Astronomy 122

This Class (Lecture 18):

Stellar Evolution:
Post-Main Sequence

Next Class:

Neutron Stars

Make-up Nightlabs!

Nightlabs due in discussion class on April 5th.

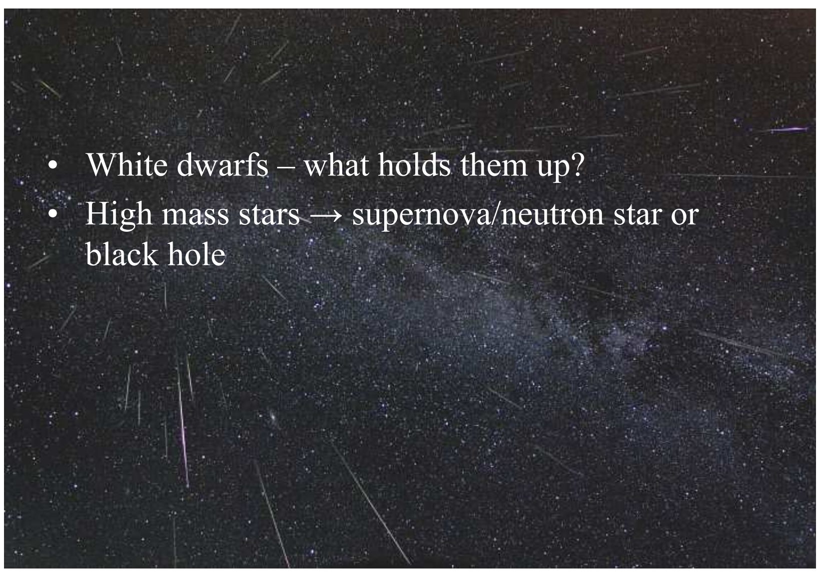
Music: *Supernova* – Liz Phair

Icko Lecture: Extra Credit

- "The Mars Exploration Rover Mission" by Dr. Steven Squyres, Goldwin Smith Professor of Astronomy at Cornell University
- Tuesday, March 28th at 7PM in Foellinger Auditorium
- Go to lecture and write a typed ~1 page analysis on the talk, make sure to discuss (1) what surprising thing you learned and (2) the most interesting aspect of the talk.

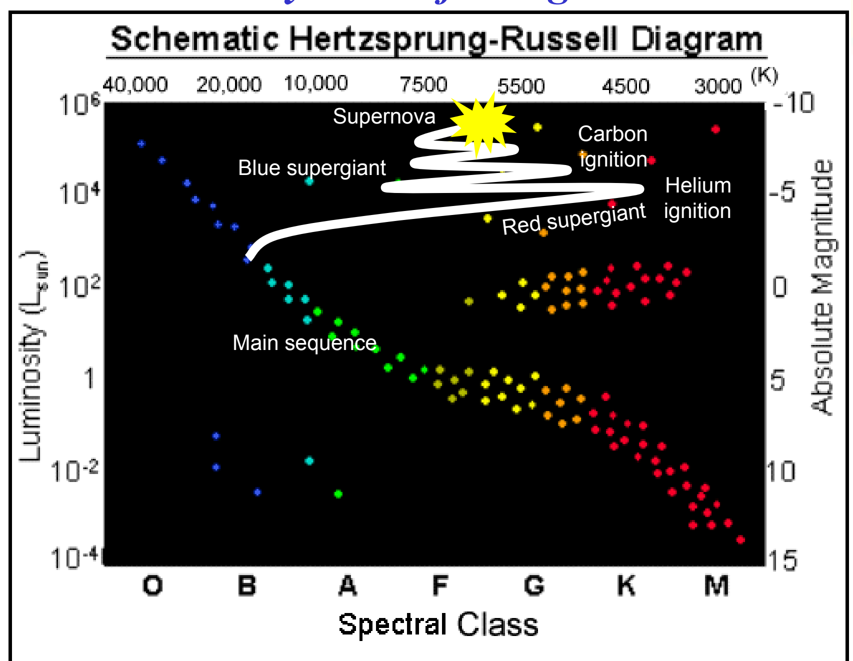
- Extra credit worth an extra 1% to your final grade.
- But, **do not walk out** of the talk until the questions have finished.

