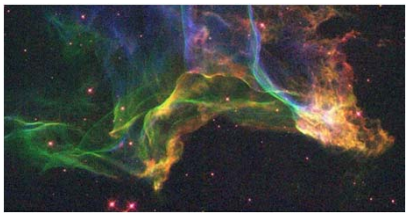
Supernovae — Oct 21

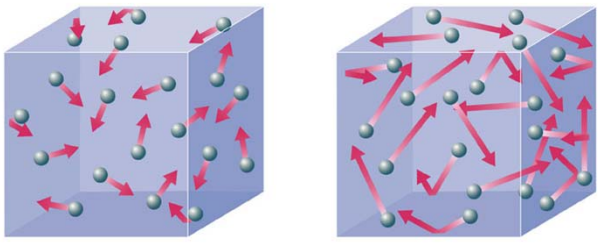


Cygnus Loop
Supernova 20,000 yr ago

- Outline
  - Degenerate gas
  - Where were the elements in the baby made?
    - Carbon was made and expelled by giants
    - Iron was made in massive stars and expelled by supernovae
    - Heavier elements were made in supernovae & in giants, where there are free neutrons. Nuclei capture neutrons.
  - A massive star ($M > 8M_{\mathrm{sun}}$) ends as supernova
  - Elements produced in massive stars

Normal/degeneracy pressure
White dwarfs

- Pressure on the walls of the box is caused by the gas hitting the walls. Gas transfers momentum to the walls.
- Mental picture: Marbles hit the walls; wall pushes back.



Longer arrows mean higher average speed.

Pressure in a "degenerate gas"

- Normal gas

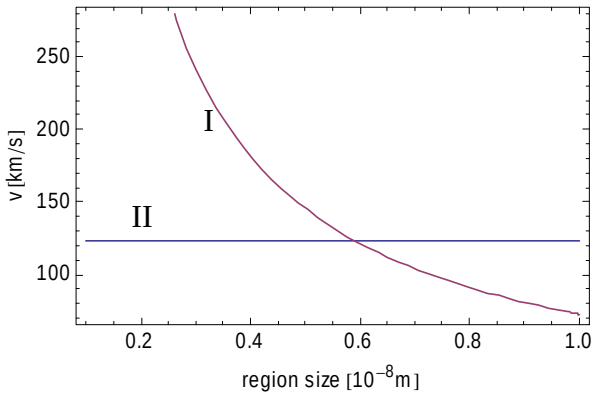
  $P\,V = n\,k\,T$

  - Pressure is greater at higher temperature because the marbles are moving faster. $mv^2=kT$
- Degenerate gas. If the gas is confined to a very small space, Newton's 2nd law becomes invalid**.**
  - New laws of motion, called quantum mechanics, apply.
- Heisenberg's uncertainty principle. Suppose a particle is allowed to move within a region of length x.

  $m\,v\,x > h$

  $momentum\,x > h$

  v is speed. h is Planck's constant.
  - A particle must move if it is confined to a small space.
  - If you confine an electron to 10^{-8}m, it moves at 70km/s.



1. Plot shows the speed of a normal gas made of electrons with a temperature of 1000K and a degenerate gas of electrons with a temperature of 0K.

   A. I is a NG. II is a DG.

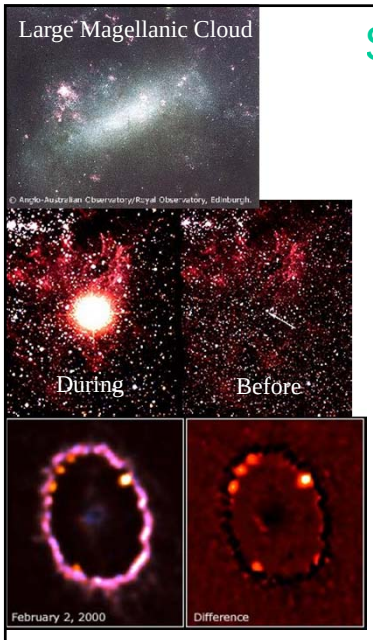
   B. I is a DG. II is a NG.

Pressure in a "degenerate gas"

- Heisenberg's uncertainty principle. Suppose a particle is allowed to move within a region of length x.

