

# Lecture 18: Supernovae

Readings: 21-6, 22-6, 22-7, 22-9, 22-10 (22-8)

## Key Ideas

End of the Life of a Massive Star:

- Burn H through Si in successive cores

- Finally build a massive Iron core

Iron core collapse & core bounce

- Explosive envelope ejection

Nucleosynthesis

- Creation of elements heavier than H & He in stars

## Last Days of a Massive Star

Burns a succession of nuclear fuels:

- Hydrogen burning: 10 Myr

- Helium: 1 Myr

- Carbon burning: 1000 years

- Neon burning ~10 years

- Oxygen burning ~1 year

- Silicon burning ~1 day

Builds up an inert iron core in the center.

## Iron Core Collapse

Iron core grows to a mass of 1.2-1.4  $M_{\text{Sun}}$

- Collapses and begins to heat up

- $T > 10$  Billion K

- Density  $\sim 10^8$  g/cc

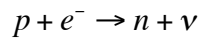
Two energy *consuming* processes kick in:

- Nuclei photodisintegrate into He, p, & n

- Protons & electrons combine into neutrons and neutrinos, neutrinos escape and carry off energy

Makes the core collapse faster, as the insufficient pressure is decreased further

## Neutronization



Because a neutron has more mass than an electron + proton, there has to be extra energy in this reaction to make it happen. That energy comes from the kinetic (=energy of motion) of the very hot proton and electron. The neutrino flies out of the star, taking energy with it.

Note that electron degeneracy pressure will not be important source of pressure in this situation because 1) at these densities, the electrons are approaching their maximum speeds=maximum pressure and 2) now they are disappearing.

## Catastrophic Collapse

Start of Iron Core collapse

Radius~6000 km ( $\sim R_{\text{Sun}}$ )

Density  $\sim 10^8$  g/cc

1 second later...

Radius  $\sim 50$  km

Density  $\sim 10^{14}$  g/cc

Collapse Speed  $\sim 0.25$  of the speed of light

## Core Bounce

Core collapses until its density is  $\sim 2.4 \times 10^{14}$  g/cc, the density of an atomic nucleus!

Then the strong nuclear force comes into play!

Inner  $0.7 M_{\text{Sun}}$  of the core

comes to a screeching halt

overshoots & springs back a bit (bounces)

Infalling gas hits the bouncing core head-on

## Post-Bounce Shockwave

Shockwave blasts out into the star:

Kinetic energy is  $10^{51}$  ergs

After 25-40 milliseconds

Traffic jam between infalling and outflowing gas

Shockwave stalls  
Meanwhile neutrinos pour out of the core (newly created neutron star):  
Get trapped by the dense surrounding gas  
This leads to rapid heating of the gas  
This leads to violent convection

## New, Improved Shockwave

Violent convection breaks the traffic jam.  
Shockwave regenerates after 300 millisec  
Blastwave smashes out through the star:  
Explosive nuclear fusion in its wake produces more heavy elements  
Heats up and accelerates the envelope  
Shock breakout a few hours later  
Breakout speed  $\sim 10\%$  the speed of sound

## Supernova!

At shock breakout  
Brightens by 10 billion  $L_{\text{Sun}}$  in minutes  
Outshines an entire galaxy of billions of stars!

Outer envelope is blasted off:  
Accelerated to a few  $\times 10,000$  km/sec  
Gas expands and cools off

Only the core remains behind

## Echoes

Supernova fades after a few months.  
Fading slows at late times  
Extra energy from gamma rays emitted by radioactive nickel and cobalt  
Fading rate depends on the amount of Ni created  
More nickel=slower fade

Example: Supernova 1987a (by the way, SN are names by the year of their discovery + letters of the alphabet. Exceptions are the historical SN).

## Historical Supernovae

1054 AD: “Guest Star” in Taurus

Observed by the Chinese (Song dynasty)  
Visible in daylight for 23 days

1572 AD: Tycho Brahe's Supernova

1604 AD: Johannes Kepler's Supernova

6000-8000BC: Vela supernova

Observed by the Sumerians, appears in legends about the god Ea.

Crab Nebula: (aka M1) remnant of Supernova in 1054

## Supernova 1987a

Nearest visible SN since 1054

February 23, 1987

15M<sub>Sun</sub> Blue Supergiant Star: SK-69°202 exploded in the Large Magellanic Cloud

Saw a pulse of neutrinos, then the blast

Continued to observe it since then

Wealth of information on SN physics

## Nucleosynthesis

Start with Hydrogen & Helium

Fuse H into elements up to Iron and Nickel

Accumulate in the core layers of stars

Supernova Explosion

“Explosive” nuclear fusion builds more *light elements* up to Iron & Nickel

Fast neutron reaction build Iron & Nickel into heavy elements up to <sup>254</sup>Cf

Of the Top Ten Most Abundant Elements

10) Sulfur

9) Magnesium

8) Iron

7) Silicon

6) Nitrogen

5) Neon

4) Carbon

3) Oxygen

## 2) Helium

are all made in explosions of massive stars. Note that helium and carbon are made in the low-mass asymptotic giant branch stars as well

## 1) Hydrogen

not made in SN.

## Supernova Remnants

What happens to the envelope

- Enriched with metals in the explosion

- Expands at a few  $\times 10,000$  km/s

### Supernova Blast Wave

- Plows up the surrounding interstellar gas

- Heats & stirs up the interstellar medium (that is, the gas between stars)

- Hot enough to shine as ionized nebulae up to a few thousand years after the explosion

## Stardust

Metal-enriched gas mixes with interstellar gas

- Goes into the next generation of stars

- Successive generations are metal-rich

Sun & planets (& us):

- Contain many metals (iron, silicon, etc)

- Only  $\sim 5$  Gyr old, so lots of stars had time to die and contribute to our stock of carbon, etc.

The Solar System formed from gas enriched by previous generations of massive stars.