Reading: Chapter 22: 22.1, 22.4-22.5, Chapter 23, through 23.5
Next 2 Lectures "live" - tune in on WebEx. Videos will be available later those days
Recitation Exercise: **Web-based reading available soon,** questions due in recitation 10/14
EXAM 2: Wednesday, October 21

Last time: **How stars form**

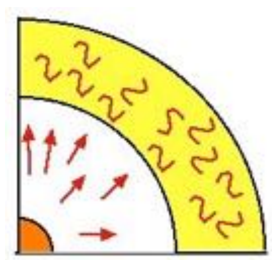
- Clues from observations - planets, young stars, and the ISM in the IR
- Gravity (somehow) overwhelms pressure, causing clouds to collapse
- Young stars shine via gravity, then finally ignite hydrogen
- Pre-main sequence stars are accompanied by disks, forming planets

Today: **main sequence to Red Giant to white dwarfs, supernova, & neutron stars**

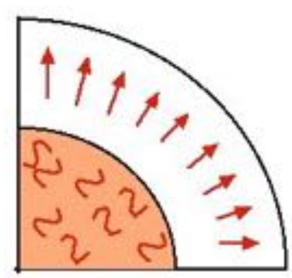
- Main sequence stars differ in their internal structure and their fates
- After hydrogen runs out, new energy sources are needed
- Fusion of heavier elements needs higher temperatures
- After helium burning comes a long slow death as a white dwarf if not massive enough
- massive stars - Supernova explosion! Neutron star!

On the main sequence...

- **Low mass stars** (below 1.5-2.0 M_{sun})
  - convection in outer layers
  - radiative transport in core
  - energy generation by proton-proton chain

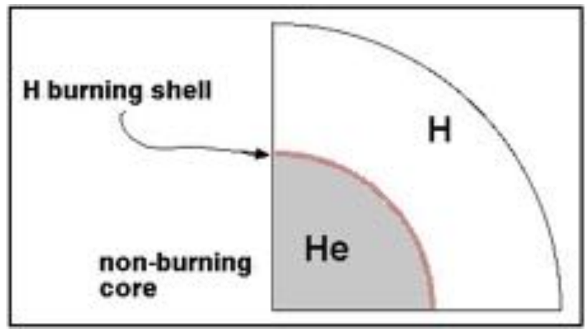


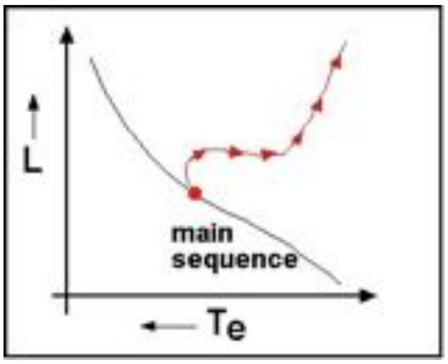
- **High mass stars** (above 1.5 - 2.0 M_{sun})
  - radiative outer layers
  - convection in nuclear burning core
  - H fusion via CNO cycle
    - C, N as catalyst for H fusion
    - active at higher T than p-p



... and off - the *road to the Red Giant!*

- **core hydrogen exhaustion**
  - pure He in core
  - H burns in shell
  - He core contracts
  - H envelope expands





Star moves off MS towards the Red Giant Branch

Helium Ignition

- eventually, contracting core reaches 10^8 K
- He fuses into carbon and oxygen
- the Triple Alpha Process

^{4}He + ^{4}He → ^{8}Be + photon

then immediately:

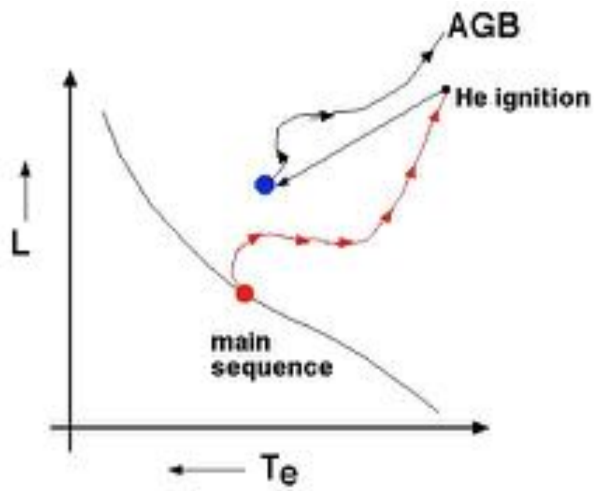
^{8}Be + ^{4}He → ^{12}C + photon (+^{4}He → ^{16}O+photon)

- **He** burning is 10% as efficient as **H** burning
- He burning at higher Luminosity than MS
- He burning phase ~ 10-100 x shorter than MS lifetime