Outline

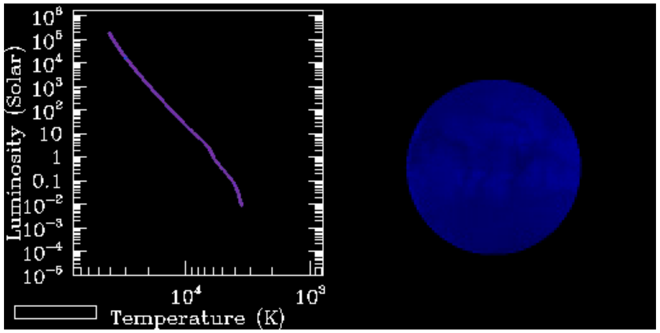


- White dwarfs – what holds them up?
- High mass stars → supernova/neutron star or black hole

Evolutionary Path of a High-Mass Star

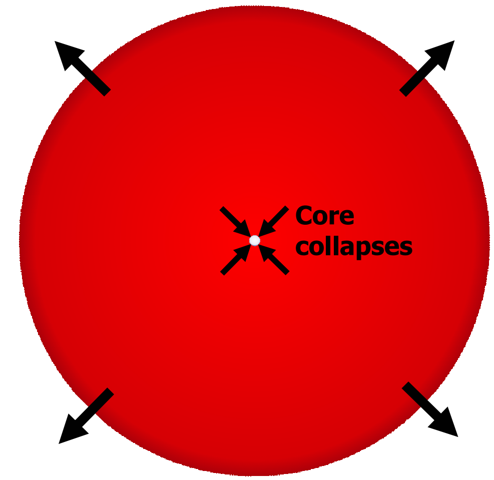


High Mass Stars (> 8 M_{sun})



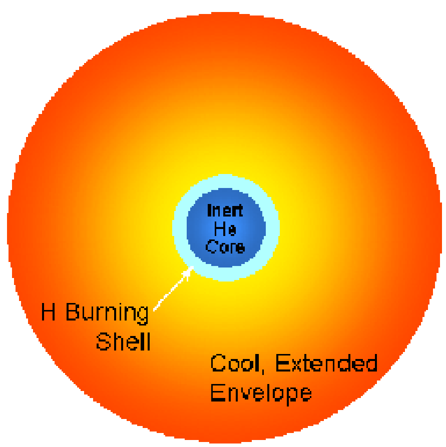
High Mass Stars (> 8 M_{sun}): When the Hydrogen Runs out?

- Similar to intermediate-mass stars in the first few stages
- When the hydrogen supply runs out the core starts to contract
- Hydrogen shell burning (around the helium core) starts
- The outer envelope expands quickly becoming a **red supergiant**



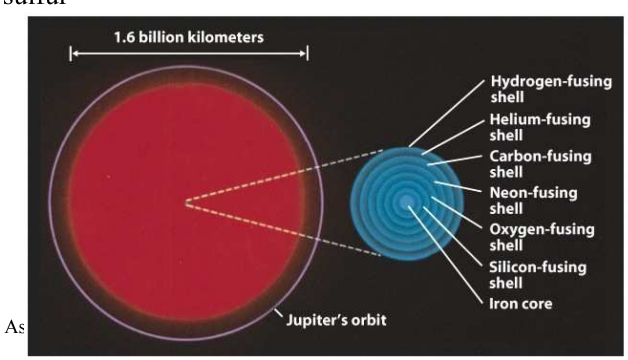
The Supergiant Phase

- Outer envelope of the star grows larger and cooler
  - Up to 5 AU in size!
  - Unlike a low mass star, brightness does not increase dramatically
- Eventually, core is hot enough that it can fuse helium atoms together (no flash)
  - Star contracts and heats up
  - Now a **blue supergiant**



Massive Stars: Cycles of Fusion

- Helium fusion is not the end for massive stars
- Cycles of core contraction, heating, ignition
- Ash of one cycle becomes fuel for the next
  - carbon ⇨ oxygen, neon, sodium, & magnesium
  - neon ⇨ oxygen & magnesium
  - oxygen ⇨ silicon & sulfur
  - silicon ⇨ iron
- Onion-skin like structure develops in the core

