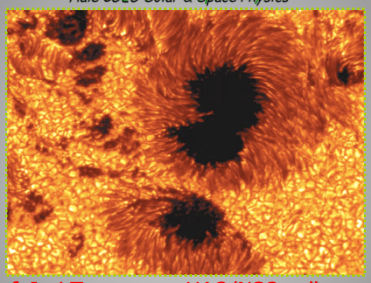
ASTR 7500: Solar & Stellar Magnetism

Hale CGEG Solar & Space Physics



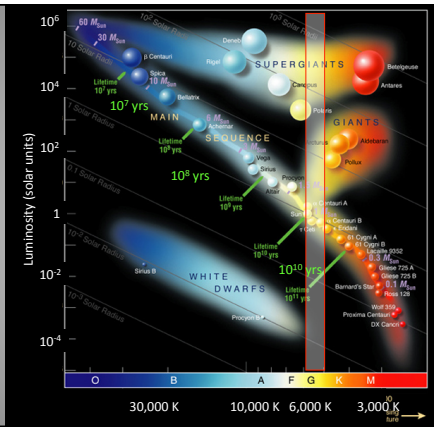
Prof. Juri Toomre + HAO/NSO colleagues

Lecture 2 Thur 24 Jan 2013

zeus.colorado.edu/astr7500-toomre

Life story of stars

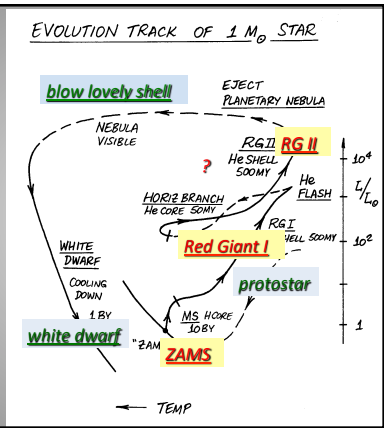
'H-R diagram'



REMINDER

Life track in H-R diagram of solar-mass star

Many meanders, but MS phase longest, red giant phase(s) shorter, finally white dwarf left to cool slowly

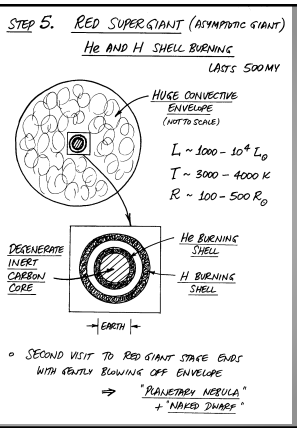


REMINDER

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



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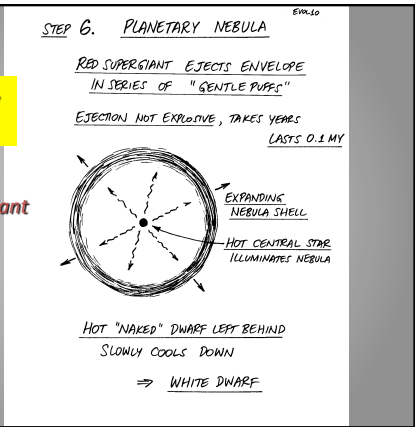
6. Planetary Nebula

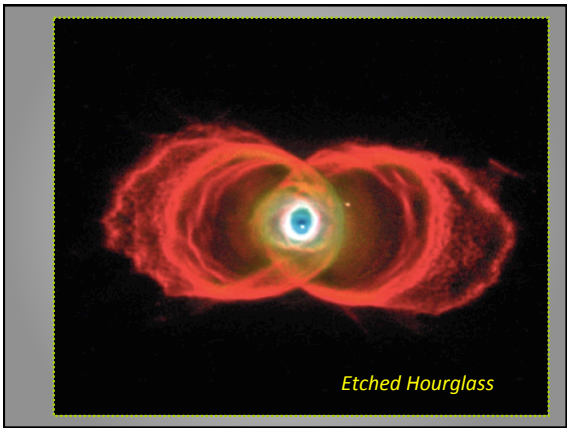
Outer shells of red supergiant "puffed off"