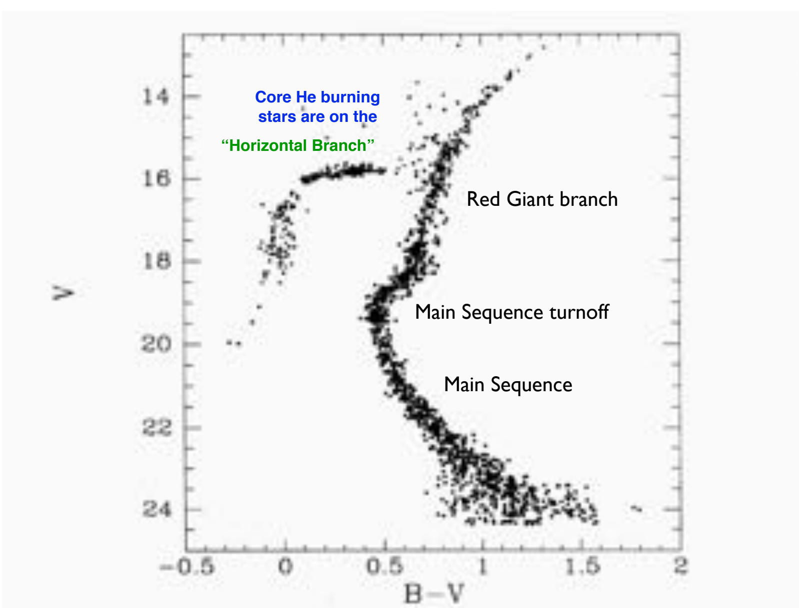
- **M < 2 M$_{sun}$**: **Helium core flash**
  - dense core at helium ignition
  - degeneracy pressure takes over, independent of T
  - thermonuclear runaway
- **M > 2 M$_{sun}$**: "quiet" helium ignition

Helium Exhaustion
- or -
Return to the Land of the Giants

- He shell outside C/O core
- H-rich outer shell
- Nuclear burning between shells
- Star returns to the giant region as an **asymptotic giant branch star**

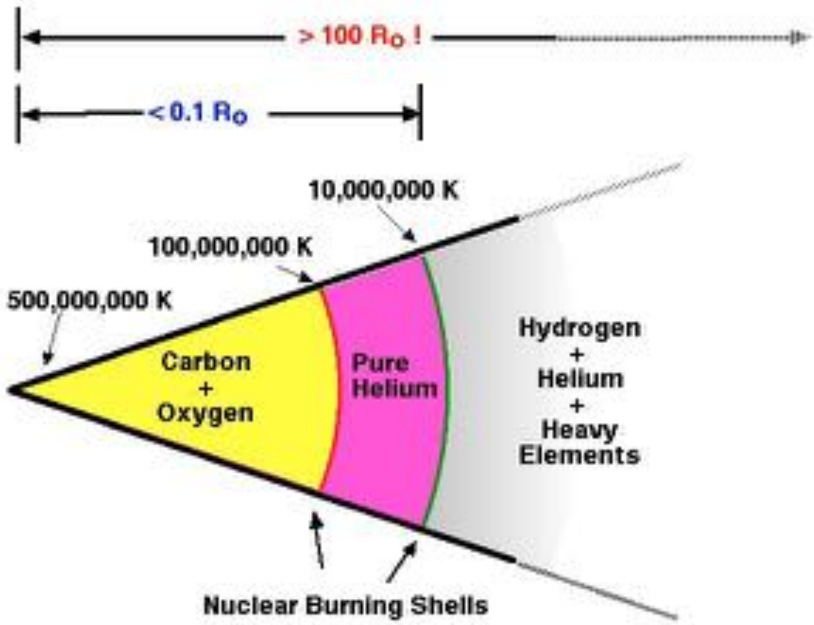


Helium core burning stars



Globular Cluster M15

Structure of a "Asymptotic Giant Branch" (AGB) Star

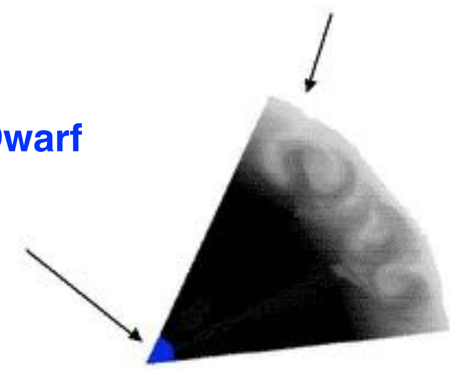


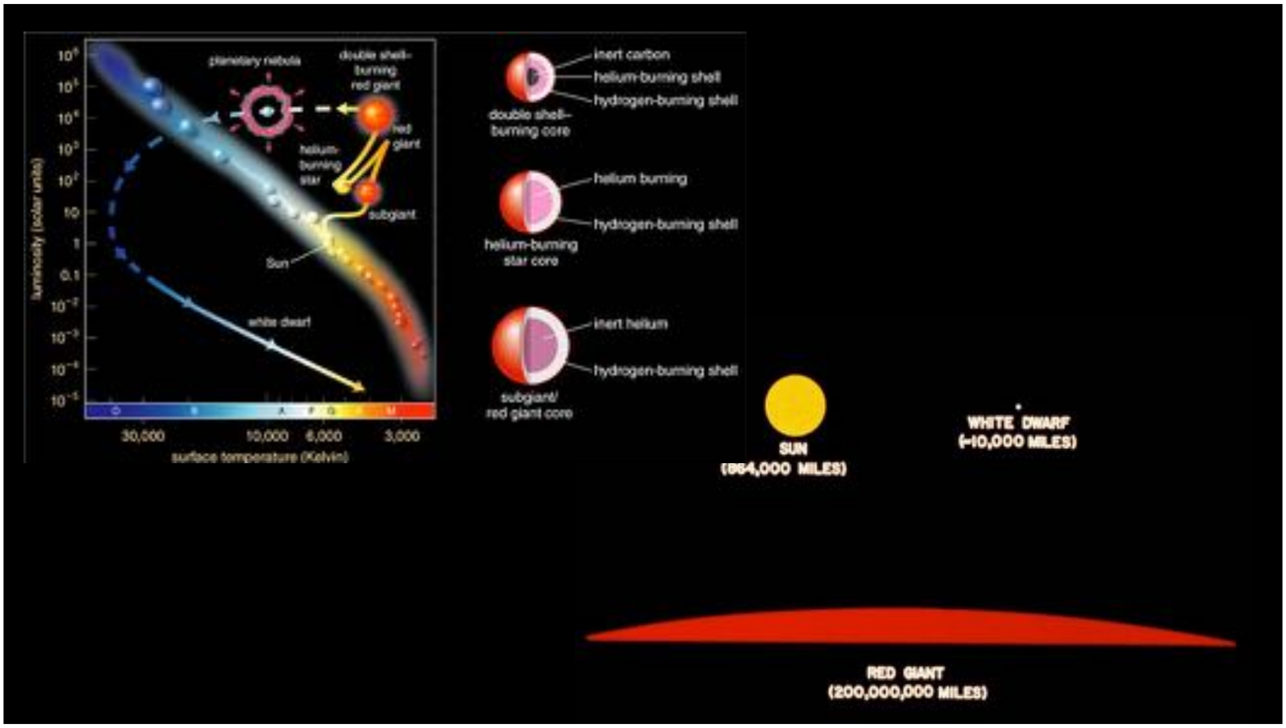
$M < 8\ M_{sun}$: C/O core too cool to ignite