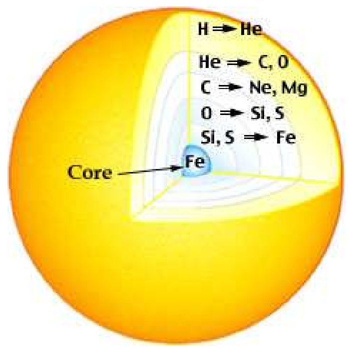


Iron – The End of the Road

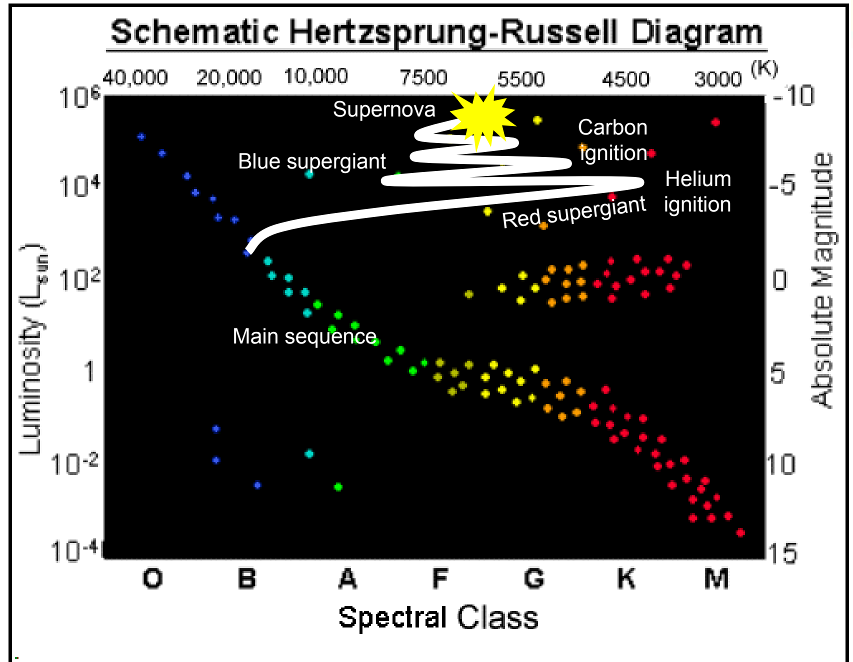
- Supergiants “burn” heavier and heavier atoms in the fusion process
- Each stage faster than the last
- After iron - no fuel left!
  - It requires energy to produce heavier atoms

Stage	Temperature	Duration
H fusion	40 million K	7 million yr
He fusion	200 million K	500,000 yr
C fusion	600 million K	600 yr
Ne fusion	1.2 billion K	1 yr
O fusion	1.5 billion K	6 mo
Si fusion	2.7 billion K	1 day

Values for a $25 M_{Sun}$ star



Evolutionary Path of a High-Mass Star

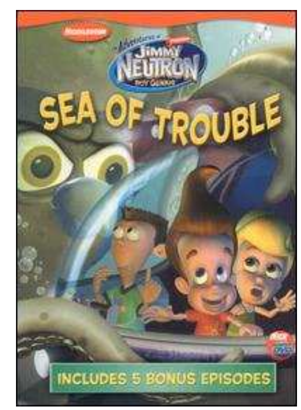


Core Collapse

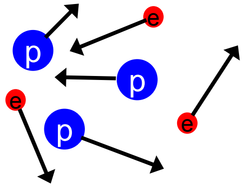
- Completely out of gas!
- Hydrostatic equilibrium is <u>gone</u>.
- The iron core of the star is supported by electron degeneracy pressure
  - Same pressure that supports a white dwarf
- Eventually, gravity wins…
  - This happens when the core > 1.4 solar masses
  - Remember the Chandrasekhar limit
  - The core has nuclear density!
    - It Earth had same density, it would be 1000 feet in diameter.

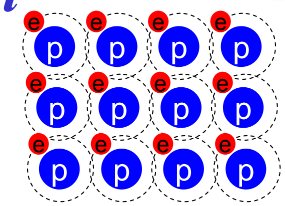
Core Collapse

- When core is greater than 1.4 M_{sun} – **core collapse!**
  - From 1,000 km across to 50 km in *1/10th of a second*
  - ***Nearly 10% speed of light!***
- The core is transformed into a sea of neutrons
  - Electrons are squeezed into protons, neutrinos released



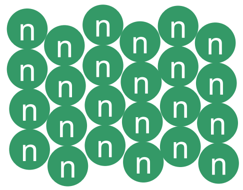
When Electron Degeneracy Just Isn't Enough

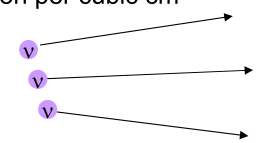




Matter in the core of a normal star

Electron-degenerate matter
1 ton per cubic cm



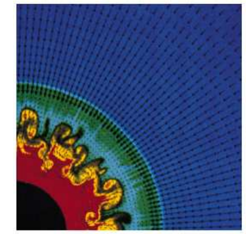


Neutron-degenerate matter
100 million tons per cubic cm

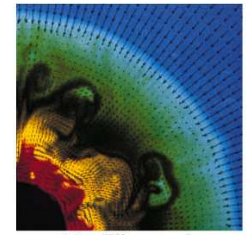
Neutrinos produced as electrons are forced into nuclei

Supernova!