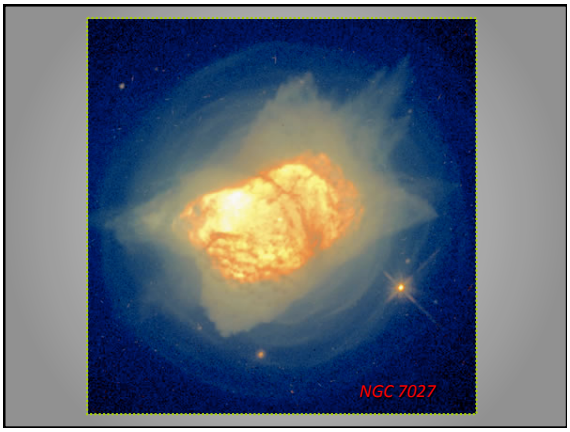
Great pictures!

"Naked" white dwarf emerges



Lovely Shapes of Planetary Nebulae





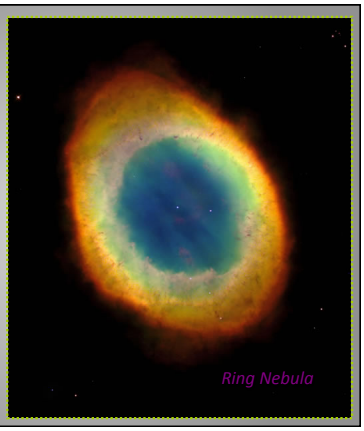
Basic Question

What is likely to account for the vast range of shapes (many beautiful) of these ejecta?

Life after brief "planetary nebula" stage ....

Hot central core emerges as

WHITE DWARF



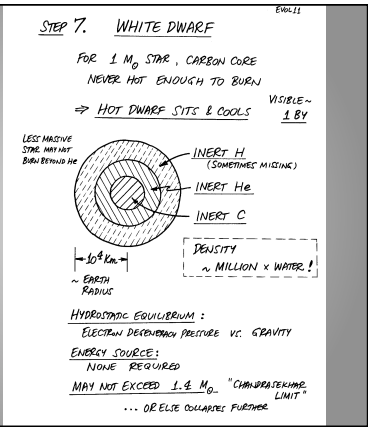
7. White Dwarf

Inert C core, He & H shells

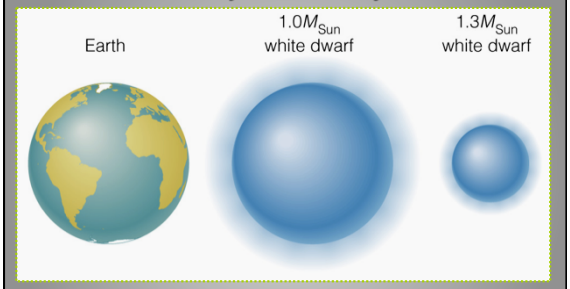
electron degeneracy pressure holds it up

Very dense, size of Earth

max mass of 1.4 M_{SUN}



Sizes of white dwarfs



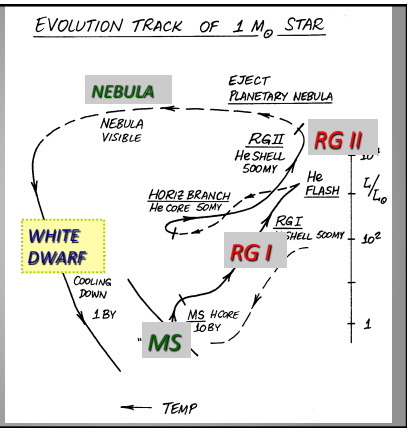
More massive white dwarfs are SMALLER !