eventually, in a quick and gentle puff...

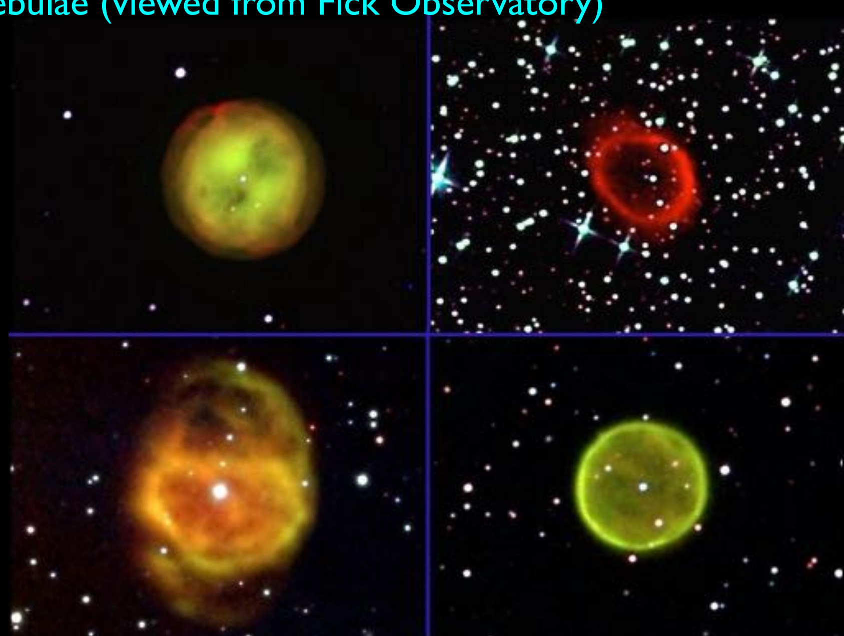
- AGB envelope becomes a **Planetary Nebula**

- AGB core becomes a **White Dwarf**
  - **$M \sim 0.6\ M_o$**
  - **R ~ size of Earth**
  - **$T_{surf} \sim 100{,}000$ K**
  - **Density ~ 100,000 grams/cm^3**





Planetary Nebulae (viewed from Fick Observatory)

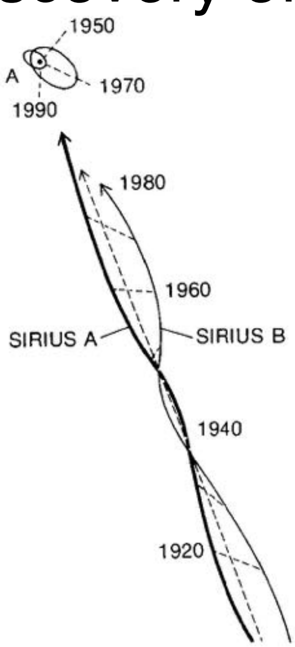


The largest PN in the Galaxy: RX J2117.1

Discovered at ISU's Fick Observatory

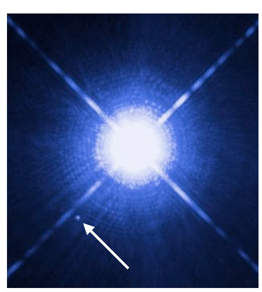
15 light years across!

