10% He, 0% other
- E. It depends on their masses

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

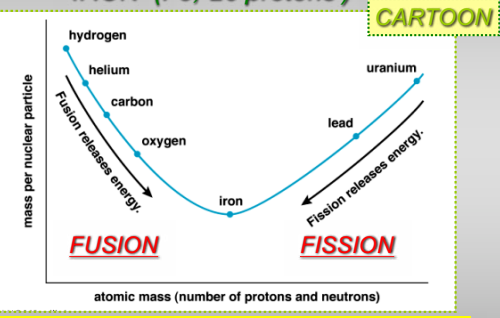


High-mass zigs and zags in H-R diagram

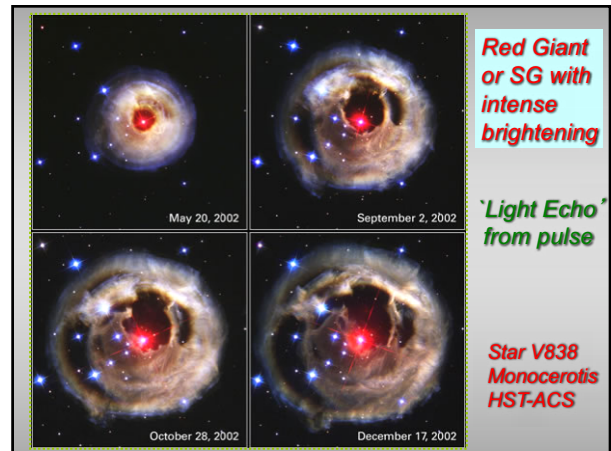
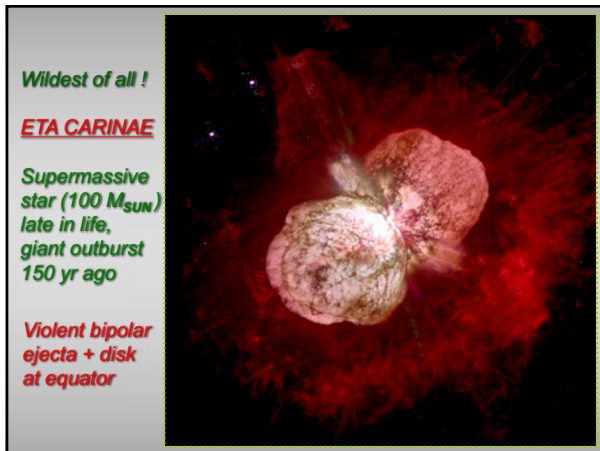
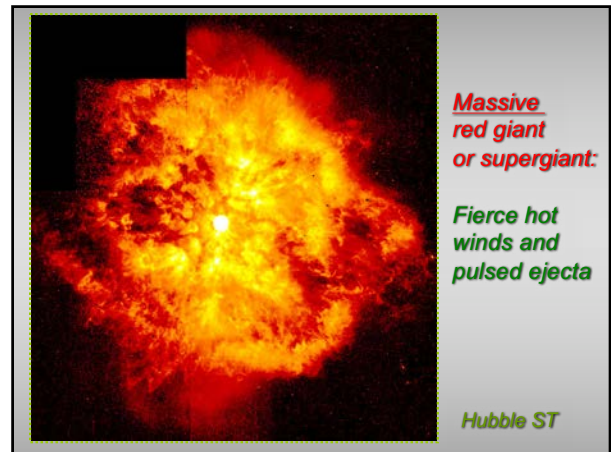
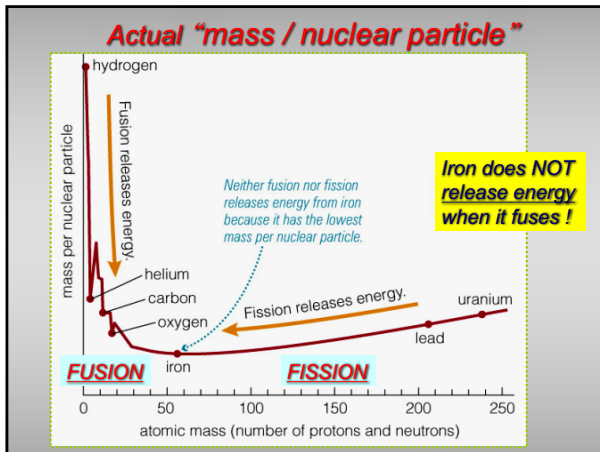
- Elements of higher mass fusion burn successively, releasing energy to support the star against gravity.
- Reactions may change too fast for outer layers to respond, so last zig/zags are small



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



Iron does NOT release energy when it fuses!



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

- LOSES ENOUGH MASS IN WIND/PLANETARY NEBULA
< 1.4 M₀ LEFT → **WHITE DWARF**
(W.D. COMPOSED OF HEAVIEST ELEMENTS PRODUCED)
- ENTIRE CORE BURNS TO IRON
NO MORE NUCLEAR ENERGY CAN BE RELEASED!
AND > 1.4 M₀ 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


- ELEMENTS DISMANTLED
Fe → ... Si → ... O → Ne → C → He → H
⇒ **NEUTRONS**
- “INVERSE BETA DECAY”
PROTONS → JAMMED TOGETHER → NEUTRONS
ELECTRONS → NEUTRINOS
- 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 explosion creates elements heavier than iron:

magic of nucleosynthesis

SN shells, and what is left at center?

