ASTR 1040: Stars & Galaxies

Crab Nebula

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Lecture 16 Thur 9 Mar 2017

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_{sun}
- Pulsars – fast spinning neutron stars with fierce magnetic fields; gradually slow down
- Beamed pulses from synchrotron radiation

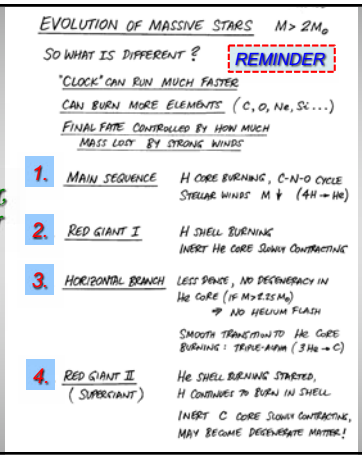
Things to do

- 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 13, signup
- Homework #7 due, new HW #8 available
- Mid-Term Exam 2 next Thur (March 16)
- Review Session next Wed by Piyush, 5pm-7pm G130 (here) Review Set 2 available

Evolution of massive stars

Clock runs faster, can burn heavier elements

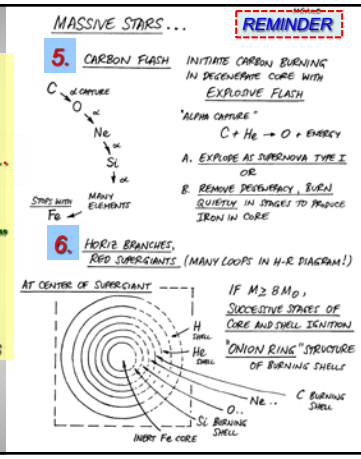
First 4 steps pretty familiar, but no helium flash



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

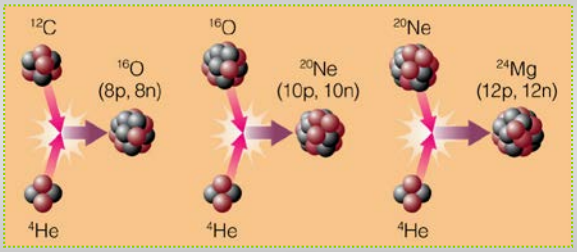
all with "alpha capture" (or He)

stars make many shallow H-R loops



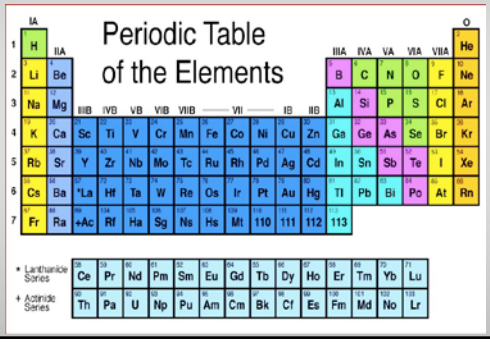
REMINDER

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



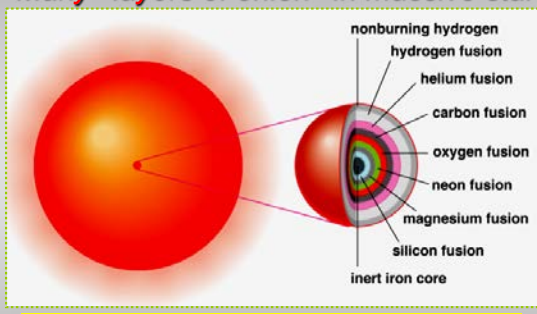
- Helium nucleus (2 protons) is absorbed, energy is released
- Elements are created going up periodic table in steps of 2