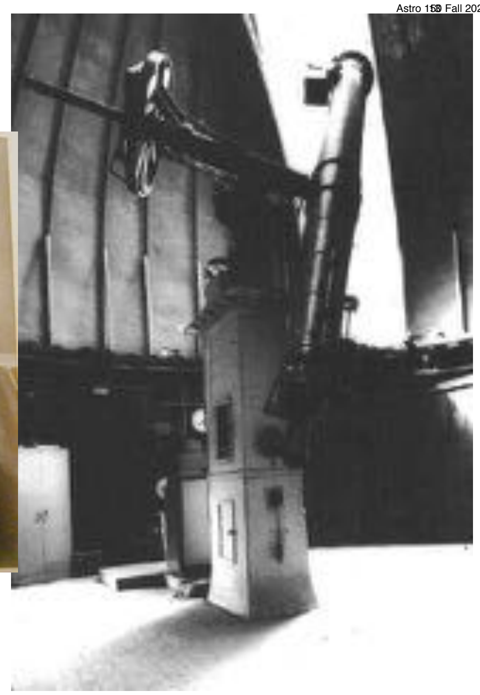
Discovery of white dwarfs



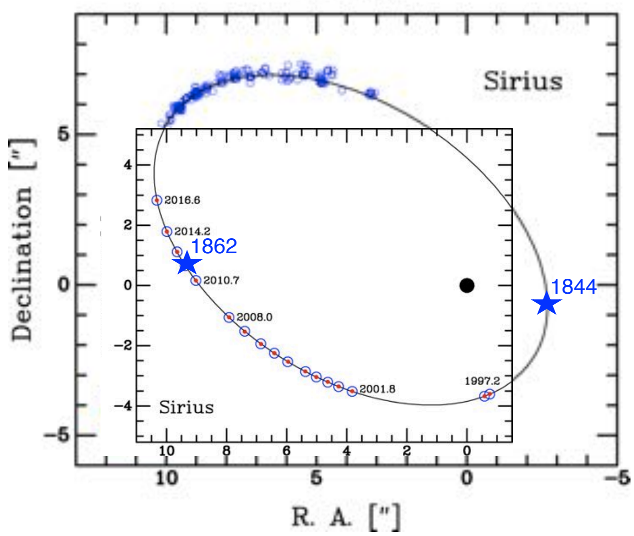
1844: Bessel
discovers a tiny wobble in the proper motion of Sirius caused by a mysteriously invisible ~ 1 M_{sun} star in orbit around it

1862: Alvan Clark
finally discovered the companion using his new 18" refractor. It was the least luminous and tiniest star ever seen…





Sirius - a shorter-period visual binary (Bond et al. 2017)



Sirius “B”

- Mass = 1.0 M_{sun}
- Luminosity = 0.002 L_{sun}
- Temperature = 9000 K

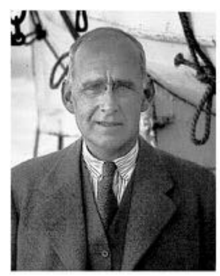
$$\frac{L}{L_{sun}} = \left(\frac{R}{R_{sun}}\right)^2 \left(\frac{T}{T_{sun}}\right)^4$$

so, R/R_{sun} = 0.018 = R_{Earth}

Sirius B: A star with the mass of the Sun
but
collapsed to the size of Earth

avg. density = 200,000 g/cc
1 teaspoon ~ Gary Sanchez + Aaron Judge !

Gravity at surface = 100,000 x Earth



- 1920s: Eddington (again)
  - normal gas pressure can never balance gravity at such high pressures
  - electrons would be forced INTO nuclei !?#$%^&

- 1930s: Subramanian Chandrasekhar
  - a **quantum mechanics** effect, **electron degeneracy**, supports WDs
  - but **only if M < 1.4 M_{sun} (relativity)**
  - **1983 Nobel Prize in Physics**

Ultimate fate of White Dwarfs

- fade and cool as residual heat is lost
- ... into the stellar graveyard
- time to cool to 5,000K is over 10 billion years
- as it cools, the C/O core CRYSTALLIZES

"Twinkle, twinkle, little star,
How I wonder what you are!
Up above the world so high,
Like a *diamond* in the sky!"
Jane Taylor (1783-1824)

- crystalline carbon is DIAMOND

THE SUNDAY TIMES

ABSOLUTELY FRANK | E-COLI MENACE | £50,000 PLAY WORLD CUP FANTASY FOOTBALL | ARSENAL'S TWIN PEAKS

17 MAY 1998 · THE SUNDAY TIMES

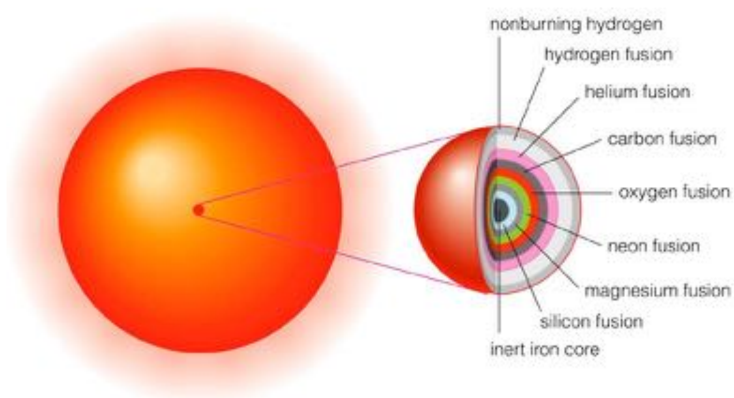
Astronomers find a diamond in the sky

by Trushar Barot

"A diamond the size of Earth would have a carat weight of 10 billion trillion trillion. The world's biggest diamond weighs 1,462 carats"