  $momentum\, x > h$

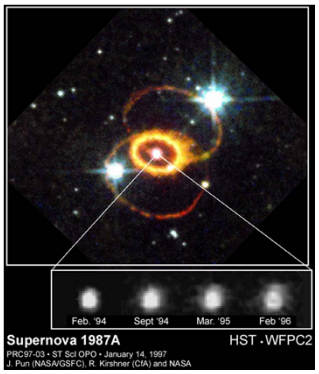
  A particle must move if it is confined to a small space.
- Pressure of a degenerate gas
  - $P\, V^{5/3} = constant\, n^{5/3}$
  - constant = h^2/m
  - Pressure does not depend on temperature!!!
- End state of the sun
  - Without any energy production, the sun would normally shrink because gravity wins.
  - However, degeneracy pressure balances gravity. The sun is stable and cannot shrink.



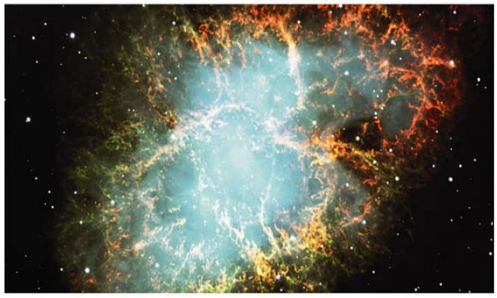
Supernova 1987A

- Exploded in Large Magellanic Cloud
  - LMC is small galaxy that orbits our own Milky Way Galaxy.

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



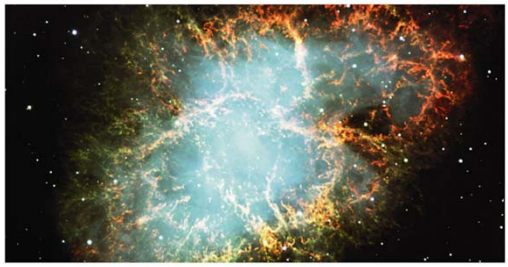
Guest star of 1054, Crab nebula



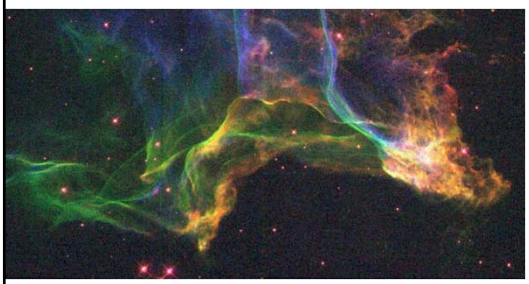
- Records of Sung Dynasty
  - In the first year of the period Chih-ho, …, a guest star appeared several degrees SE of Thien-kuan. After more than a year it gradually became invisible.–p550.
- Gas expelled in 1054AD, still glowing, still moving.
- Other SN
  - 1572 Tycho
  - 1604 Kepler

Supernova remnants

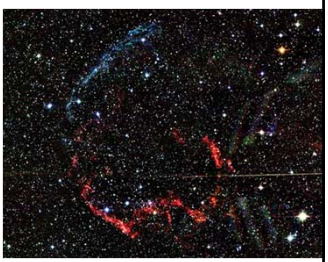
We expect one supernova in Milky Way every 25-100 yrs.



Crab
1,000 yrs old



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



IC 443
8000 yrs old

Supernovae

- Explosion releases enormous energy
- Luminosity in photons temporarily exceeds that of whole galaxy full (100 billion) of stars.

What is a supernova? Why sun becomes a white dwarf, not a supernova

- In future double-shell burning sun, hot enough to burn
  $3\,^4He \rightarrow {}^{12}C$
- When He exhausted, gravity wins, and core contracts.
- Electrons are so tight that they become degenerate.
- New source of pressure to resist gravity.
- Temperature not hot enough to burn carbon.

Reaction	Min. Temp.
$4\,{}^1H \rightarrow {}^4He$	10^7 ° K
$3\,{}^4He \rightarrow {}^{12}C$	$2x10^8$
${}^{12}C + {}^4He \rightarrow {}^{16}O$, Ne, Na, Mg	$8x10^8$
Ne → O, Mg	$1.5x10^9$
O → Mg, S	$2x10^9$
Si → Fe peak	$3x10^9$

What is a supernova? Why sun becomes a white dwarf, not a supernova

- Sun has one more trick after He is exhausted in core.
  - Burn He in a shell
- Sun is not massive enough to shrink further and get hot enough to burn carbon.
  $T = M/R$
  - Core is supported by pressure of degenerate electrons.
  - Temperature does not rise to burn anything else.
- End of the road: planetary nebula & white dwarf core