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



REMINDER

Many "layers of onion" in massive star



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

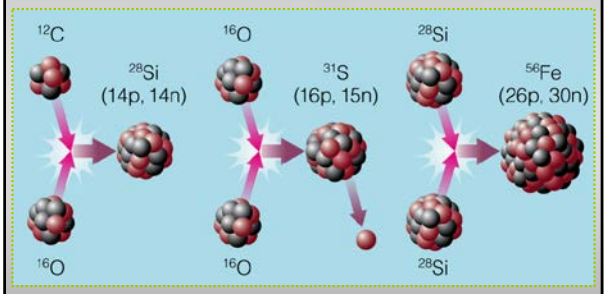
Clicker Question

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*

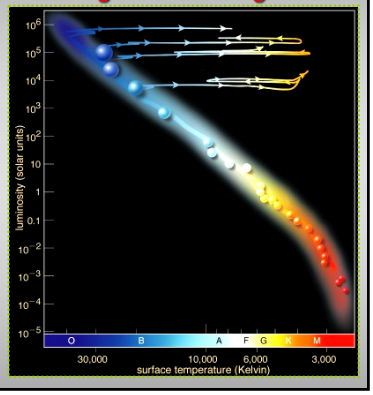
REMINDER

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



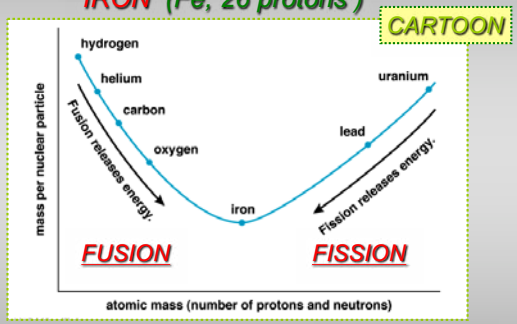
High-mass zigs and zags in H-R diagram

- *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*



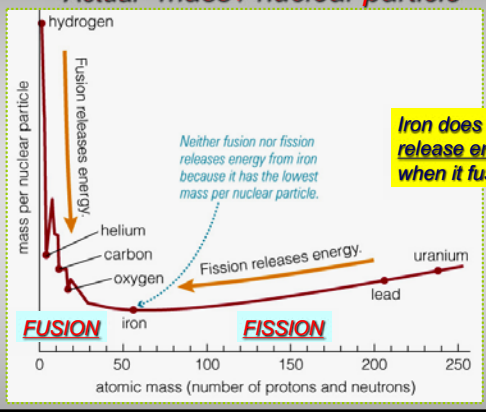
"Onion-shell fusion burning" stops with IRON (Fe, 26 protons)

CARTOON



Iron does NOT release energy when it fuses !

Actual "mass / nuclear particle"



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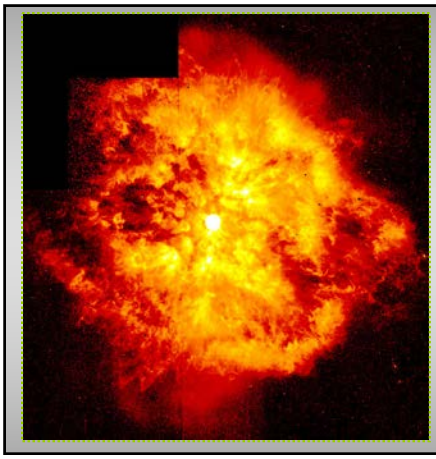


Massive red giant or supergiant:

