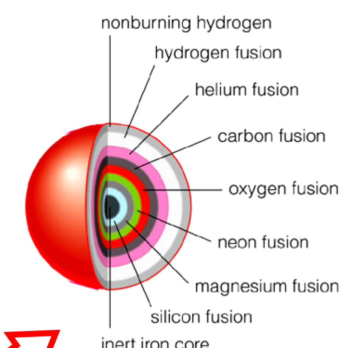
What stars do

- Gravity ➔ Star always trying to contract, become more dense.

- Nuclear burning interrupts this
  - High temperature ➔ high pressure
  - *Pressure* halts gravitational contraction.

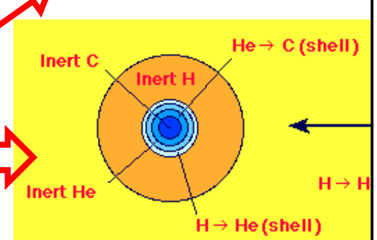
Summary: Nuclear burning in stars

Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10^{7} ^{o} K
3 ^{4}He ➔ ^{12}C	2×10^{8}
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	8×10^{8}
Ne ➔ O, Mg	1.5×10^{9}
O ➔ Mg, S	2×10^{9}
Si ➔Fe peak	3×10^{9}



Evolution through nuclear burning.

$M_{initial} > 8M_{\odot}$	Nuclear burning all the way to iron.
$M_{initial} < 8M_{\odot}$	Nuclear burning shuts off after He burning.

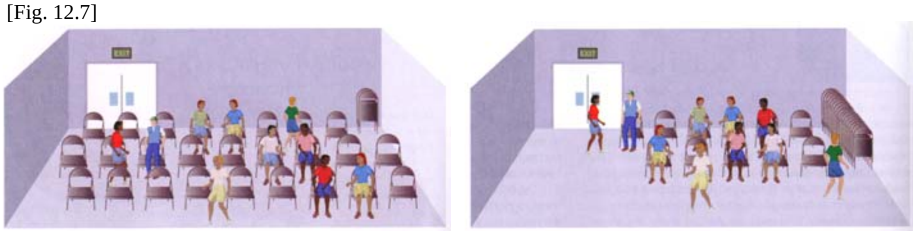


Oops - I previously said $2M_{\odot}$

Sufficiently high density ➔ Electron degeneracy.

- *Pauli exclusion principle* ➔ cannot have two electrons in same place with exactly same energy.

[Fig. 12.7]



Normal gas = room for electrons to squeeze together.

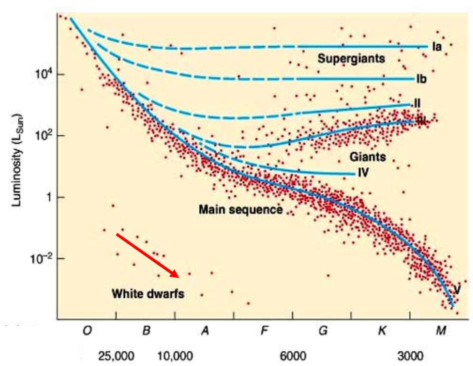
Degenerate gas = almost all energy levels filled.

- Pressure from “degenerate” electrons depends only on density, *NOT* on temperature.
- Can have high pressure without nuclear burning.

Possible ending #1: a white dwarf

- For mass < $1.4M_{\odot}$
  - Pressure from electron degeneracy can support star

➔ ***white dwarf***



- A giant crystal-like lattice of nuclei.
- Electrons conduct heat outwards to surface.
- Surface is steadily-cooling thermal emitter.
  - White-dwarfs evolve down and to right on H-R diagram.

Interactive HR Diagram

HR – The Movie

Possible ending #1: a white dwarf

Electron degeneracy ➔ pressure to support star up to 1.4 $M_\odot$.