- Core basically becomes a large atomic nucleus– ultra-high density!
- During collapse, envelope "bounces" off stiff core and produces a shock wave
  - Material is so dense, that it is opaque to the neutrinos produced
  - Neutrinos give the shock a "kick"
  - Rips the outer layers of the star apart
- Star explodes in a **supernova**
- Releases a tremendous amount of energy
  - 99% of the energy in the form of neutrinos
- >90% of the mass of star is ejected into space!
  - Fast, hot,

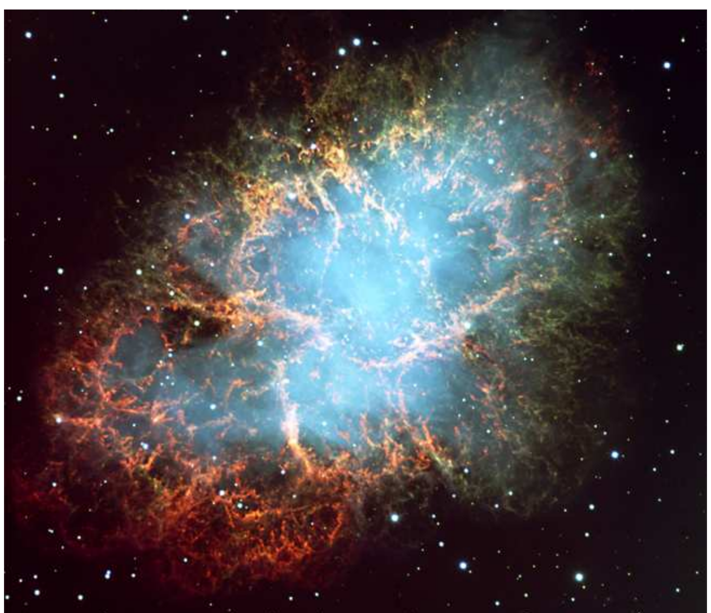


10 milliseconds

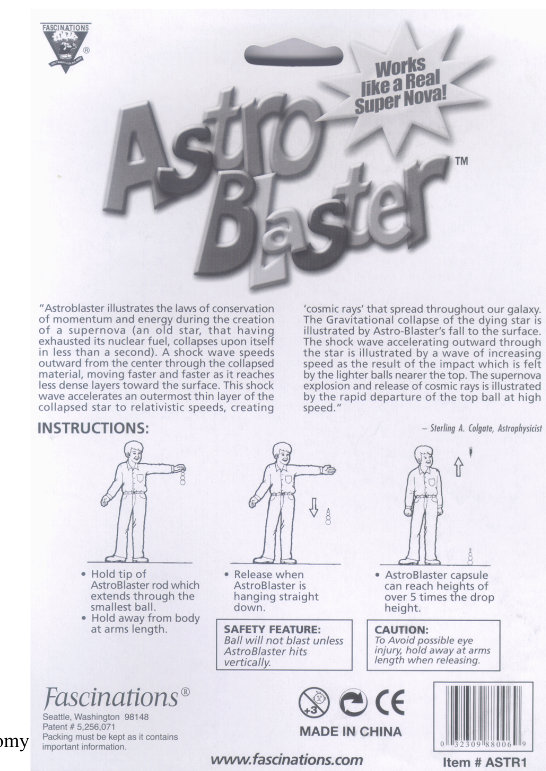


20 milliseconds

Game Over!



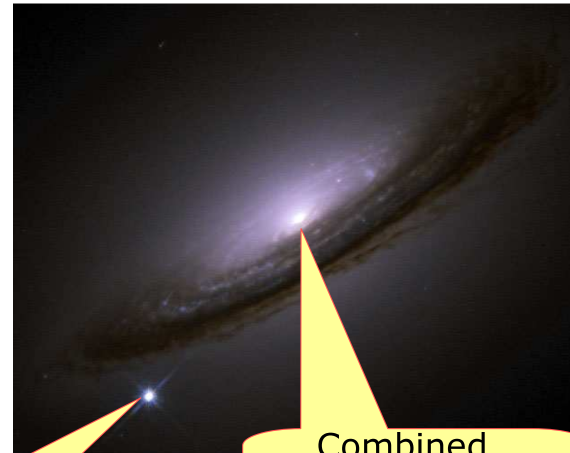
AstroBlaster!



Supernova!

