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_{Sun}

- Collapses and begins to heat up
- T> 10 Billion K
- Density ~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

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

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 (~R_{Sun})

Density ~10^8 g/cc

1 second later…

Radius ~50 km

Density ~10^{14} g/cc

Collapse Speed ~0.25 of the speed of light

Core Bounce

Core collapses until its density is ~2.4×10^{14} g/cc, the density of an atomic nucleus!

Then the strong nuclear force comes into play!

Inner 0.7 M_{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 laster

Breakout speed ~10% the speed of sound

Supernova!

At shock breakout

Brightens by 10 billion L_{Sun} in minutes

Outshines an entire galaxy of billions of stars!

Outer envelope is blasted off:

Accelerated to a few x 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
$15M_{Sun}$ Blue Supergiant Star: SK-69^{o}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 Nicket
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 ^{254}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 x 10,000 km/s

<u>Supernova Blast Wave</u>

- 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 ~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.