Triple-alpha process

Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10 MK
3 ^{4}He ➔ ^{12}C	200 MK
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	800 MK
Ne ➔ O, Mg	1500MK
O ➔ Mg, S	2000MK
Si ➔Fe peak	3000MK

What is a supernova? Why massive star becomes a supernova

- History of a massive star
- During double-shell burning phase, hot enough to burn
  $3\,^{4}He \rightarrow {}^{12}C$
- When He exhausted, gravity wins, and core contracts.
- Temperature rises by larger amount b/c gravity is stronger.
- Temperature hot enough to burn carbon.
  $^{4}He + {}^{12}C \rightarrow {}^{16}O$, etc

Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10^{7} ° K
3 ^{4}He ➔ ^{12}C	$2x10^{8}$
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	$8x10^{8}$
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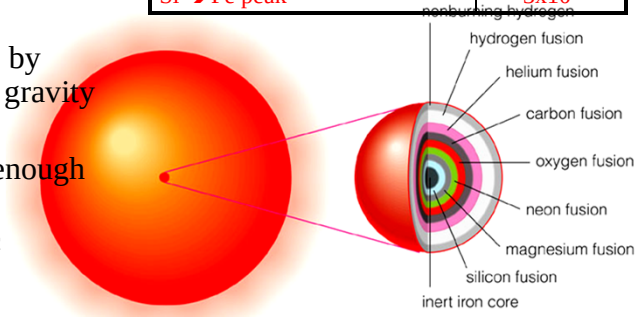
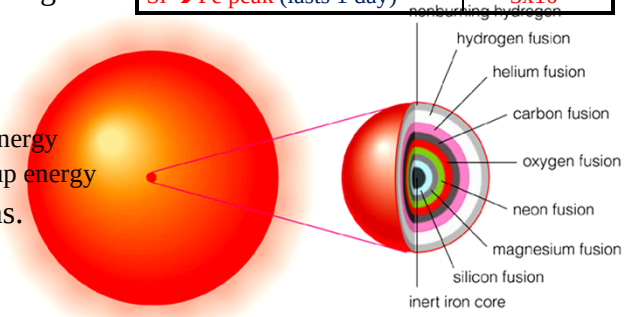


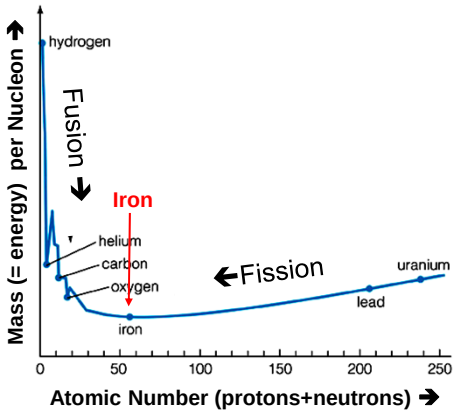
What is a supernova? Why massive star becomes a supernova

- Hot enough to burn
  $^4He + {}^{12}C \rightarrow {}^{16}O$, etc
- When C exhausted, gravity wins, and core contracts.
- Temperature rises.
- Temperature hot enough to burn neon.
  $^{20}Ne + {}^4He \rightarrow {}^{24}Mg$
- Disaster with iron
  - Burning releases energy
  - Fusing iron takes up energy
- Gravity finally wins.

Reaction	Min. Temp.
$4\ {}^1H \rightarrow {}^4He$	10^7 ° K
$3\ {}^4He \rightarrow {}^{12}C$	$2x10^8$
$^{12}C + {}^4He \rightarrow {}^{16}O$, Ne, Na, Mg	$8x10^8$
Ne → O, Mg	$1.5x10^9$
O → Mg, S	$2x10^9$
Si → Fe peak (lasts 1 day)	$3x10^9$



- Fusion of stable nuclei less massive than iron releases energy
- Fusion of stable nuclei more massive than iron requires input of energy and therefore cannot occur.



What is a supernova? Why massive star becomes a supernova

- Disaster with iron
  - Burning releases energy
  - Fusing iron takes up energy
- Gravity finally wins.
- Star collapses in few seconds
- Rebounds as supernova
  - Reason for rebounding is topic of current research
- Expel outer layers.

Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10^{7} o K
3 ^{4}He ➔ ^{12}C	$2x10^{8}$
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	$8x10^{8}$
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