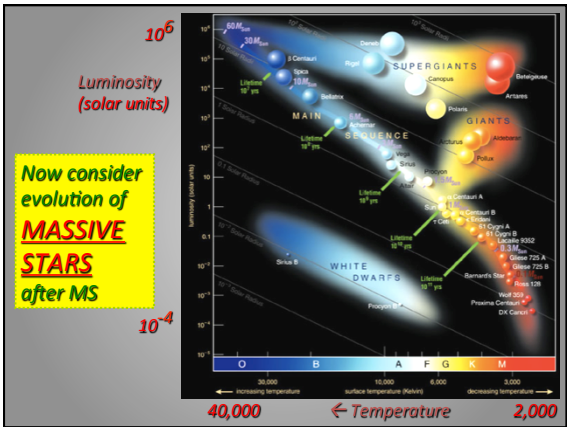
Many exhibit STRONG MAGNETIC FIELDS: 10^4 to 10^9 G

Final stage:

Cooling white dwarf --- snooze ....

But if WD has binary companion, much fun can begin !





Now consider evolution of **MASSIVE STARS** after MS

Evolution of massive stars

Clock runs faster, can burn heavier elements

First 4 steps pretty familiar, but no helium flash

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

SO WHAT IS DIFFERENT ?

"CLOCK" CAN RUN MUCH FASTER

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

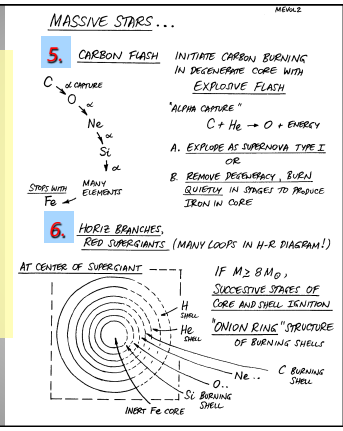
FINAL FATE CONTROLLED BY HOW MUCH MASS LOST BY STRONG WINDS

1. MAIN SEQUENCE — H CORE BURNING, C-N-O CYCLE; STELLAR WINDS $\dot{M}$ ↑ (4H → 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 ($3\,He \rightarrow C$)
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 ..

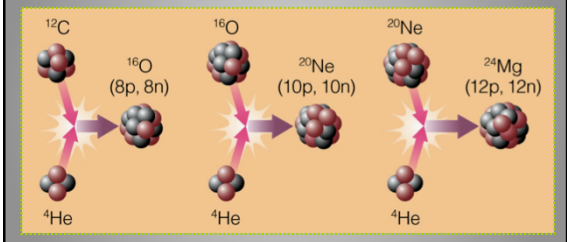
all with "alpha capture" (or He)

stars make many shallow H-R loops



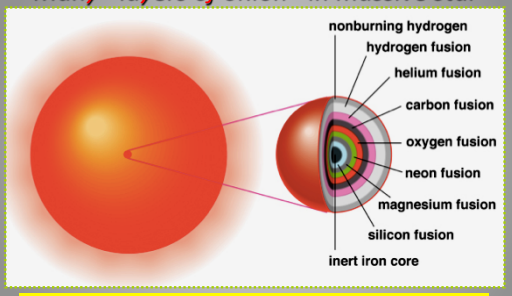
Fusion by "helium-capture" (alpha-particles) burns C, O, Ne, Mg, Si ..

"layers of onion"



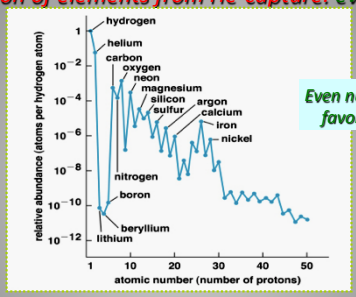
- Helium nucleus (2 protons) is absorbed, energy is released
- Elements are created going up periodic table in steps of 2

Many "layers of onion" in massive star



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

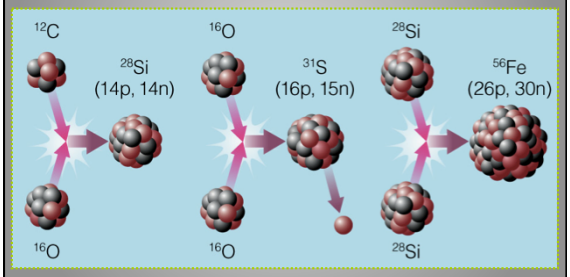
Creation of elements from He-capture: evidence



Even numbers favored !

