

**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

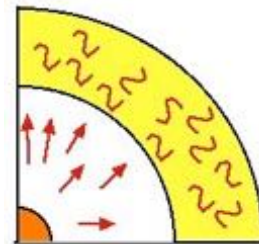
### Today: main sequence to Red Giant to white dwarfs, supernova, & neutron stars

- 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...

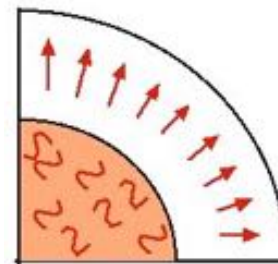
### • **Low mass stars** (below $1.5-2.0 M_{\text{sun}}$ )

- convection in outer layers
- radiative transport in core
- energy generation by proton-proton chain



### • **High mass stars** (above $1.5 - 2.0 M_{\text{sun}}$ )

- 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

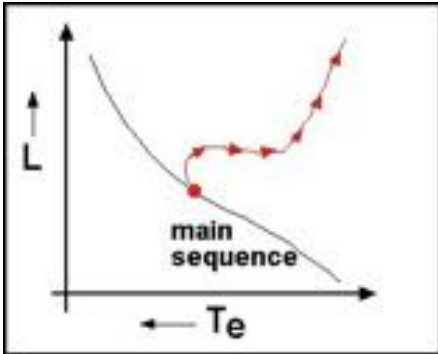
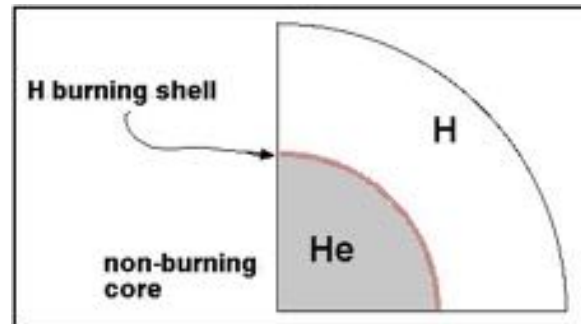


## ... and off - the *road to the Red Giant!*

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### • core hydrogen exhaustion

- pure He in core
- H burns in shell
- He core contracts
- H envelope expands



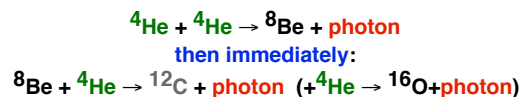
Star moves off MS towards the Red Giant Branch



## Helium Ignition

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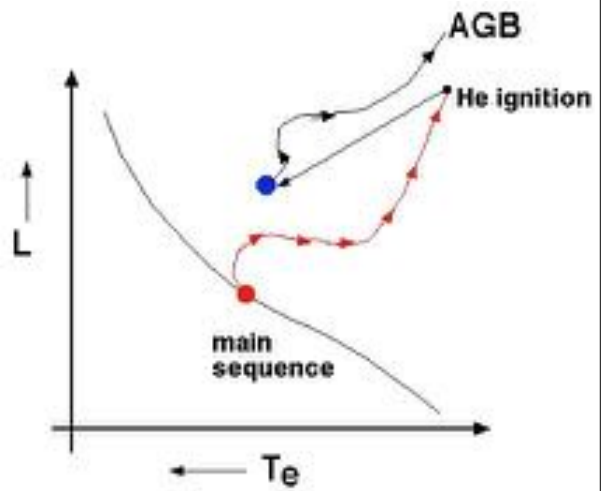
- eventually, contracting core reaches  $10^8$  K
- He fuses into carbon and oxygen
- the **Triple Alpha Process**



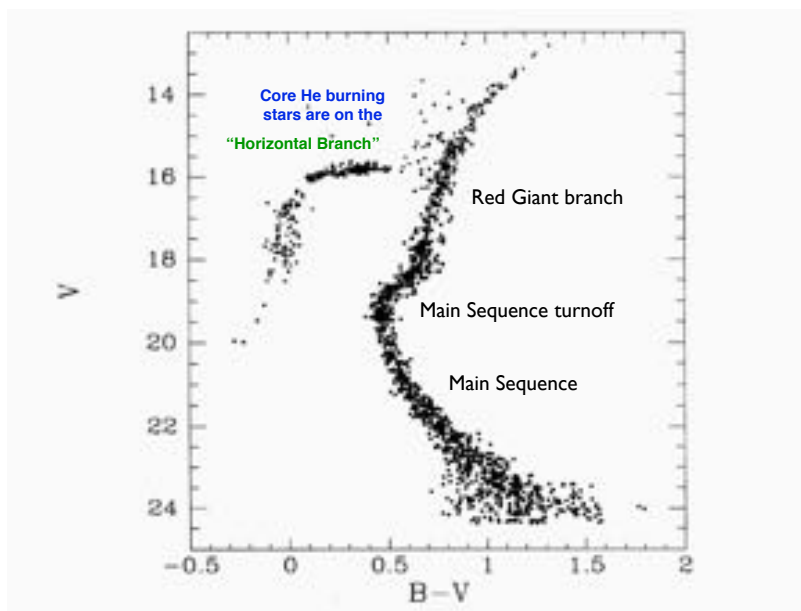
- He burning is 10% as efficient as H burning
- He burning at higher Luminosity than MS
- He burning phase  $\sim 10$ - $100$  x shorter than MS lifetime
- $M < 2 M_{\text{sun}}$ : **Helium core flash**
  - dense core at helium ignition
  - **degeneracy pressure** takes over, independent of T
  - **thermonuclear runaway**
- $M > 2 M_{\text{sun}}$ : “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**