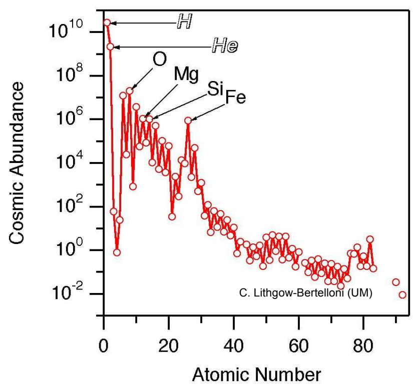
Bright as a Galaxy

- Supernovae are **bright**
  - A star's brightness increases 10,000 times!
  - Rivals an entire galaxy!



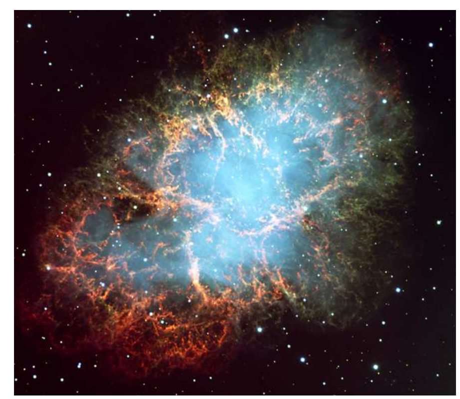
Making Heavy Elements

- During the explosion, energy-consuming fusion reactions are possible
- Heavy elements up to plutonium (& beyond?) are produced
- Dominant product: iron



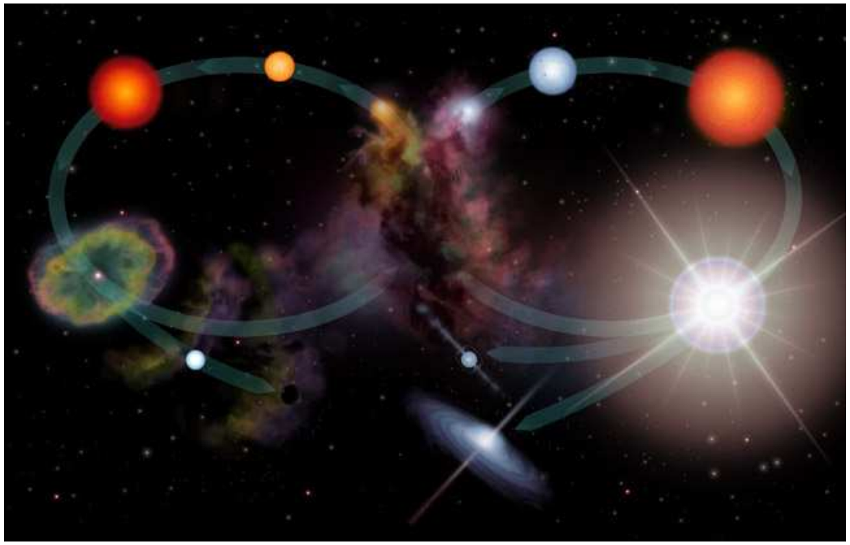
Making Heavy Elements

- These by-products are *blasted* into space (>90% of star)
- Ejection is fast, hot, and enriched.
- Supernovae provide much of the building blocks for planets… and us!
- **We are recycled supernova debris!**
- **Star stuff.**



Delenn, B5

Stellar Evolution Re-Cycle



Stellar Evolution Cycle

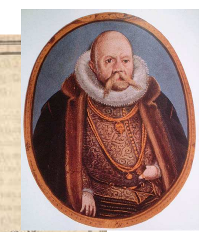
- Stars form out of the interstellar medium
- They manufacture helium, carbon, nitrogen and more in their interiors by nuclear fusion
- Heavier elements (iron, lead, uranium, etc..) are made by supernovae
- Stars give these processed materials back to the interstellar medium when they die
- The processed materials are included in the gas and dust out of which the next generation of stars and planets will form

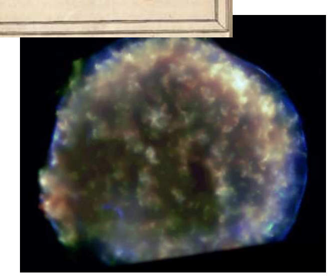
Supernova Explosions in Recorded History

- 1054 AD
- Europe: no record
- China: "guest star"
  - So bright, could see it during the day for most of July.
- Anasazi people
  - Chaco Canyon, NM
  - Rock Paintings
- Modern view of this region of the sky:
  - **Crab Nebula** — a supernova remnant
  - Massive star supernova