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
⇒ CREATES 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



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**

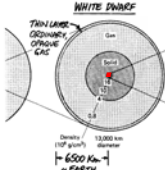
NEUTRON STARS

NEUTRON DEGENERACY PRESSURE
CAN STOP CORE COLLAPSE IF MASS $\leq 2-3 M_{\odot}$
→ NEUTRON STAR (SUPERDENSE MATTER)

LIKE WHITE DWARF (ELECTRON DEGENERACY PRESSURE)
 $\left\{ \begin{array}{l} \text{MORE MASSIVE} \\ \text{NEUTRON STAR} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{SMALLER} \\ \text{RADIUS} \end{array} \right\}$

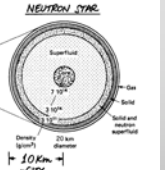
DEGENERATE MATTER CAN HAVE COMPLICATED "EQUATION OF STATE" → GAS, LIQUID, SOLID!

WHITE DWARF



Radius: 10,000 km
Density: 10⁹ g/cm³
~ 6000 km ~ EARTH

NEUTRON STAR

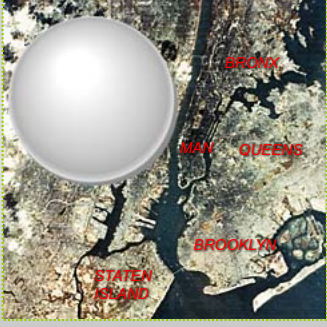


Radius: 10 km
Density: 10¹⁵ g/cm³
~ 10 km ~ CITY

... STAR CAN HAVE A CRUST!

Favorite Postcard: Size of Neutron Stars

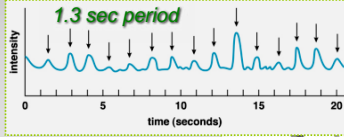
- Structure determined by gravity vs. neutron degeneracy pressure
- Size ~ 10 km. More massive, smaller !!
- Crushing gravity at its surface, so not a nice neighbor ...or place to visit ... as tourist – try Big Apple instead.



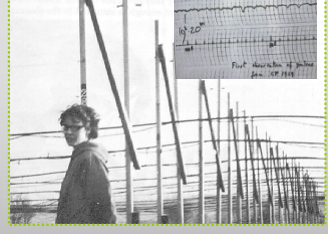
Neutron star over NYC!

Observing the 'First' Pulsar: BIG discovery

1.3 sec period



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



PULSARS:

"Pulsar" = rotating neutron star

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

Thomas Gold 1968

INGREDIENTS ... NEUTRON STAR WITH

1. RAPID SPIN
2. FIERCE MAGNETIC FIELD

DIRRECT RESULT OF COLLAPSE

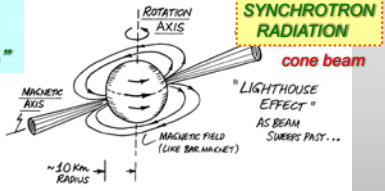
MAGNETIC FIELD NOT ALIGNED WITH SPIN (OR ROTATION) AXIS

STRONG BEAMS OF LIGHT (VISIBLE, X-RAY...) BY RADIATION CONE

SYNCHROTRON RADIATION

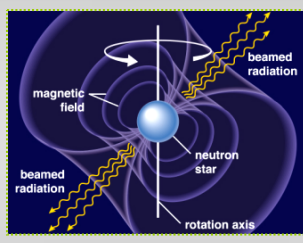
cone beam

"LIGHTHOUSE EFFECT" AS BEAM SWEEPS PAST...




~10 km RADIUS

Pulsars and Neutron Stars



Pulsars are lighthouses in our Galaxy!



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

RELATIVE INTENSITY

SHORT WAVELENGTH LONG

SYNCHROTRON RADIATION EMITTED BY ELECTRON SPIRALING ALONG MAGNETIC FIELD

RADIATION CAN BE IN VISIBLE AND/OR RADIO PORTIONS OF SPECTRUM
DEPENDS ON ELECTRON'S 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

intensity (relative)

wavelength (nm)

15,000 K star
the Sun (5,800 K)
3,000 K star
310 K human
Synchrotron

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

0.033 s 0.033 s 0.033 s 0.033 s 0.033 s

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, γ -RAY, RADIO

CRAB NEBULA SUPERNOVA REMNANT

PULSE PATTERNS:

X-ray
visible
radio


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

PERIOD TIME


Pulsars and Neutron Stars




magnetic field
neutron star
rotation axis
beamed radiation

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 millisecc (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 *"millisecc"* pulsar, ~174 rot/sec
- PSR B1937+21 *fastest* pulsar, ~642 rot/sec  surface of star moving at 1/7 c!