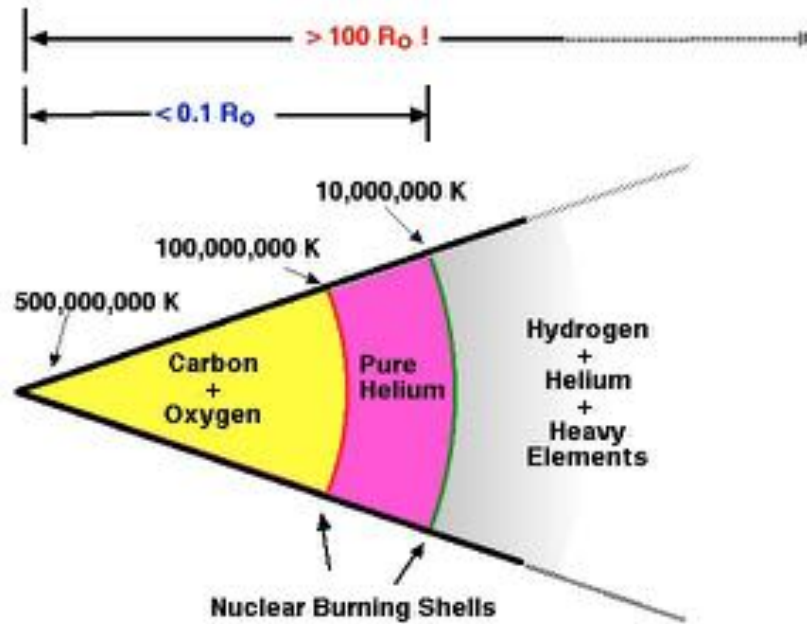


## Helium core burning stars



Globular Cluster  
M15

# Structure of a “Asymptotic Giant Branch” (AGB) Star



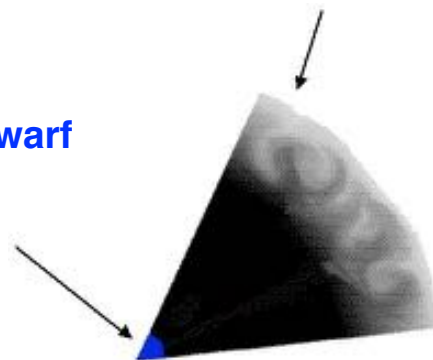
## $M < 8 M_{\text{sun}}$ : C/O core too cool to ignite eventually, in a quick and gentle puff...

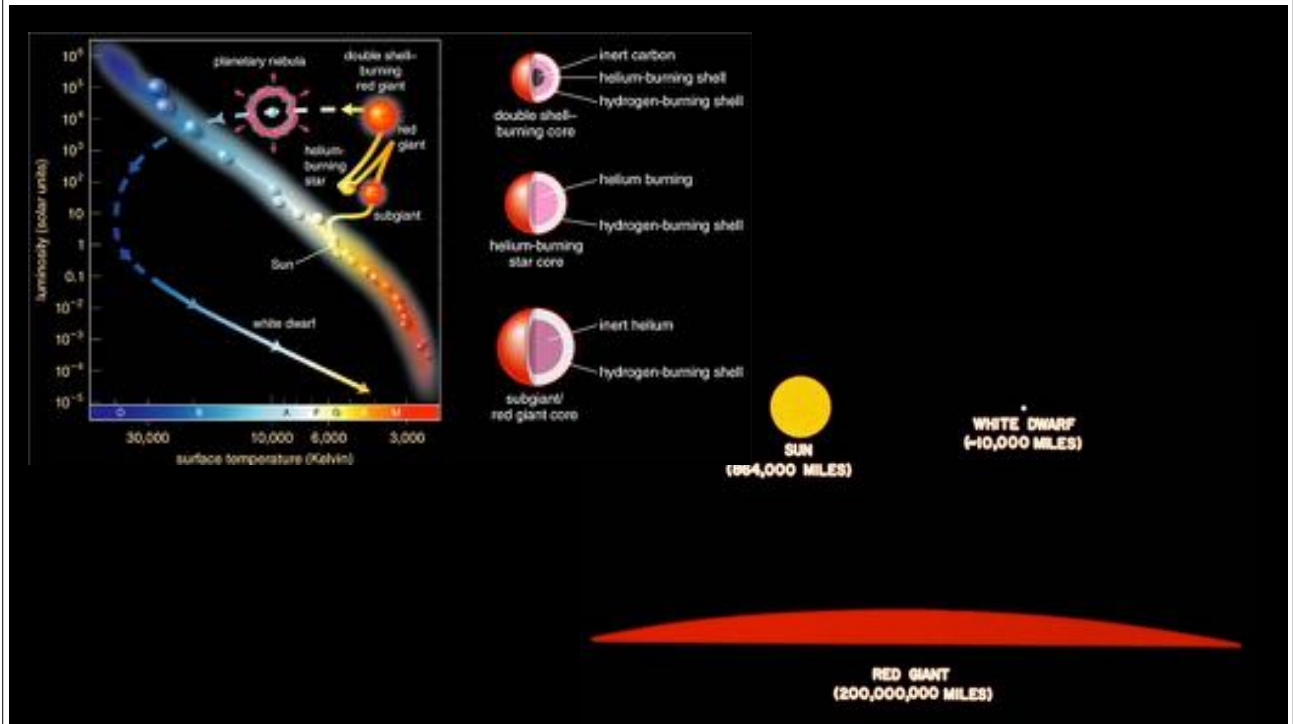
- AGB envelope becomes a **Planetary Nebula**