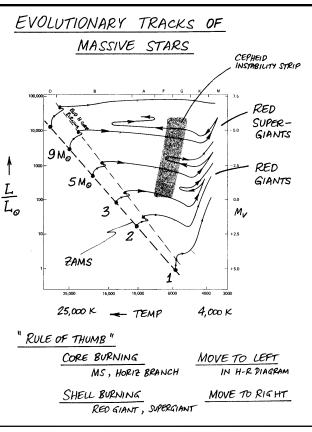
- Mixture of elements in our near universe follows the pattern of He-capture fusion reactions, up to iron
- Even heavier elements are made by nucleosynthesis during supernova explosion

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



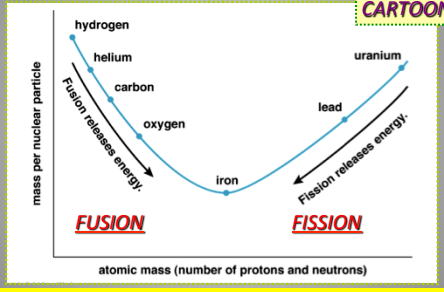
BIG Evolutionary SWINGS

Cross the pulsational instability strip: Cepheids



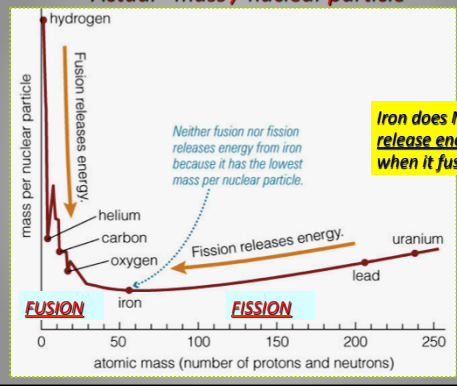
"Onion-shell fusion burning" stops with IRON (Fe, 26 protons)

CARTOON



Iron does NOT release energy when it fuses !

Actual "mass / nuclear particle"



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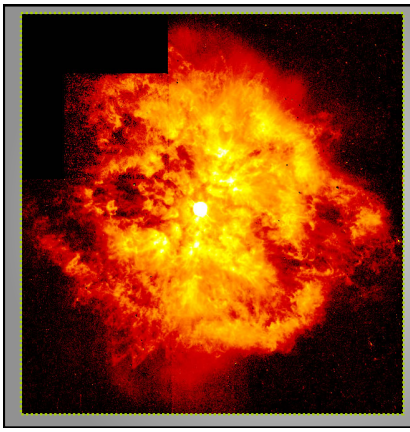


Massive red giant or supergiant:

Fierce hot winds and pulsed ejecta

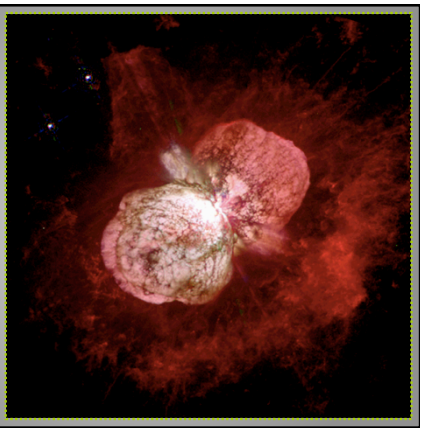
Hubble ST

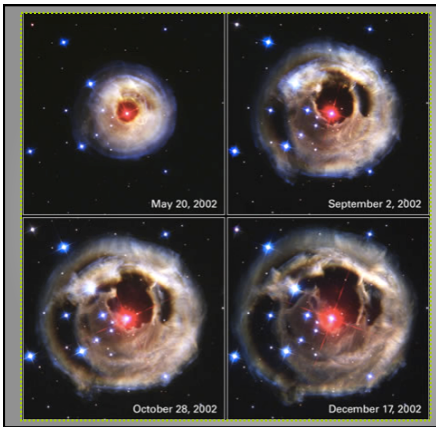
Wildest of all !