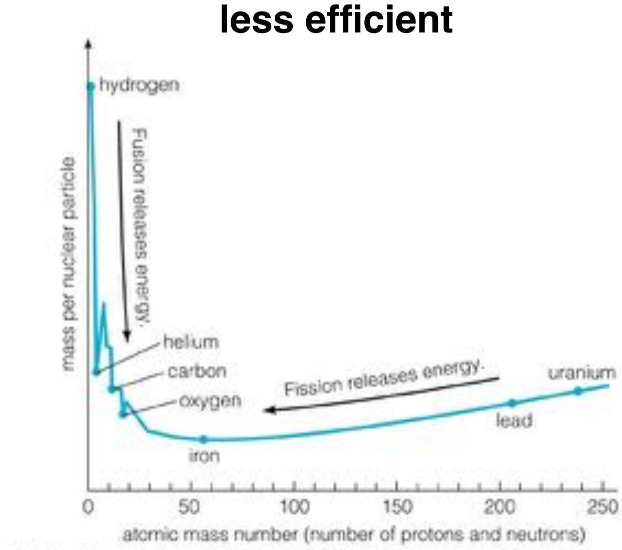
M > 8 M_{sun}: out with a ***BANG***

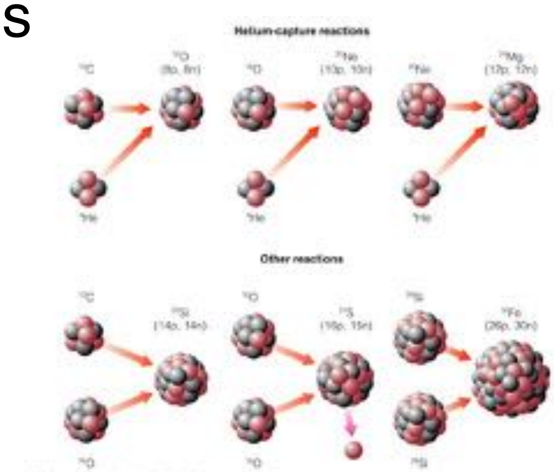
- can reach higher core temperatures
- C/O fusion for support ... all the way to IRON
- Onion Skin Structure



Advanced Burning Stages

Each successive stage is **less efficient**





So each stage takes a **shorter time** to complete

The Iron Catastrophe

- heavier elements → less energy per reaction
- Iron and beyond: fusion consumes energy
- burning iron accelerates collapse
- iron core undergoes runaway gravitational collapse
  - reaches high density and temperature
  - synthesis of elements heavier than Iron
  - neutron degeneracy sets in
  - core stiffens and "bounces"
  - shoves envelope away from star with a burst of energy