$M \sim 1-5 M_{\odot}$   
 $R \sim 2$  light years!  
 $T \sim 10,000$  K

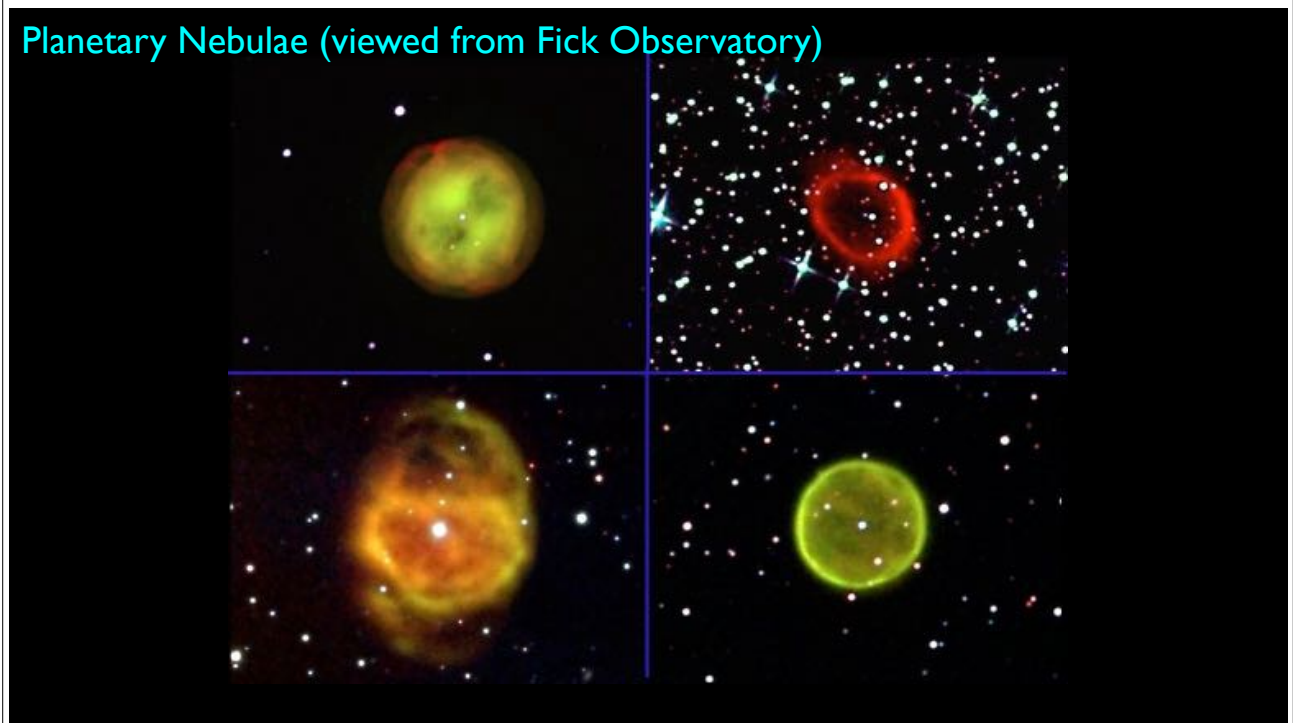
- AGB core becomes a **White Dwarf**

- $M \sim 0.6 M_{\odot}$
- $R \sim$  size of Earth
- $T_{\text{surf}} \sim 100,000$  K
- **Density  $\sim 100,000$  grams/cm<sup>3</sup>**





### Planetary Nebulae (viewed from Fick Observatory)



## The largest PN in the Galaxy: RX J2117.1

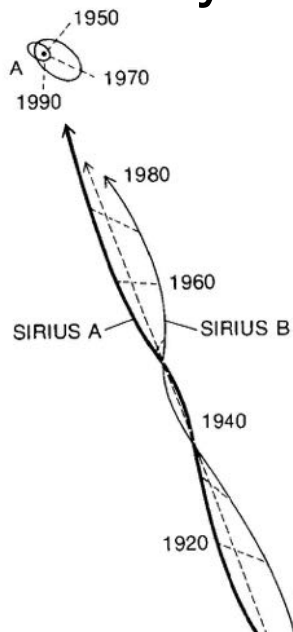


Discovered at ISU's  
Fick Observatory

15 light years  
across!

## Discovery of white dwarfs

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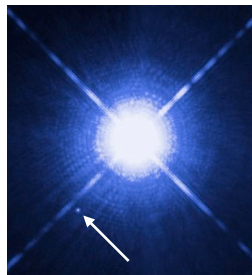


1844: Bessel

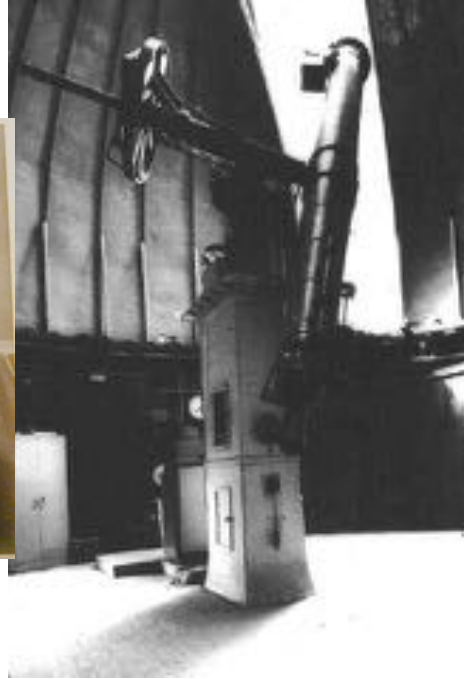
discovers a tiny wobble in the proper motion of Sirius caused by a **mysteriously invisible**  $\sim 1 M_{\text{sun}}$  star in orbit around it