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

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

MENU 4

FINAL FATE OF MASSIVE STAR

TWO POSSIBILITIES....

1. LOSES ENOUGH MASS IN WIND / PLANETARY NEBULA
   $< 1.4\ M_\odot$ LEFT $\Rightarrow$ 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
   $\Rightarrow$ NEUTRON STAR
   OR
   BLACK HOLE

"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!

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

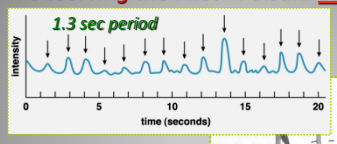
SN REMNANT BECOMES UNDETECTABLE AFTER ABOUT 1 MILLION YEARS

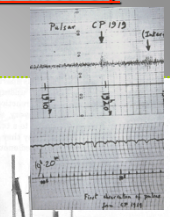
"Core Collapse SUPERNOVA"

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

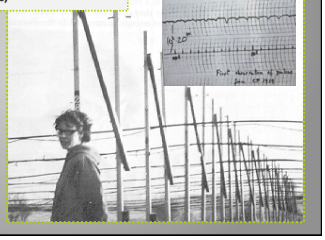
Crab Nebula (M1), first seen as SUPERNOVA on 4 July 1054 from China -- visible in daytime

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"

Magnetic fields: 10^9 to 10^{15} G

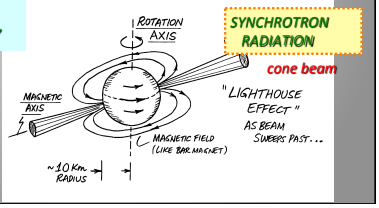
Thomas Gold 1968

PULSARS :

INGREDIENTS .... NEUTRON STAR WITH
1. RAPID SPIN
2. FIERCE MAGNETIC FIELD
} DIRECT RESULT OF COLLAPSE

MAGNETIC FIELD NOT ALIGNED WITH SPIN (OR ROTATION) AXIS

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



SYNCHROTRON RADIATION
cone beam
"LIGHTHOUSE EFFECT" AS BEAM SWEEPS PAST...

Neutron stars

More massive, smaller in size!

Star with a crystal crust !

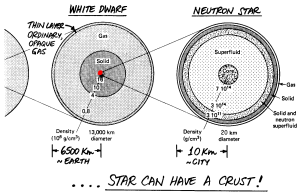
Idea of neutron stars first suggested in 1930s (Landau, Zwicki, Baade, Oppenheimer) ... but seemed like wild dreaming

NEUTRON STARS

NEUTRON DEGENERACY PRESSURE
CAN STOP CORE COLLAPSE IF MASS ≤ 2-3 $M_\odot$
⇒ NEUTRON STAR (SUPERDENSE MATTER)

LIKE WHITE DWARF (ELECTRON DEGENERACY PRESSURE)
{MORE MASSIVE NEUTRON STAR} ⇒ {SMALLER RADIUS}

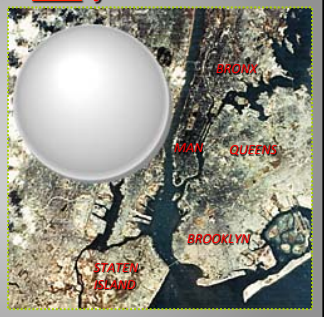
DEGENERATE MATTER CAN HAVE COMPLICATED "EQUATION OF STATE" ⇒ GAS, LIQUID, SOLID!



.... 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.

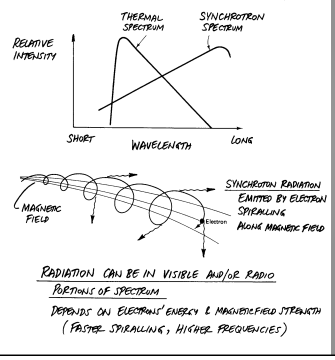


Neutron star over NYC !