  ... all in a few SECONDS

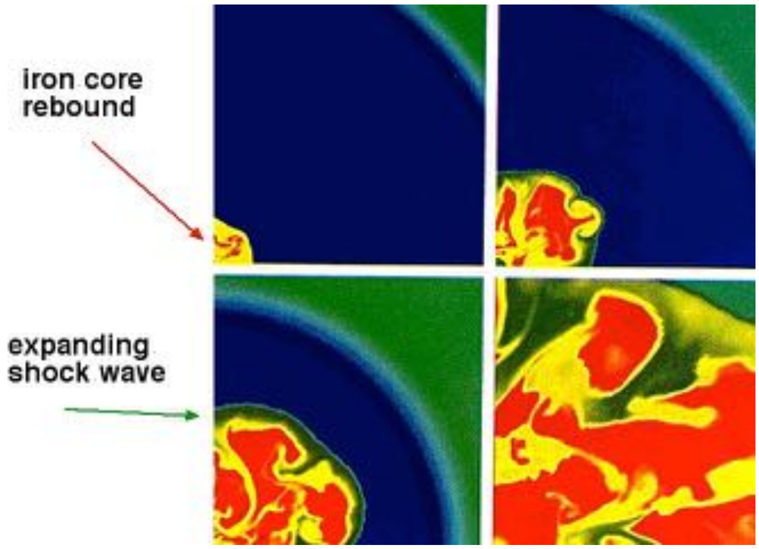
a..... SUPERNOVA

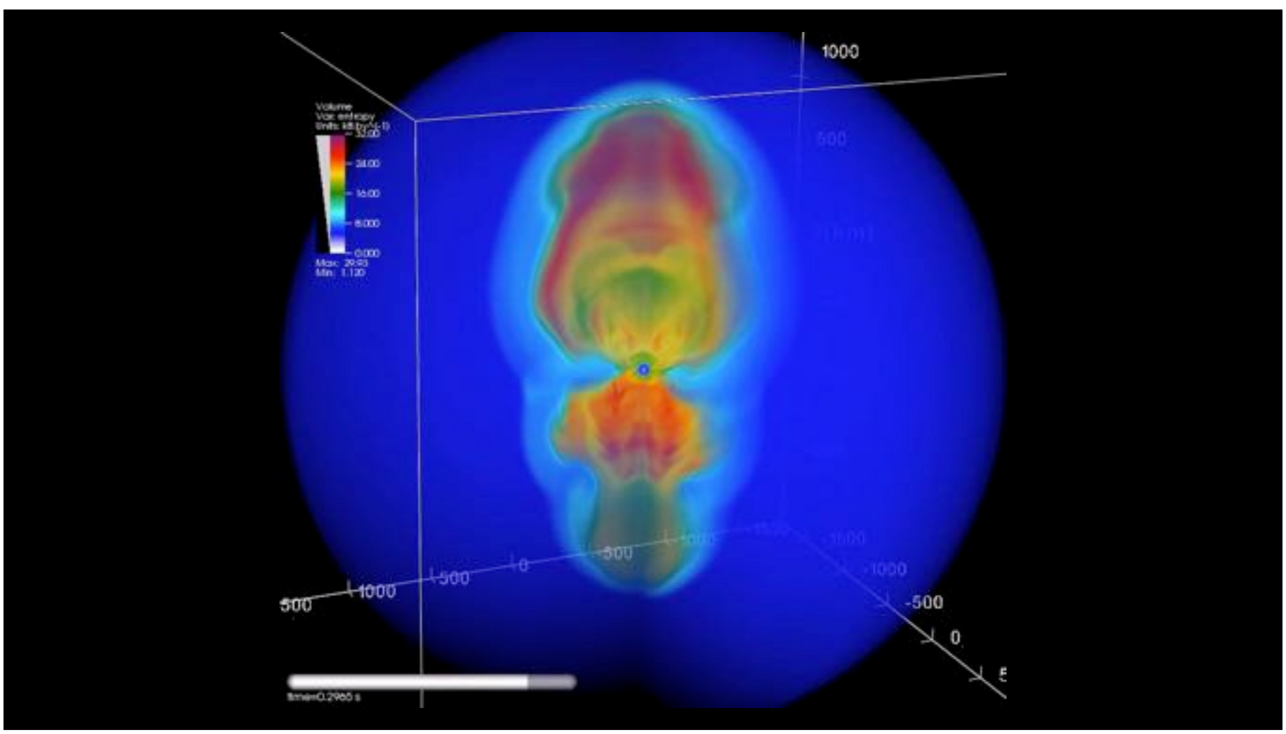
a cataclysmic stellar explosion

Backyard Supernova

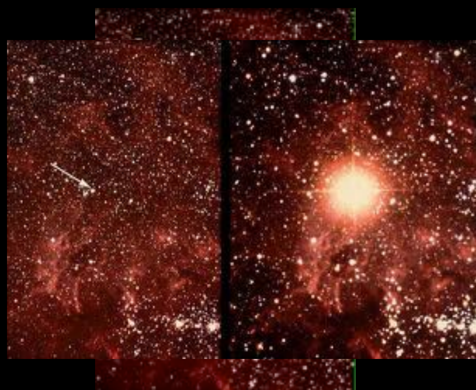
computer model of the first few moments of a Supernova

(i.e. Bethe et al, 1990)





SN 1987A in the Large Magellanic Cloud



Supernova in M71

SN in spiral galaxy NGC 2525

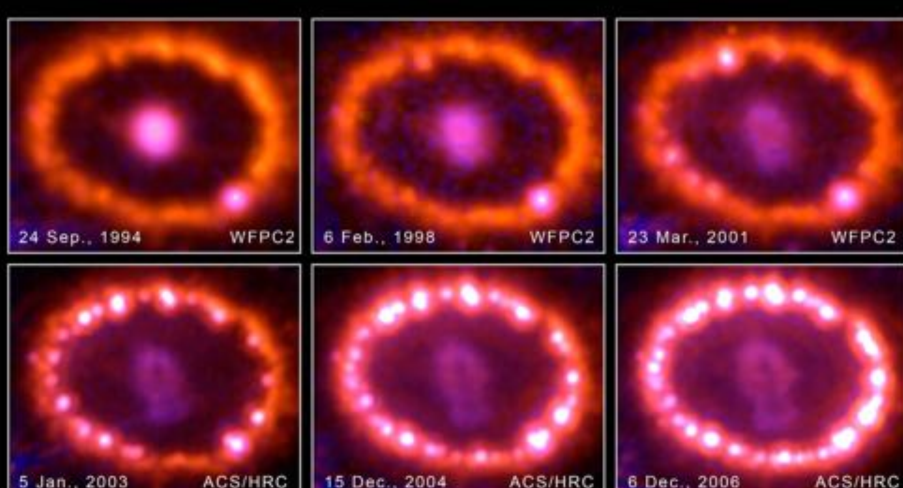
a *Supernova*: a star blown apart

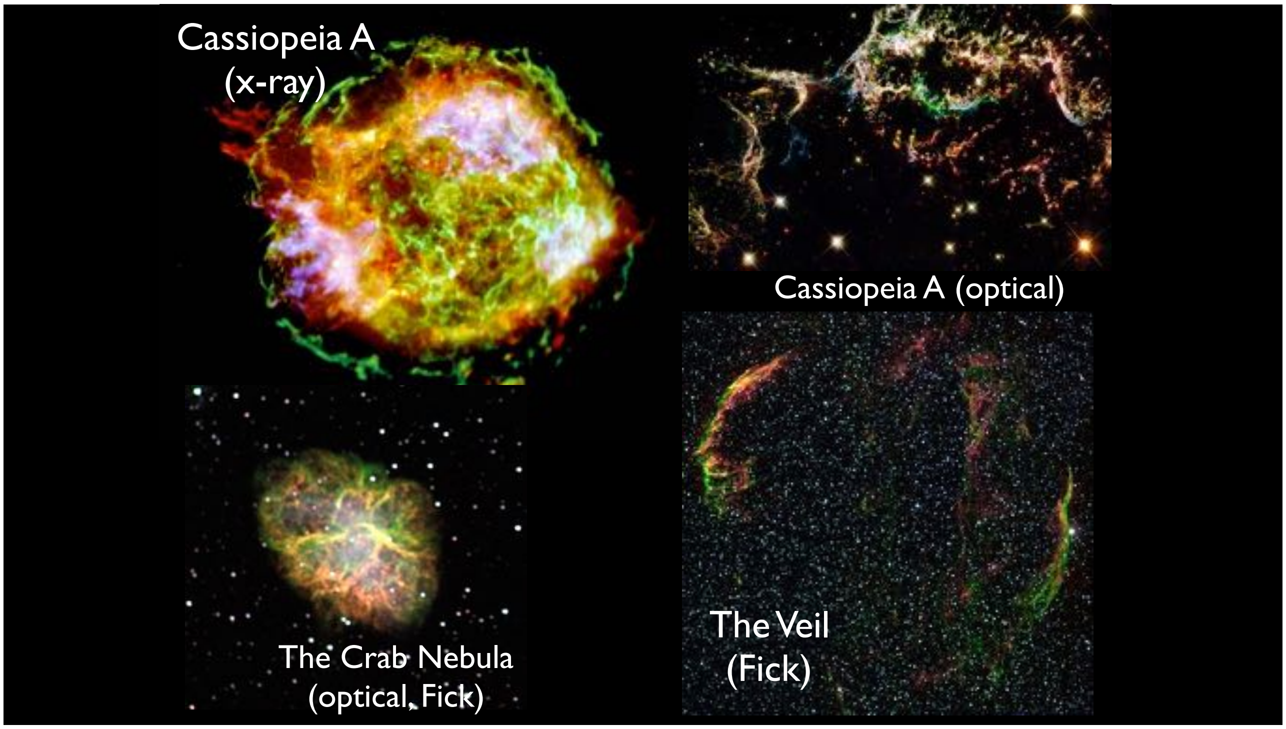
- can outshine an entire Galaxy for weeks
- produce heavy elements and neutrinos
- **in the supernova core**
    - high temperature and density
    - nucleosynthesis of heavy elements (Bethe et al. 1980s)