1862: Alvan Clark

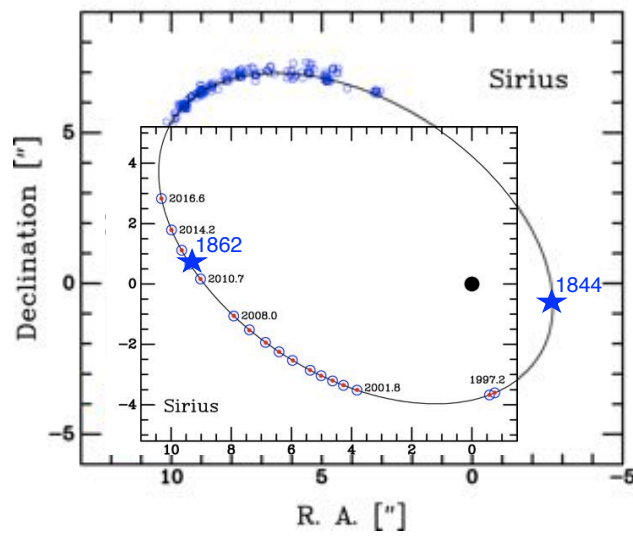
finally discovered the companion using his new 18" refractor. It was the **least luminous and tiniest star** ever seen...







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



## Sirius “B”

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

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

so,  $R/R_{\text{sun}} = 0.018 = R_{\text{Earth}}$

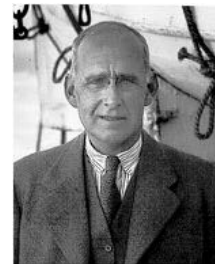
**Sirius B: A star with the mass of the Sun  
but  
collapsed to the size of Earth**



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  $M < 1.4 M_{\text{sun}}$  (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**



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**

ASTRONOMERS believe they have located the first star made of a solid diamond the size of Earth. Roughly visible in the constellation Centaurus and at 17 light years from Earth—a star's throw in galactic distance—is this one of the closest stars in the Milky Way.

It is known only by the unassuming designation of BPM37093, although its status is to be confirmed by the astronomer, who has presented evidence of its gem-like qualities.

The 30-year astronomers have wondered whether diamonds could be present under the unusual conditions of a white dwarf, where a star's nuclear fuel has run out and its residual ash of carbon and oxygen continues to smoulder at a modest 12,000°C.

Now they think they are on the verge of a discovery that could make this star every girl's best friend. "We think BPM37093 is primarily made up of carbon and oxygen in a crystallized state," said Steve Kawaler of Iowa State University. "That would make it a diamond with a blue-green tint. This star could be a diamond in the sky."

The intense gravity of a white dwarf creates the enormous pressures that enable carbon to exist as a crystal. Kawaler said: "A white dwarf is a very, very dense star. One teaspoon of matter from these stars weighs a ton."

A diamond the size of Earth would give BPM37093 a carat weight of 10 billion trillion trillion, according to the lower limit of the age of the Milky Way and, in turn, extend the estimated age of the universe," said Kawaler.

The Iowa researchers used the Hubble Space telescope to examine the star, reaching up another remarkable success for astronomy. Earlier this year, scientists announced they had used the telescope to observe the first planet in orbit around a

possibility of life on planets around the diamond star. Ralf Wijn, an astronomer at the University of Amsterdam in the Netherlands, said: "The formation of an old white dwarf star gives out a lot less energy than in stars, so it would be difficult for life to exist. The more likely places to look for life are close to stars, such as Europa or Titan, the moons orbiting Jupiter and Saturn."

The diamond star's big density and temperature means human expeditions will not be possible, even if it could be reached. No human could survive the gravitational pressure, said Martin Barstow, a professor at Liverpool University and co-astronomer of the White Dwarf Telescope project, a network of astronomers. "Everything would be fine, except you would not have resources like houses or buildings. Everything would be compressed out of all reason. The atmosphere would be five or six kilometres thick like an impossibly thick blanket," he said.

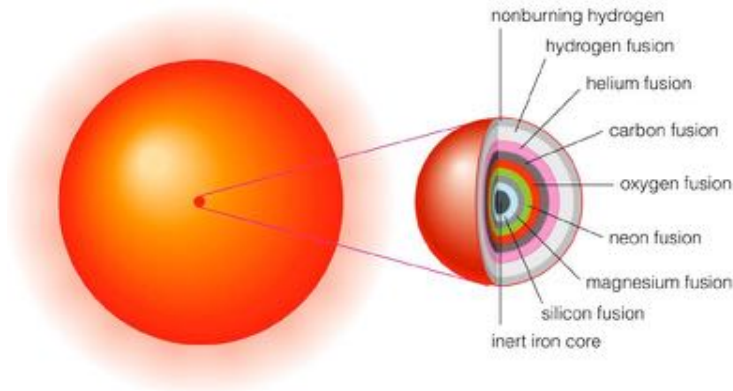
Could there be planets of gold and silver out there somewhere? Barstow believes not. "It's only located carbon in the most abundant material that gets produced in these stars."

**A GEM IN THE HEAVENS**

HOW A STAR IS BORN AND DIES

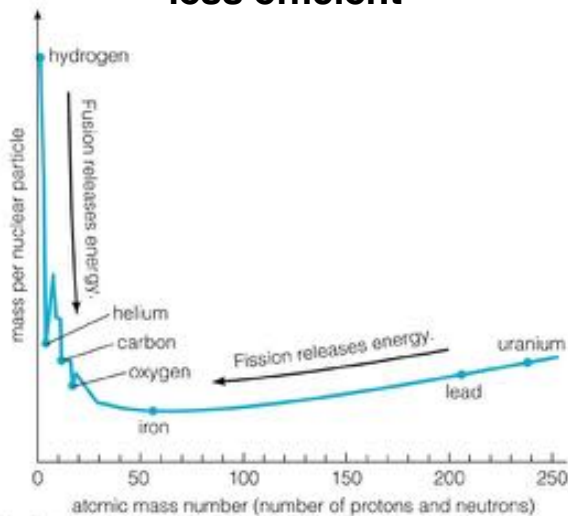
# M > 8 M<sub>sun</sub>: out with a **BANG**