Possible ending #2: a neutron star

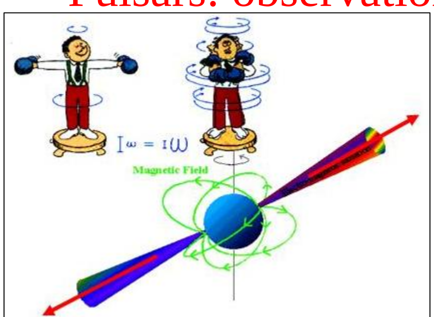
If degenerate electron pressure *cannot* support the star:

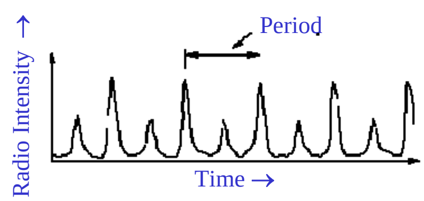
$e^- + p^+ \rightarrow n$ + neutrinos

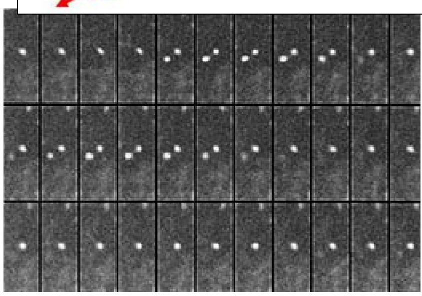
- Still denser state of matter than electron degeneracy.
  - Sun: 1,000,000 km diameter
  - White dwarf: 10,000 km (~ same diameter as Earth)
  - Neutron star: 20 km

- Degenerate pressure of neutrons can support stars up to 3$M_\odot$

Pulsars: observations of neutron stars







High-speed time series in visible light.
Pulsar next to a star of constant brightness.

- Originally found repeating radio bursts
- Rapidly spinning neutron star emits light in beams.
  - Dozens now known.
  - Pulses repeat with 0.001 to 10 sec. periods.

Up to 3x mass of Sun.
Size of Lansing.
Spins 30x per second.

Possible ending #1: a white dwarf

Electron degeneracy ➔ pressure to support star up to 1.4 $M_{\odot}$.

Possible ending #2: a neutron star

If degenerate electron pressure *cannot* support the star:

$e^{-} + p^{+} \rightarrow n$ + neutrinos

- Degenerate pressure of neutrons can support stars up to $3M_{\odot}$

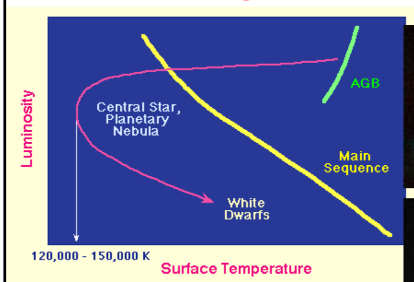
Possible ending #3: a black hole

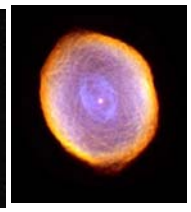
- Complete collapse
- Will be described in next lecture

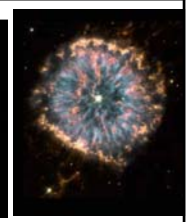
Here: Evolution through nuclear burning.	
$M_{initial} > 8M_{\odot}$	Nuclear burning all the way to iron.
$M_{initial} < 8M_{\odot}$	Nuclear burning shuts off after He-flash.

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

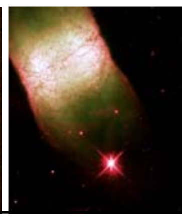
Hubble images of Planetary Nebulae





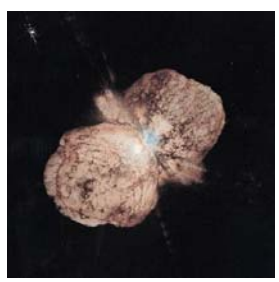


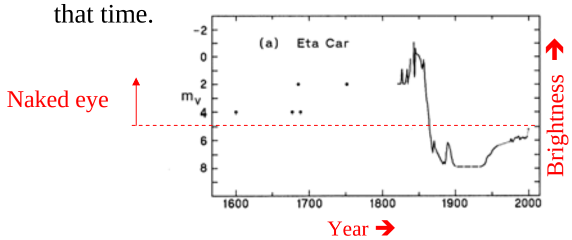
These are former Red Giants, blowing away outer 25% of their mass because of intense energy production in middle layers of star.



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.

