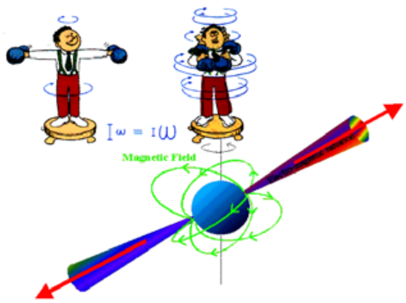
The Pulsar "Lighthouse"



Chandra - X-Ray Sources - Pulsar

Circumference of spinning star = $2\pi R$.

- Energy is emitted by charged particles accelerated along poles of magnetic field.
- Magnetic field is tilted relative to spin axis.
- Collapsed star spins rapidly.
  - conservation of angular momentum.
- What is diameter?
  - Star's surface cannot spin faster than speed of light.

    $2\pi R / t < c$

    ➔ $R < ct/(2\pi)$
  - 0.001 sec period ➔ R < 50 km
- It *has* to be a neutron star.

Possible ending #3: a black hole

- Degenerate pressure of neutrons can support stars only up to $3M_\odot$
- For $M > 3M_\odot$: Further collapse ➔ black hole
  - Mass is so concentrated that light cannot escape.
    - One way to think about it:
      - $v_{\mathbf{escape}} = \sqrt{2GM/R}$ becomes greater than speed of light.
      - So photons can't escape.
  - Black holes now known on three size scales:
    - $M \sim$ a few $M_\odot$ (Single star. $R_{\mathbf{Schwarzschild}} = 9$ km)
    - $M \sim 10^5 M_\odot$ (recently found in 2 globular clusters)
    - $M \sim 10^8 M_\odot$ (Quasar in center of a galaxy)
- What is the state of the mass inside the black hole???

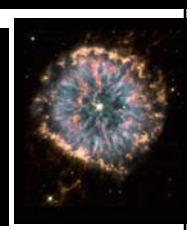
How do stars get from here to there?

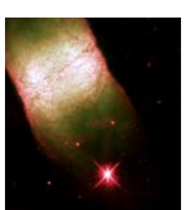
Here: Evolution through nuclear burning.	
$M_{initial} > 3M_{\odot}$	Nuclear burning all the way to iron.
$M_{initial} < 3M_{\odot}$	Nuclear burning shuts off after He-flash.

There: Final state.	
$M_{final} > 3M_{\odot}$	Black hole.
$1.4 < M_{final} < 3M_{\odot}$	Neutron star.
$M_{final} < 1.4M_{\odot}$	White dwarf.

Hubble images of Planetary Nebulae

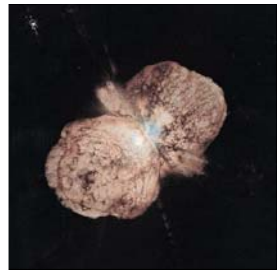
These are former Red Giants, blowing away outer 25% of their mass because of intense energy production in middle layers of star.

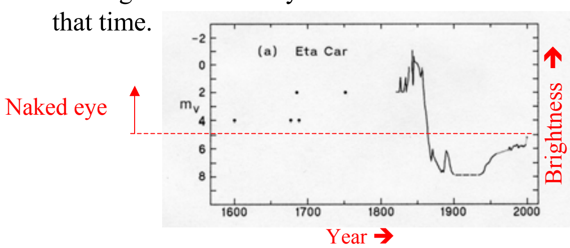




Very massive stars also expel material late in life

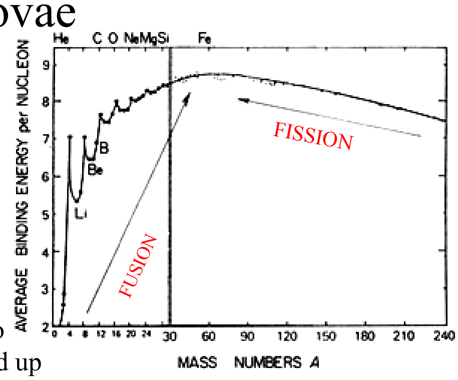
- Eta Carinae
  - 150 $M_\odot$
  - 4 million $L_\odot$
  - Highly variable in luminosity.
  - This material ejected in 1843.
    - Major brightening recorded.
    - Ejected 3 $M_\odot$
    - 2nd brightest star in sky at that time.