- **The only place in the Universe where elements heavier than IRON are made**

- Supernova Remnants
    - clouds of material ejected by SN
    - distribution of heavy elements into space
    - trigger for later star formation?

Supernova 1987a remnant




Cassiopeia A
(x-ray)
Cassiopeia A (optical)
The Crab Nebula
(optical, Fick)
The Veil
(Fick)

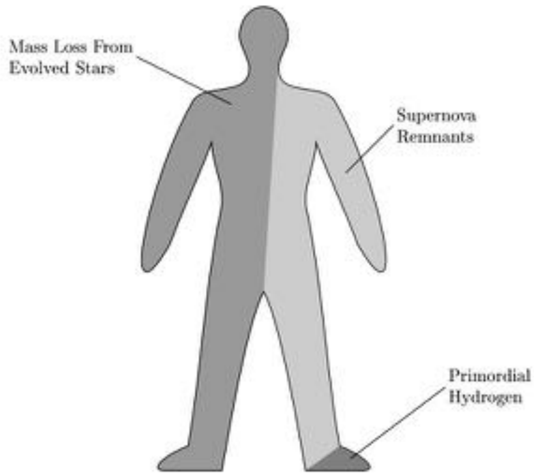
All matter heavier than carbon was once in the core of a star that exploded as a supernova

- including calcium in our teeth, gold in our jewelry, iron in our blood, copper in our coins...

"We are star dust
We are golden
And we've got to get ourselves
Back to the garden."

Joni Mitchell (*Woodstock*, 1969)

An Astrophysicist's View of the Human Body



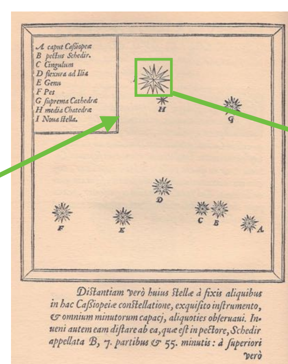
from Everett Lipman, UCSB Physics

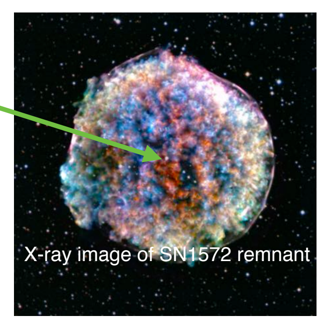
"Recent" supernovae

- 1987: Large Magellanic Cloud
- 1885: Andromeda

- 1604: Kepler's SN
- 1572: Tycho's SN

- 1054: the Crab Nebula progenitor





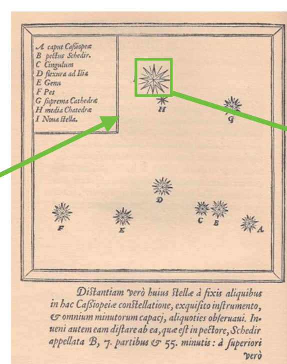
X-ray image of SN1572 remnant

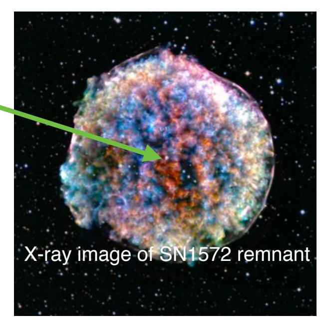
“Recent” supernovae

- 1987: Large Magellanic Cloud
- 1885: Andromeda

- 1604: Kepler’s SN
- 1572: Tycho’s SN

- 1054: the Crab Nebula progenitor

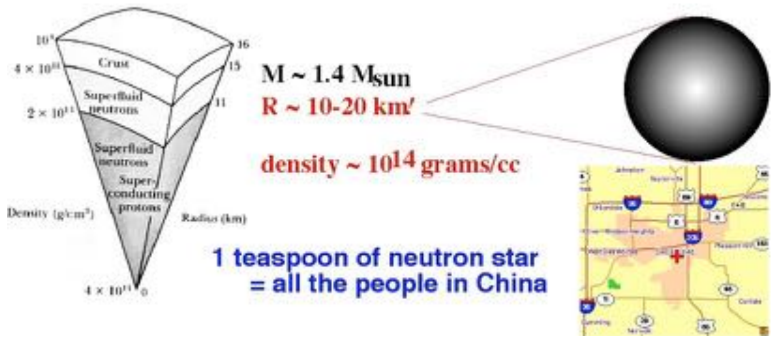




- **What’s Left?** a **Neutron Star** endpoint of stellar evolution for stars between 8 and ~25 M_{sun}