Fierce hot winds and pulsed ejecta

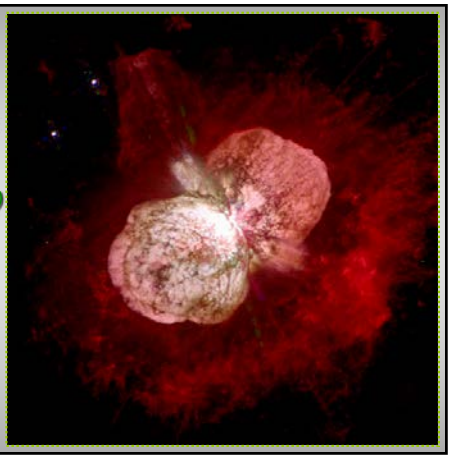
Hubble ST

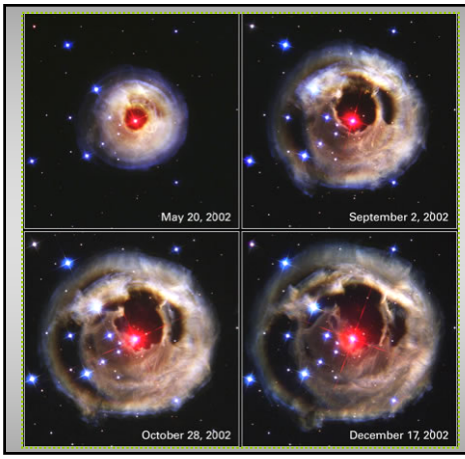
Wildest of all !

ETA CARINAE

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

Violent bipolar ejecta + disk at equator



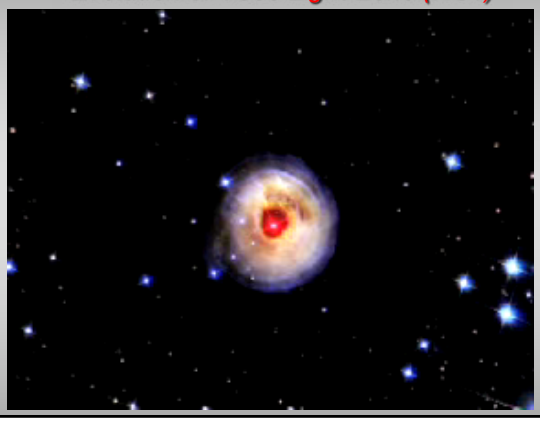


Red Giant or SG with intense brightening

`Light Echo' from pulse

Star V838 Monocerotis HST-ACS

Evolution of V838 Light Echo (HST)



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 + 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 ?

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!

FLUXES OUTWARD

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

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!

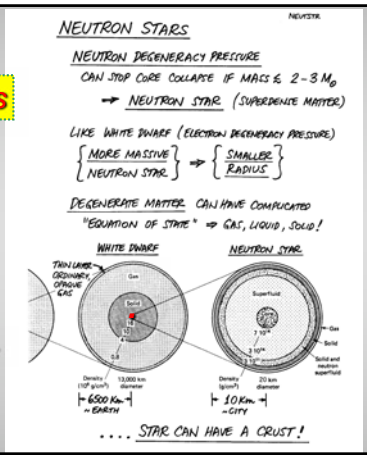
- Petroglyph from Chaco Canyon:
- Correct position relative to new moon for Crab Supernova, but some doubt
- Check this on your SkyGazer software

Neutron stars

More massive, smaller in size!

Star with a crystal crust !

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

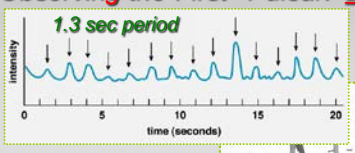


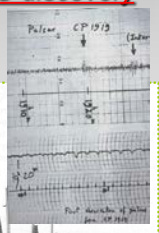
Favorite Postcard: Size of Neutron Stars

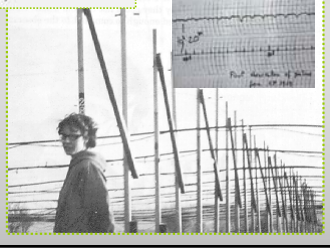
- Structure determined by gravity vs. neutron degeneracy pressure
- Size ~ 10 km. More massive, smaller !!
- Crushing gravity at its surface, so not a nice neighbor …or place to visit …. as tourist – try Big Apple instead.

Neutron star over NYC !