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

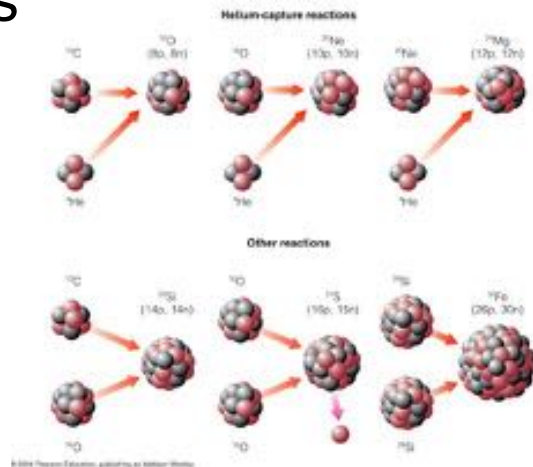


## Advanced Burning Stages

Each successive stage is **less efficient**



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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

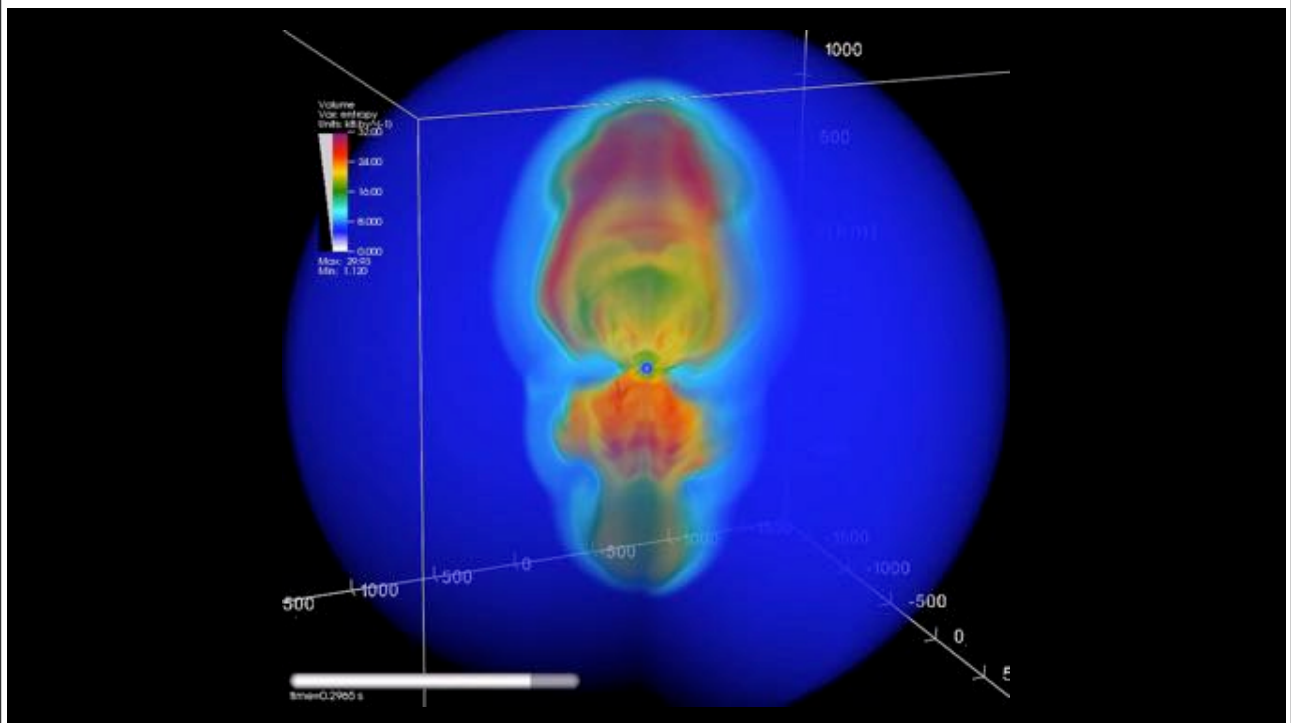
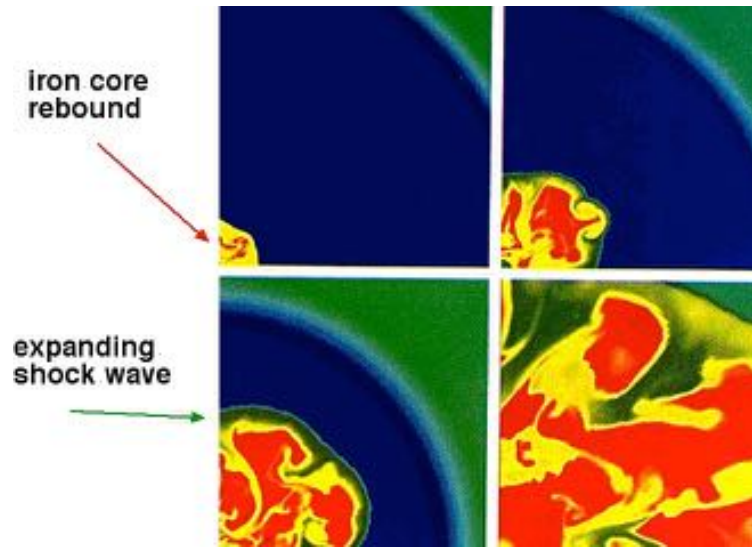
... all in a few **SECONDS**