Neutron Stars

- $M_{core} > 1.4\ M_{sun}$ - collapse past WD
  - nuclei packed tightly together
  - protons absorb electrons; only neutrons left
  - collapse halted by neutron degeneracy pressure



- **How do you find something so small?**

Neutron Stars

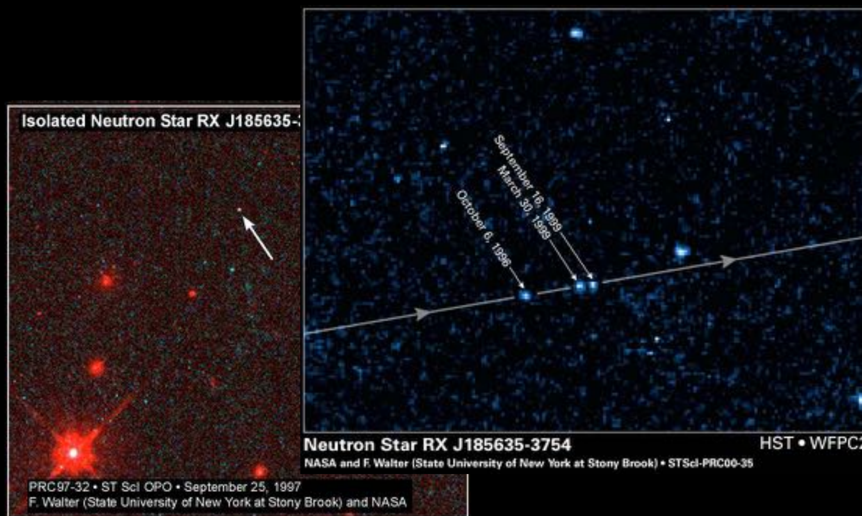
- Mass ~ $2.0\ M_{sun}$
- Radius ~ $0.00002\ R_{sun}$
- Temperature ~ 5×10^5 K

$$\frac{L}{L_{sun}} = \left(\frac{R}{R_{sun}}\right)^2 \left(\frac{T}{T_{sun}}\right)^4$$

so, L/L_{sun} ~ 0.001 - nearly all in X-ray

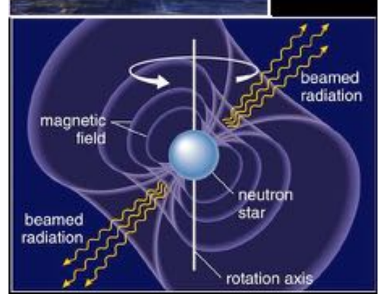
SMALL, DIM, and RARE: (end product of O, B star evolution) means:
- **closest is still pretty far away**
- **very unlikely to see in optical (or even X-ray)**
- **concentrated and extreme stars**

isolated neutron stars first



Discovery of Neutron Stars - Pulsars (1967)

- 1966-67: Tommy Gold (and Franco Pacini)
  - **why does the Crab nebula shine??**
    supernova leaves a rapidly rotating
    neutron star
  - neutron star has an
    intense magnetic field (10^{11} Gauss)
    for comparison:
    - **Earth magnetic field = 1/2 G (compass needle)**
    - **Strongest permanent magnet ~ 14,000 G**
    - **Strongest magnetic field produced ~ 4×10^5 G**
- light produced by
  motion of e^- in magnetic field
- light **energy** derived **from** NS **rotation**
- spin rate should **decrease** with time



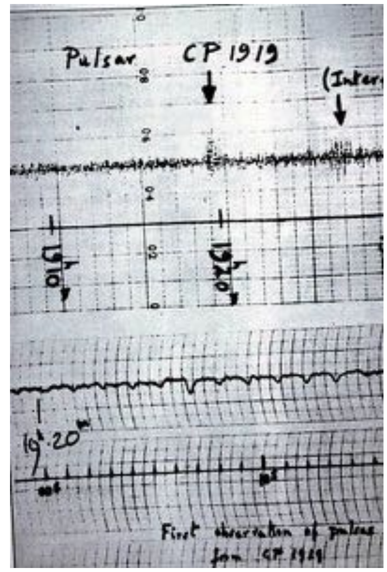
Discovery of Neutron Stars - Pulsars (1967)

- 1967: **S. Jocelyn Bell** discovers a radio signal:
  - **regularly pulsing**
  - **rapid**
    (once every 1.33 seconds)
  - **extraterrestrial**
  - aliens? LGM1, LGM2, ...
    - no. why not?
  - Neutron stars !

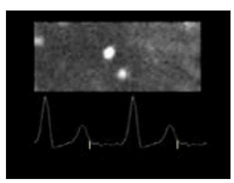
PSR 0329:
0.72 s

Vela:
0.089 s

1974 Nobel Prize to... Tony Hewish
(Bell's advisor ?!#@)



Pulsars - a new tool for astronomy and physics



Crab Pulsar
(0.033 s)

- **Binary Pulsars**:
  precise tests of general relativity (1993 Nobel, Hulse & Taylor)
- **Pulsars with Planets**
  timing "jitter" -> planet-sized companions (Alex Wolsczan)
- ***Millisecond* Pulsars**
  PSR 1937 (0.00167s)
  - fast pulsar, small dP/dt
  - recycled pulsars spun-up by companion (Don Backer)
  - should have companion - most do, many do not!
- **"Black Widow" Pulsars**
  pulsar blasts away its companion (Dan Stinebring)