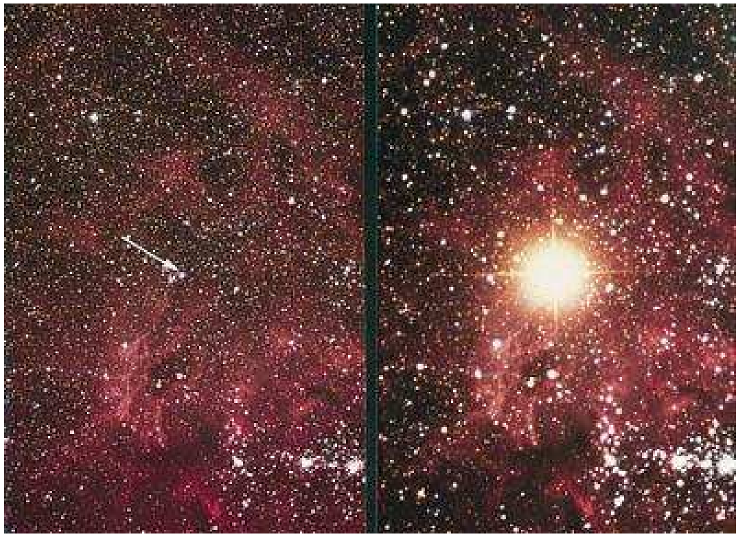
Supernova Explosions in Recorded History

- November 11, 1572
- Recorded by Tycho Brahe
  - Called it a **"nova stella"** (new star)
- For about two weeks the supernova could be seen in the daytime!
- Modern view (X-rays):
  - Tycho's Supernova Remnant
- Probably a white dwarf supernova (Ia)





Supernova 1987A

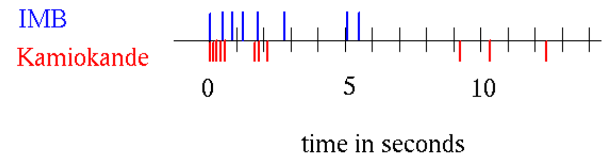


Original star was a B3 blue supergiant

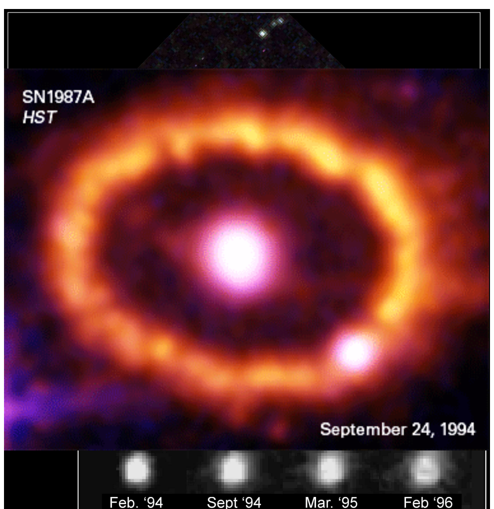
Before Feb. 23, 1987

Supernova 1987A

- Supernova are rare
- Only about ~3/century in a galaxy.
- Last was 400 yrs ago (Tycho)
- 1987A happened in the satellite galaxy LMC (150,000 lyrs away)
- Star was about 20 $M_{\odot}$
- Detected neutrinos from the core (most of explosion energy) for 13 secs about 20 detected.



Supernova 1987A - Today



Supernova 1987A Explosion Debris
Hubble Space Telescope • WFPC2

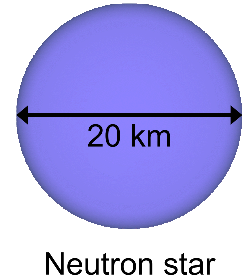
Death throes

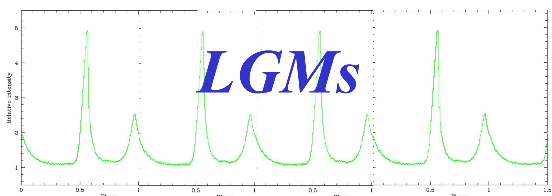
- What triggers a supernova?
  - Hydrostatic equilibrium is lost, gravity wins
  - Iron core with $M > M_{Chandra}$
- What happens?
  - Quick core collapse overcoming electron degeneracy pressure.
  - Rebound off the core, explosion of envelope
- What are end products?
  - Enriched ejecta and compact neutron star (if core mass < 3 solar masses)

Supernova Leftovers

- What's left of the star's core after a massive star supernova?
- A **neutron star**
  - About 1.4 – 2 solar masses
  - Very small diameter – around 20 km!
  - Composed of a sea of neutrons
    - Supported by *neutron degeneracy pressure!*
    - Teaspoon of neutron star material on Earth would weigh almost 1 billion tons!!!!
  - Surface gravity – 200 billion times that on Earth
  - Escape velocity – half the speed of light