a... **SUPERNOVA**  
a **cataclysmic** stellar explosion

# Backyard Supernova



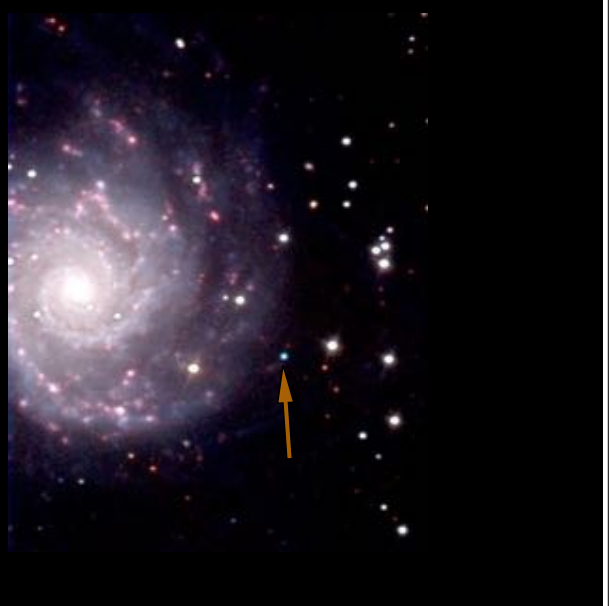
# computer model of the first few moments of a Supernova (i.e. Bethe et al, 1990)



SN 1987A in the  
Large Magellanic  
Cloud



Supernova in M71



## SN in spiral galaxy NGC 2525

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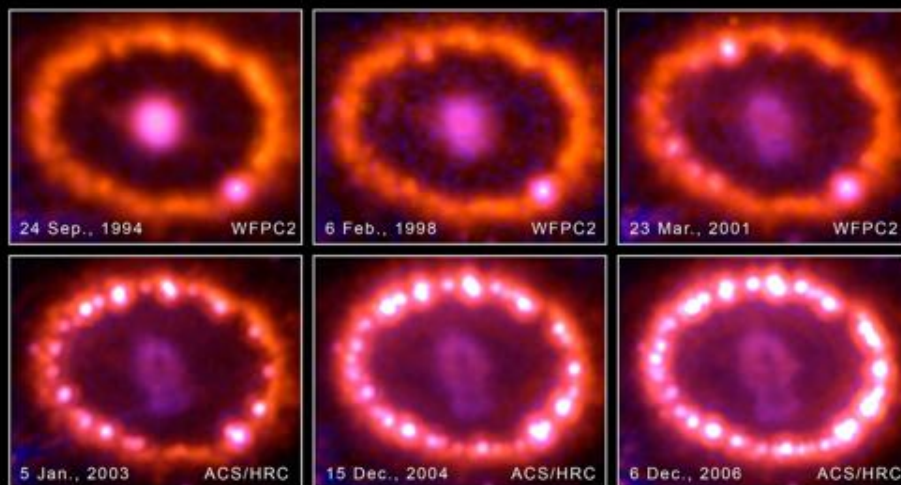