Observing the `First' Pulsar: BIG discovery



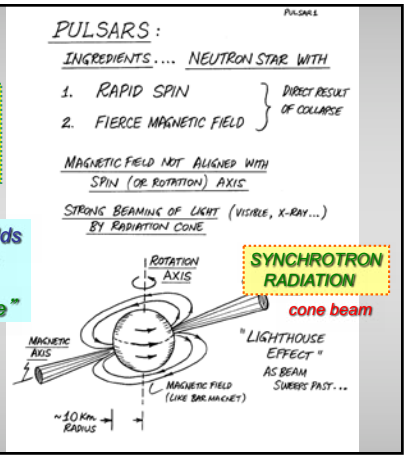




- Jocelyn Bell : Cambridge (UK) graduate student in 1967 (+ Anthony Hewish) discovered pulsars by accident
- Little Green Men (LGM) ? Just WHAT could cause signal?

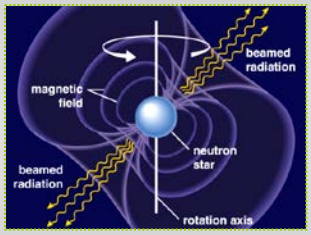
"Pulsar" = rotating neutron star

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



Thomas Gold 1968

Pulsars and Neutron Stars

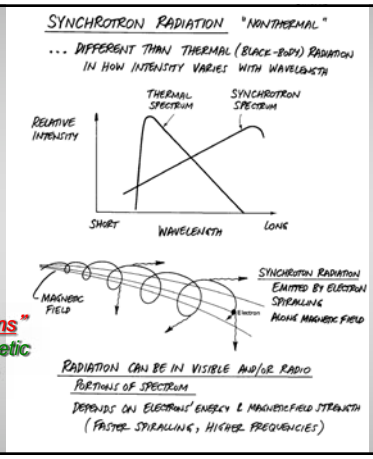


Pulsars are lighthouses in our Galaxy!

Synchrotron radiation

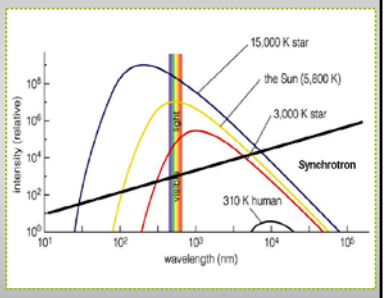
beaming from neutron star … and many other energetic places (quasars)

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



Synchrotron Radiation

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

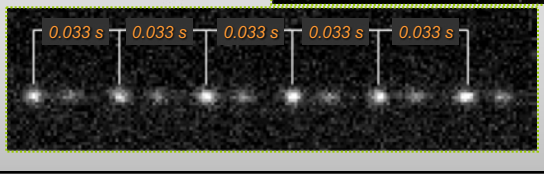


Why pulsars spin so fast:
Vast shrinking conserves angular momentum

- 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



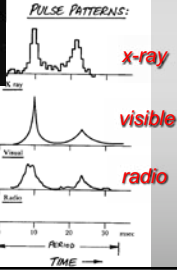
Crab's pulse patterns

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, γ-RAY, RADIO

CRAB NEBULA SUPERNOVA REMNANT

PULSE PATTERNS:

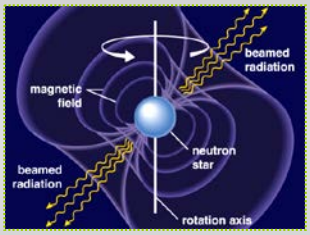


- PULSAR DISCOVERED IN 1967 FOUND TO BE VERY GRADUALLY SLOWING DOWN IN SPIN (PULSE RATE)
- PULSAR "ON" FOR SMALL FRACTION OF EACH CYCLE
- PULSE SHAPES IN PULSARS CAN BE INTRICATE

Spinning Bowling Ball Demo

Neutron Star in the Lab

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 millisec (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!

SNR: Crab Nebula M1

4 July 1054