Relative Sizes of Stellar Corpses

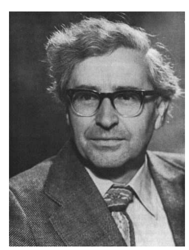




LGMs

- In the late 1960s, Jocelyn Bell discovered radio pulses from the constellation Vulpecula that repeated regularly
  - Every 1.337… seconds
- What could it be?
- Perfect timing, but no real encoding of signal.
- Jokingly called LGMs, then Pulsars.

Jocelyn Bell Burnell

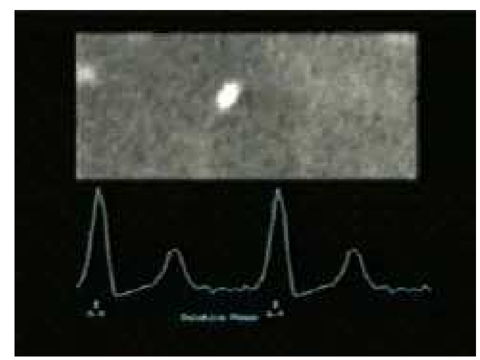


Anthony Hewish

http://www.radiosky.com/rspplsr.html

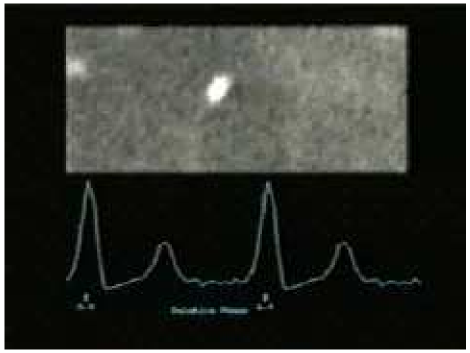
Pulsars

- What could it be?
  - Pulses were too fast to be a variable star
- A rotating star?



Pulsars

- Very precise, better than atomic clocks.
- Periods from 8.51s to 1.56 ms!
- Could they be something spinning?
  - Would have to be small to be spinning that fast
- They must be spinning neutron stars!

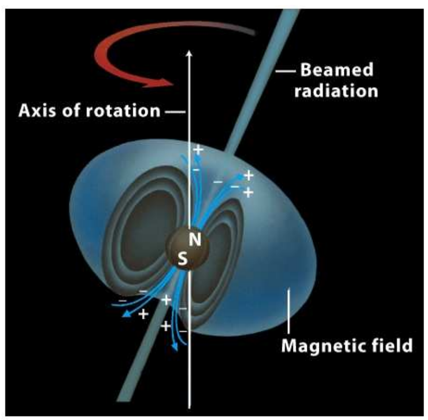


What are Pulsars?

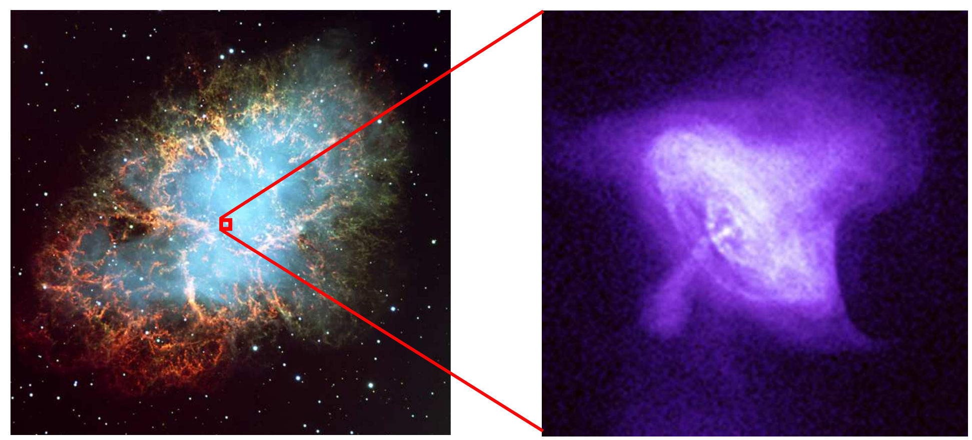
- When the core collapses, its spin and magnetic field strength increases
- Typically
  - Surface field strength over 1 trillion times that of the Earth
  - Rotation rate up to 1000 times per second
- Magnetic field beams radiation into space
- If the Earth is in the beam's path, we see the pulsar

What are Pulsars?