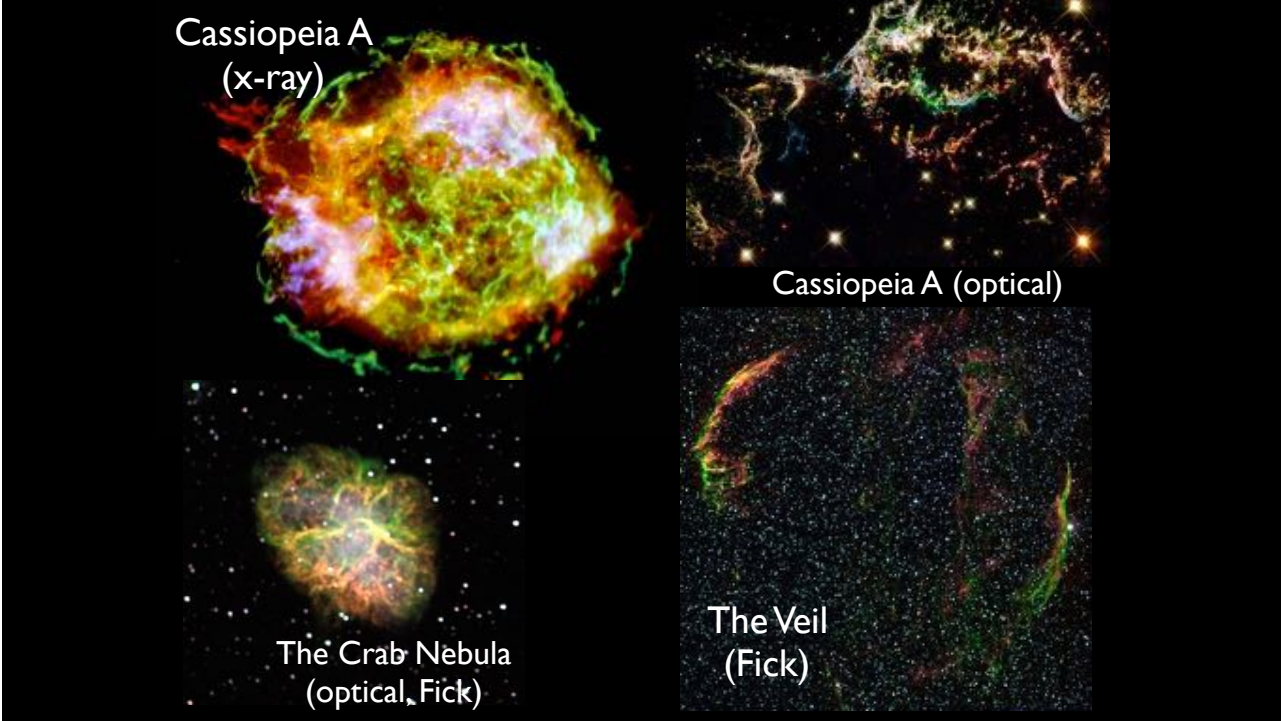
## a **Supernova**: a star blown apart

- 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





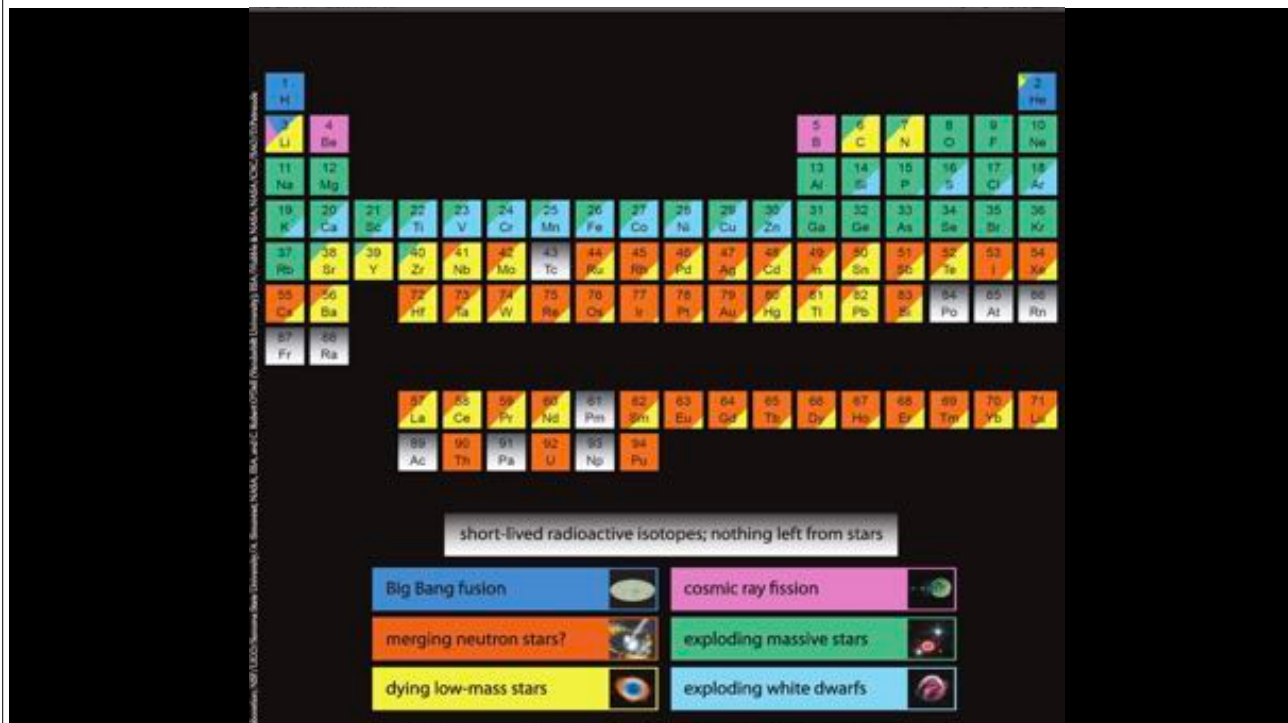


## All matter heavier than carbon was once in the core of a star that exploded as a supernova

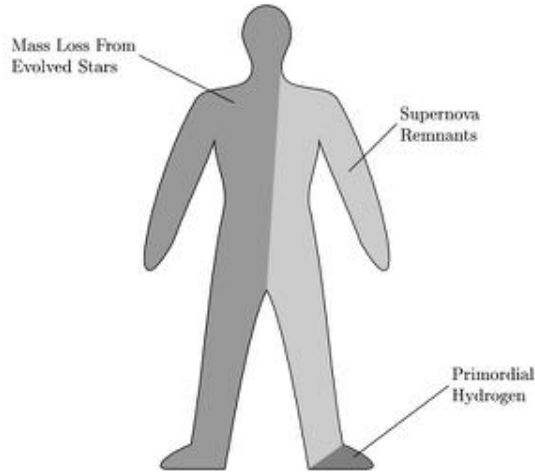
- including calcium in our teeth, gold in our jewelry, iron in our blood, copper in our coins...

“We are star dust  
 We are golden  
 And we’ve got to get ourselves  
 Back to the garden.”

Joni Mitchell (*Woodstock*, 1969)



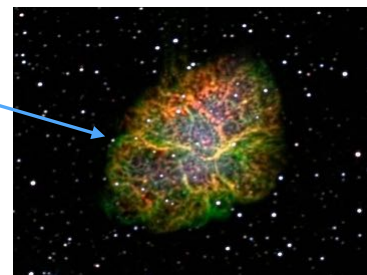
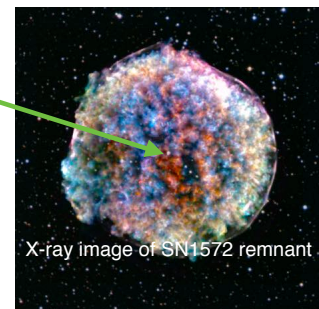
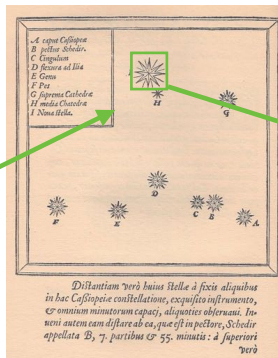
# An Astrophysicist's View of the Human Body



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

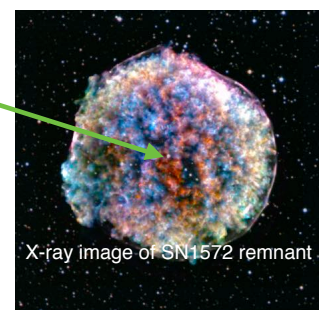
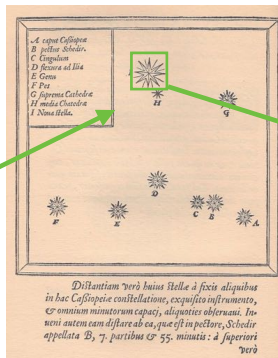