Synchrotron radiation

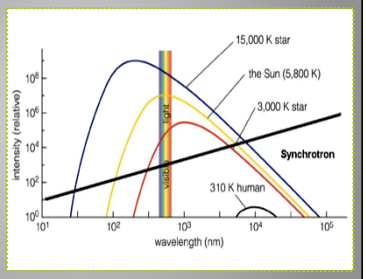
beaming from neutron star … and many other energetic places (quasars)

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



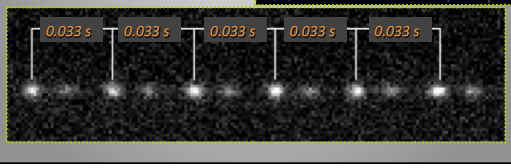
Synchrotron Radiation

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



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



Back to famous friend !

SN: Crab Nebula M1

4 July 1054

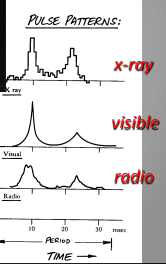
Crab's pulse patterns

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

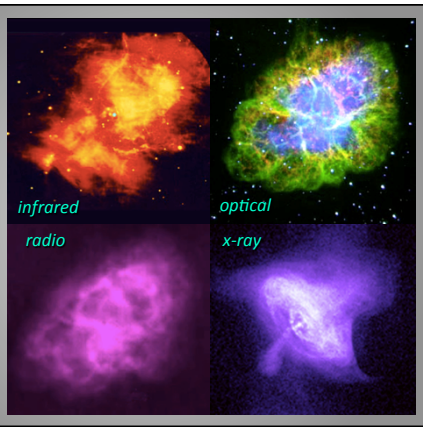
CRAB NEBULA SUPERNOVA REMNANT

PULSE PATTERNS:

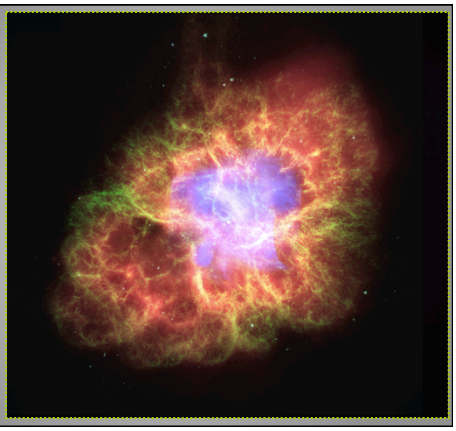


- PULSAR DISCOVERED IN 1967 FOUND TO BE VERY GRADUALLY SLOWING DOWN IN SPIN (PULSE RATE)
- PULSAR "ON" FOR SMALL FRACTION OF EACH CYCLE
- PULSE SHAPES IN PULSARS CAN BE INTRICATE

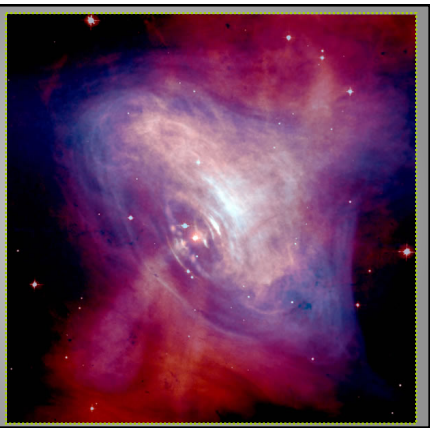
Crab Nebula SNR



Crab SNR composite Oct 06:
Spitzer (IR), Chandra (X), Hubble (V)