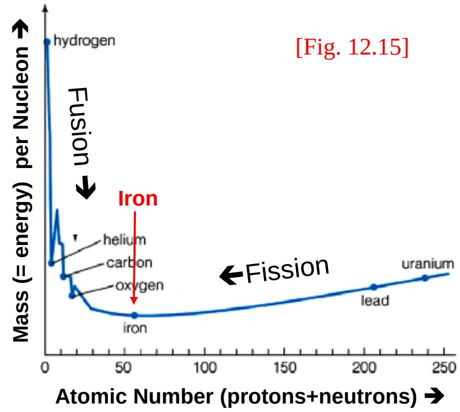


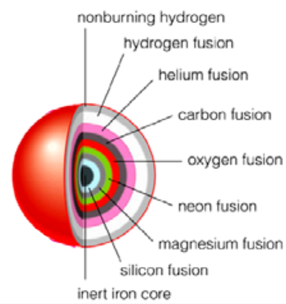


Supernovae

- For M > 7-8 $M_\odot$, stars end up with iron cores

  ➔ No further nuclear burning possible
- Core eventually becomes too massive to be held up by degenerate electron pressure:
  - $e^- + p$ ➔ n
  - Sudden core collapse: 10⁴ km ➔ 20 km
  - Then core rebounds
  - Outer layers fall in, then get hit by rebounding core.





Supernovae

Kapow!

- For M > 7-8 $M_\odot$, stars end up with iron cores

  ➔ No further nuclear burning possible
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  - Sudden core collapse: 10⁴ km ➔ 20 km
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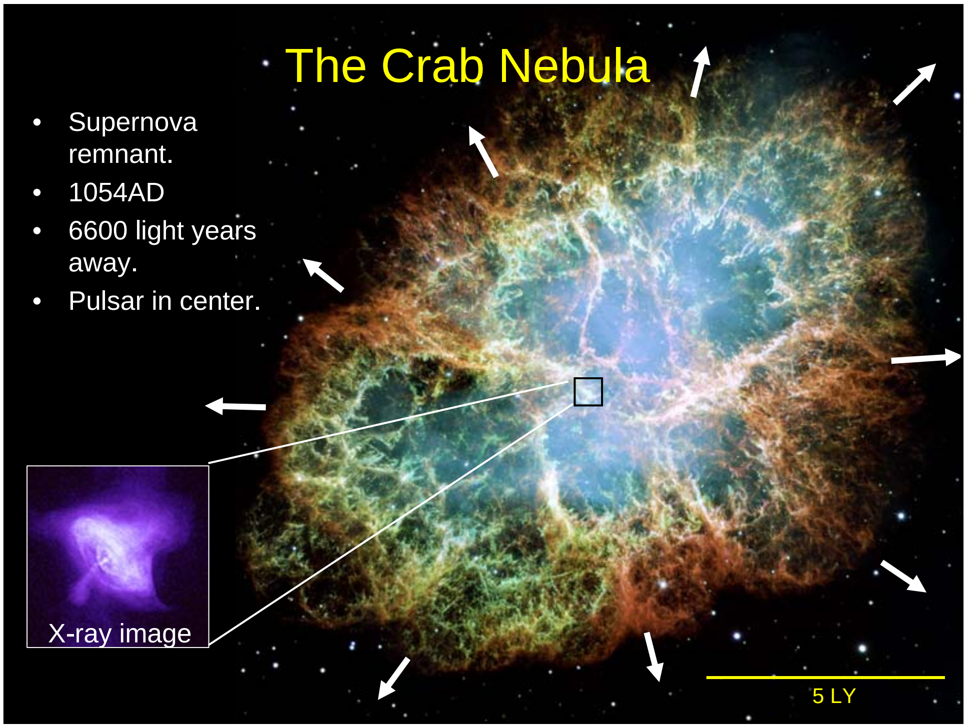
  - Outer layers fall in, then get hit by rebounding core.

expanding
remnant

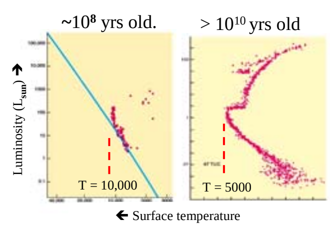


What we have learned about stars

We can measure:
- Luminosity
- Mass
- Size
- Chemical composition

Computer "models" assuming:
- Made of gas.
- Neither contracting nor expanding.
- Neither heating up nor cooling down.
- Specify method of energy transfer.

Lifetimes of stars:
- We see both young and old clusters.
- Sun's structure consistent with 4.5 billion yr age.



Oldest stars about 13 billion years old.

Nucleosynthesis:
- Stars make heavy chemical elements.
- Can then blow them out into space.