## “Recent” supernovae

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- **1987**: Large Magellanic Cloud
- **1885**: Andromeda
- **1604**: Kepler’s SN
- **1572**: Tycho’s SN
- **1054**: the Crab Nebula progenitor



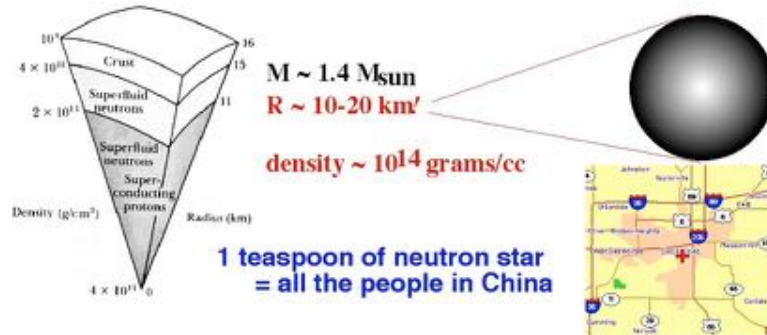
- **What’s Left?** a **Neutron Star**  
endpoint of stellar evolution for stars  
between 8 and  $\sim 25 M_{\text{sun}}$





# Neutron Stars

- $M_{\text{core}} > 1.4 M_{\text{sun}}$  - 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  $\sim 2.0 M_{\text{sun}}$
- Radius  $\sim 0.00002 R_{\text{sun}}$
- Temperature  $\sim 5 \times 10^5 \text{ K}$

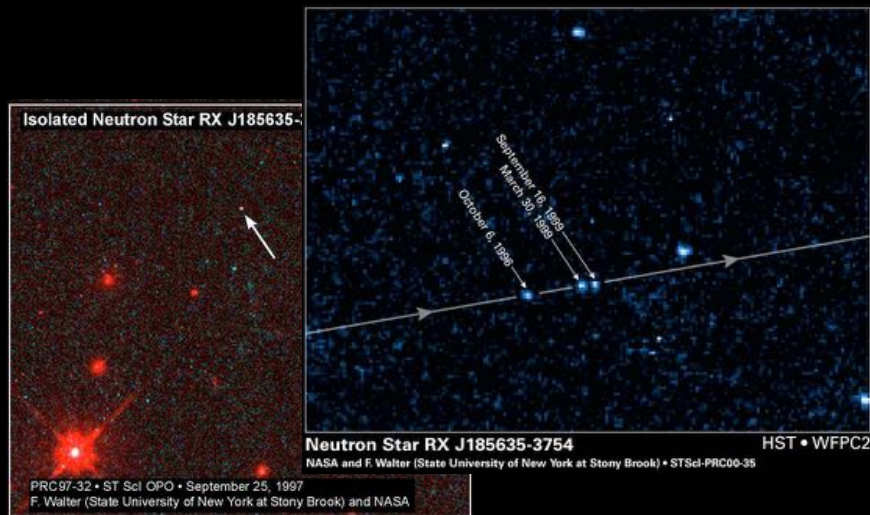
$$\frac{L}{L_{\text{sun}}} = \left(\frac{R}{R_{\text{sun}}}\right)^2 \left(\frac{T}{T_{\text{sun}}}\right)^4$$

so,  $L/L_{\text{sun}} \sim 0.001$  - 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

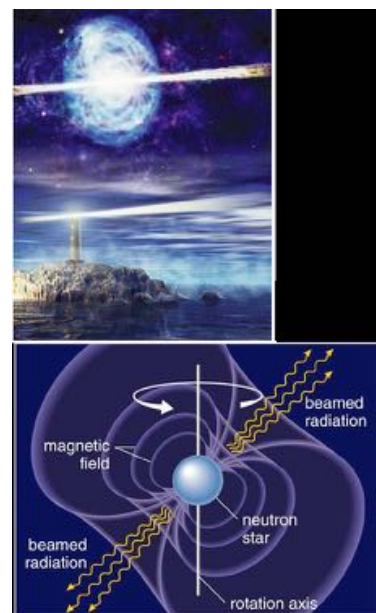


## Discovery of Neutron Stars - Pulsars (1967)

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### • 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  $\sim 14,000$  G
  - Strongest magnetic field produced  $\sim 4 \times 10^5$  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)

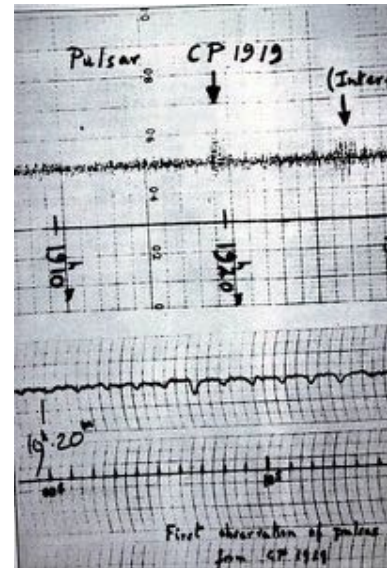
- **1967: S. Jocelyn Bell** discovers a radio signal:
  - **regularly pulsing**
  - **rapid**  
(once every 1.33 seconds)
  - **extraterrestrial**
  - aliens? LGM1, LGM2, ...
    - no. why not?
  - Neutron stars !

PSR 0329:  
0.72 s

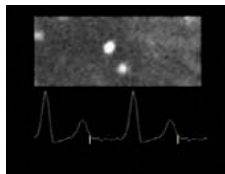
Vela:  
0.089 s



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 Wolszczan)
- **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)