- Intense beams of radiation emanate from regions near the north and south magnetic poles of a neutron star
- These beams are produced by streams of charged particles moving in the star's intense magnetic field
- As the Pulsar gives energy to its surroundings, it slows down.
- The periods increase (few billionths of a second each day)



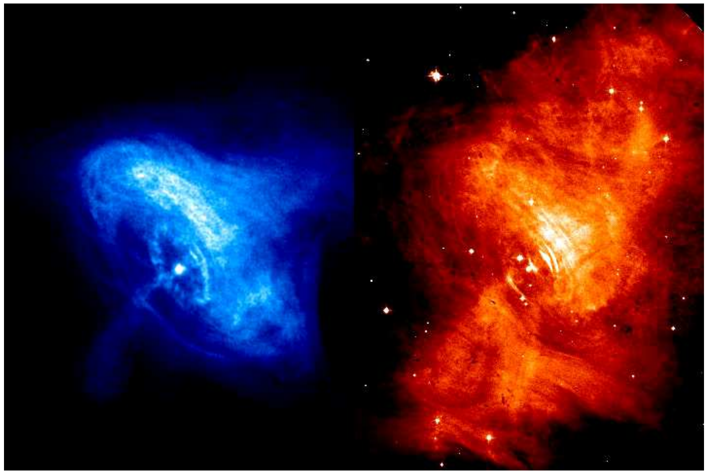
Crab Nebula – Remnant of the Supernova of 1054



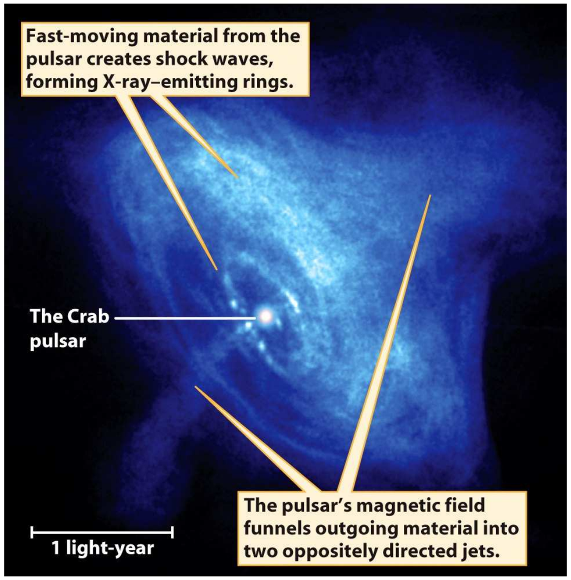
Optical - ESO

X-ray - Chandra

Crab Nebula – Remnant of the Supernova of 1054

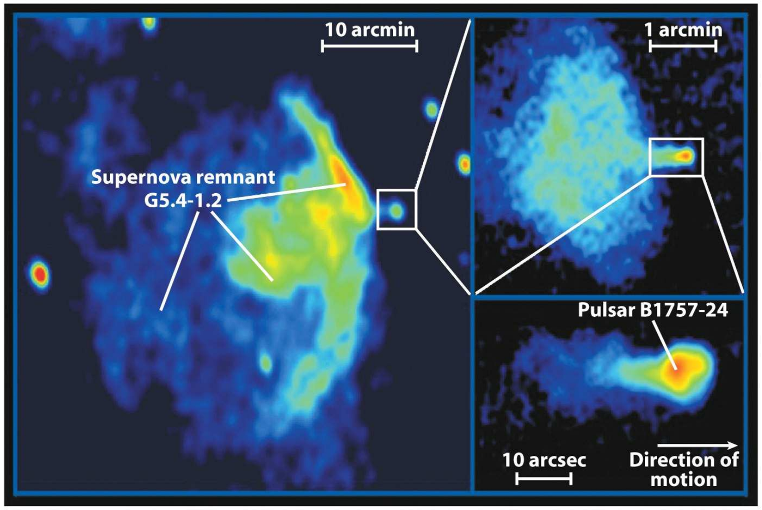


The Crab



Escaping Pulsars

- Some Pulsars are ejected during the supernovae.
- Can outrun the explosion.
- This one is 600 km/s



When Neutron Degeneracy Isn't Enough

- Maximum neutron star mass
  - About 3.0 $M_{\odot}$
  - Original star around 30$M_{\odot}$
- Beyond this mass, neutron degeneracy cannot stop gravity
- Nothing left to stop, so total collapse– gravity rules!
- **A black hole**
  - $v_{esc} > c$

Stellar Evolution Recap