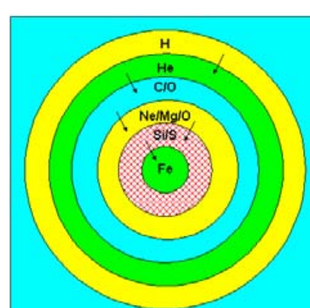




Supernovae

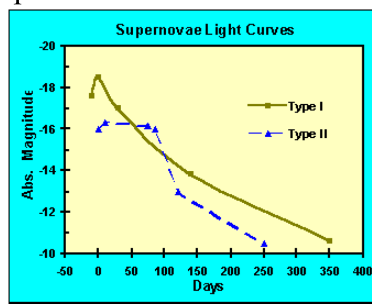
- Stars more massive than 7-8 $M_\odot$ cannot "gracefully" lose mass and become white dwarfs.
- Massive stars end up with iron cores.
- No further nuclear burning possible
  - Combining iron into heavier elements soaks up energy.
- Outer layers of star gradually contract onto core which becomes too massive to be held up by degenerate electron pressure
  - $e^- + p \rightarrow n$
  - Sudden core collapse: 10^4 km ➔ 20 km
  - Then core rebounds
  - Outer layers fall in, then get hit by rebounding core.





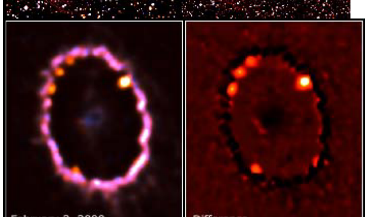
Kapow!

- Explosion releases huge kinetic energy
  - ➔ heating ➔ lots of photons
- Luminosity in photons temporarily exceeds that of whole galaxy full (10^{11}) of stars.
- But far greater luminosity in neutrinos
  - $e^- + p$ ➔ n + neutrino

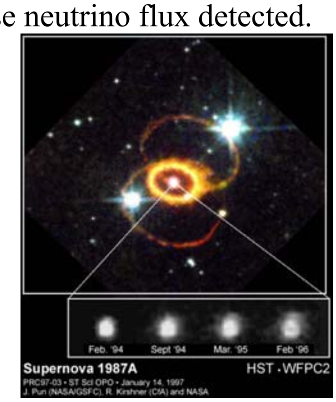


Supernova 1987A

- Exploded in Large Magellanic Cloud
  - Small spiral galaxy that orbits our own Galaxy.
- Caught in act of exploding and intensively studied.
- Intense neutrino flux detected.

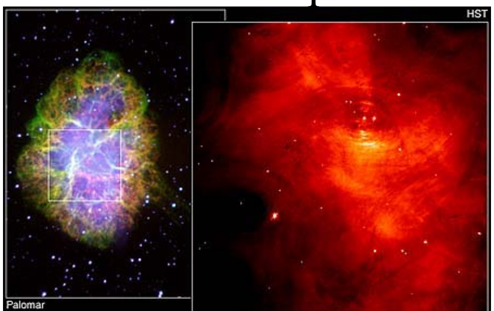


Pre-existing circumstellar ring lit up first by photons from SN, now by blast wave from SN.



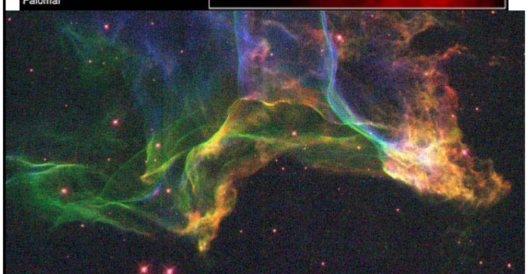
Supernova remnants

We expect one supernova in Milky Way every 25-100 yrs.



Crab Nebula.
1054 AD.
Ripples are due to energy being dumped into gas by beam from pulsar.

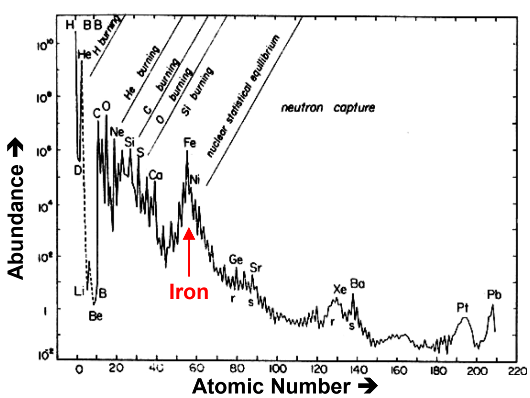
IC 443
8000 yrs old



Cygnus Loop
20,000 yrs old.
2500 LY away.

History of our Galaxy: Traced through Nucleosynthesis

- H ➔ He
  - main sequence, red giants
  - supplements primordial He.
- He ➔ C, N
  - red giants, helium flash, etc.
- C, N ➔ Fe
  - cores of massive stars.
- Fe ➔ heavier elements (U, etc).
  - supernova explosions.
  - bombardment by neutrons.



- Recycling back into interstellar gas
  - Planetary nebula shells
  - Other mild-mannered mass loss
  - Supernovae

Chemical history of our galaxy

- *Chemical enrichment*
  The buildup of the heavy elements through nucleosynthesis.
- Galaxy started with just H, He, Li
- H ➔ He ➔ C ➔ O burning has steadily built up carbon, oxygen.
- Elements like iron built up (somewhat) more recently.