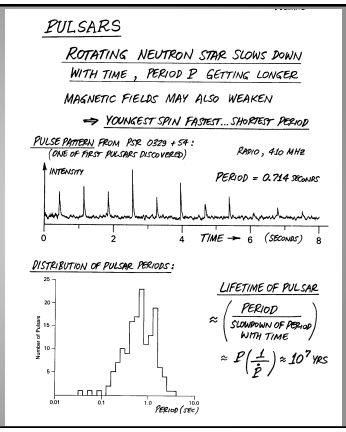


Chandra X-ray view of Crab center

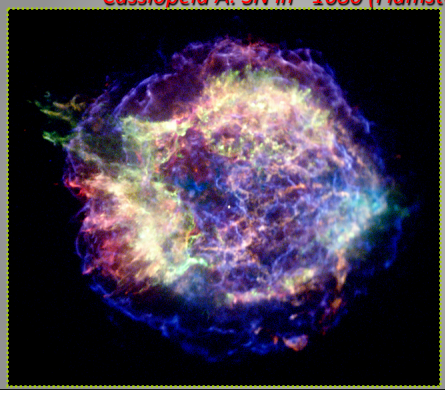


Gradual slowing down of pulsar rotation

Energy emitted in pulses comes from rotational kinetic energy



Cassiopeia A: SN in ~1680 (Flamsteed)



Youngest SNR in MW (Chandra X-ray image) synchrotron emission

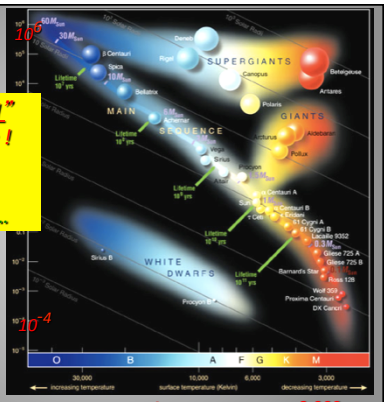
Neutron star at center

Cass A: Viewed with Spitzer IR

"Stellar graveyard" is very much alive !

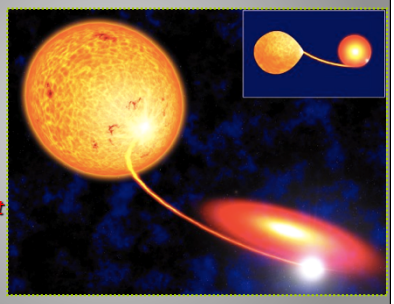
Mass transfer in binaries adds jazz...

white dwarfs, neutron stars or black holes == all can play !



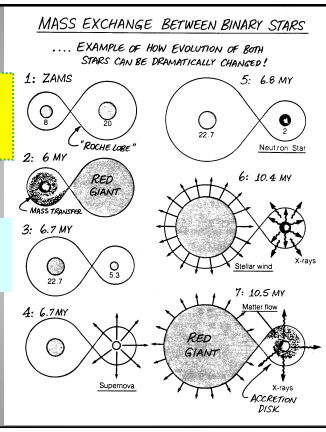
"Compact Companions" in Binary Systems

- Mass transfer from red giant companion spirals onto accretion disk
- Inner parts become VERY hot -- glow in UV, X-rays



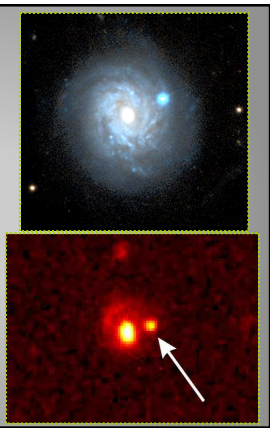
Stages in mass exchange in binary system

Here consider two massive stars == clock runs fast



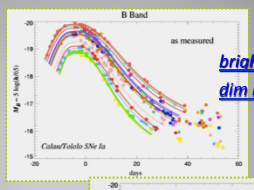
SUPERNOVAE in Other Galaxies

- Bright enough to be seen as sudden, bright point in other galaxies
- 1 per 100 years per galaxy means that if you monitor 100 galaxies, see ~ 1 SN per year)
- If monitor a million galaxies, likely to find 30+ new ones each night!
- In overall universe, one SN goes off every second



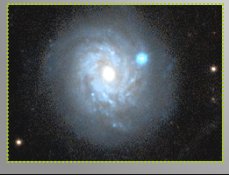
White dwarf supernovae

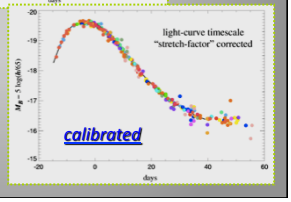
- Carbon fusion explosion: mass transfer in binary takes white dwarf 'over the edge'
- Roughly same amount of energy released (calibrate)



brighter SN

dim more slowly!

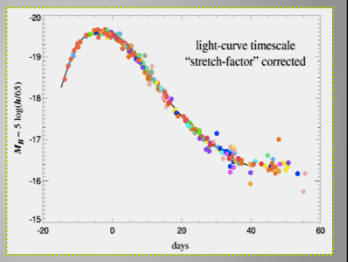




calibrated

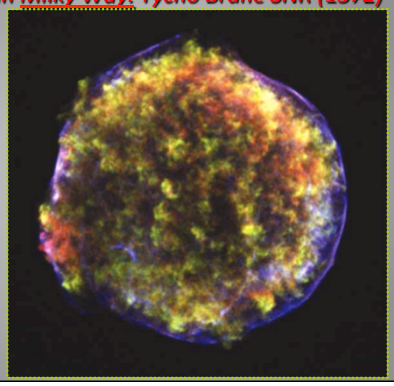
Practical difficulty: White dwarf SN

- Need to catch them within a day or two of the explosion
- Need to monitor thousands of galaxies to catch a few per year → galaxy clusters are useful
- Need spectroscopic follow-up to identify SN type and redshift



Major surveys underway or planned:
Palomar Transient Factory (PTF), PanSTARRS, LSST ...

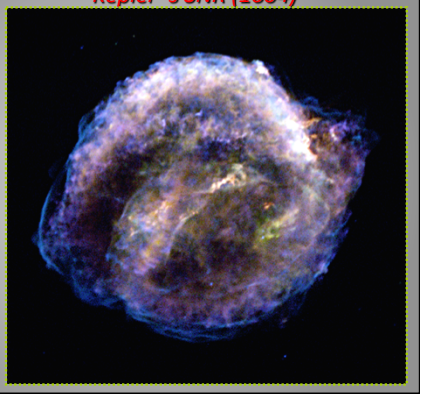
In Milky Way: Tycho Brahe SNR (1572)



Chandra
X-ray

20 ly across

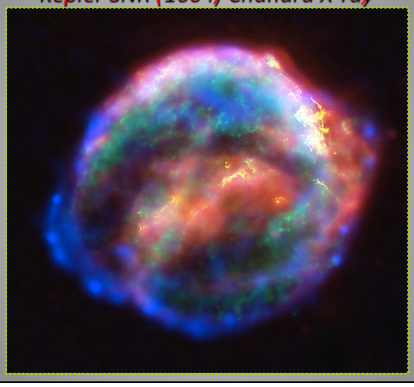
Kepler's SNR (1604)



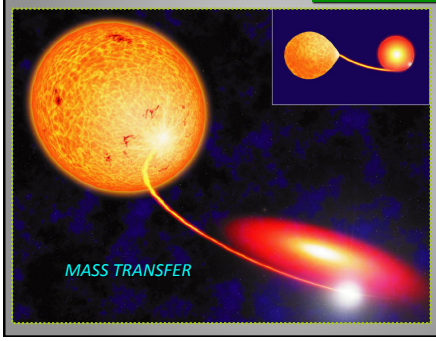
Chandra
X-ray image
red: oxygen
yellow: iron
blue: shock

"prompt"
Type Ia SN

Kepler SNR (1604) Chandra X-ray



Since white dwarfs in evolving binary systems come "alive" – what about neutron stars ?



Binary WD:
Hot accretion disks, novae, supernovae

Neutron star:
Radiation with more vigor, no SN

On to the Sun in Lecture 3
with Mark Miesch from HAO