Lecture 14. The Solar Interior

So why doesn't Sun just collapse into an invisible point? Basic questions of stellar astrophysics:

What keeps stars shining? What holds them up?

The Solar "Energy Crisis"

What keeps them shining? Best illustrated for the Sun:

We know total power (energy/sec) being generated now by the Sun:

Solar Luminosity: 4×10^26 Watts (Watt = 1 Joule/sec)

We know from Moon geology that the oldest rocks in the solar system are about 4×10^9 years old (1.2×10^{17} sec)

=> the sun has been generating this luminosity for over 4 billion years

So: the total amount of energy generated by the sun in this time is

\[ \text{Energy} = 4 \times 10^{26} \text{ Joules/sec} \times 1.2 \times 10^{17} \text{ sec} \]
= 4.7×10^{43} Joules !!

How much fuel is available? 1 \( M_{\text{sun}} = 2 \times 10^{30} \) kg, if pure fuel.

That means this fuel must have a mass efficiency

4.7×10^{43} \text{ Joules} / 2 \times 10^{30} \text{ Kg} = 2.3 \times 10^{13} \text{ Joule/Kg}

Let’s look at the mass efficiency of some typical sources of energy

• Chemical fuel (eg hydrocarbons): 2×10^7 Joule/kg (would keep sun going only 5000 yr)
• Leftover heat from formation: 10^{11} Joule/kg ( " 25 Myr)

The basic puzzle here is Where does the energy really come from?

It turns out (Kelvin, 1800's): you can't understand it on the basis of the physics we have discussed so far: the solution (in this case) is Nuclear Energy:

• Chemical energy: energy comes from rearrangement of electron energies in atoms and molecules. The energy due to the electrostatic force.
• **Nuclear energy**: energy comes from rearrangement of protons and neutrons inside nucleus of atom. The energy is due to the nuclear forces.

Iron (\(^{56}\text{Fe}\)) has the most stable nucleus, so you can (in theory) get energy by transmuting into Iron:

**Fission**: Break up nuclei of high atomic weight into lighter ones (works for elements heavier than Iron)

**Fusion**: Combine ("fuse") small nuclei into heavier ones (works for elements lighter than Iron)

### Nuclear Structure

The nuclear forces are:

• "Strong" Force. This holds the protons and neutrons together. In particular, it overcomes the electrostatic force between the protons, but only when the protons are within about \(10^{-13}\) cm of each other (it is a very "short range" force).

• "Weak" Force. This (among other things), holds the neutron together. Outside of the nucleus, the neutron is actually unstable, and comes apart:

\[
\text{n} \rightarrow \text{p}^+ + \text{e}^- + \nu \quad (\nu \text{ is the "neutrino", an almost massless, chargeless subatomic particle})
\]

### Thermonuclear Fusion

Since Sun is mostly Hydrogen, and the largest step is from H to He, the nuclear process potentially yielding the most energy is Hydrogen Fusion.

The simplest Hydrogen Fusion reaction is the "proton-proton chain":

\[
\begin{align*}
\text{H} + \text{H} &\rightarrow \text{H} + \text{e}^+ + \text{neutrino} \quad \text{Happens} \\
\text{H} + \text{H} &\rightarrow \text{He} + \text{gamma ray} \quad \text{twice}
\end{align*}
\]

\[
\text{He} + \text{He} \rightarrow \text{He} + \text{H} + \text{H}
\]

Note: "proton-proton chain" is only one way of getting He from H. There are more complex pathways which are favored in other stars (later)

**Ingredients** (recall the superscript number on left is the atomic weight, the sum of the number of protons and neutrons):
### Products:

- **1H**: Common Hydrogen
- **2H**: Deuterium
- **3He**: Helium 3
- **4He**: Common Helium

### Hydrogen Fusion Bottom Line:

- **4 H -> He + Energy + Neutrinos**

#### Efficiency:

Efficiency: $6.3 \times 10^{14}$ Joules/Kg. This is 25x more than enough! (Note: The product He has a mass 99.3% of 4 H nuclei. The 0.7% of the mass has been converted to energy by famous equation $E = Mc^2$. More later)

#### Stability:

Why doesn’t all the Hydrogen in the Universe spontaneously fuse in a humongous Hydrogen Bomb?

The hydrogen nuclei (pure protons) in the first step have positive charge, so they push each other away. Must slam them together very hard. Protons must get close enough that the strong force overcomes electrostatic repulsion.

Requires temperature of 16 million °K (Thermo-Nuclear)!

- Hydrogen bomb: this temperature reached only very briefly, then disintegrates
- Fusion reactor: gas must be contained at this temperature

It is hard to make fusion reactors on the Earth, but the inner part of the sun is sufficiently insulated to reach $10^7$ °K.

#### Verification:

We have no direct evidence that this is actually happening, except:
Neutrinos

Very elusive particles. Interact so infrequently with matter that escape interior of sun (also go right through most telescopes!). Attempts to observe these see 1/3-2/3 of those expected. Stay tuned.
Lecture 15. The Interior of the Sun

What holds them up?
High temperatures in sun (and other stars) mean material is gaseous throughout (exceptions later). It turns out gas is much easier to understand than solid or liquid, so can make simple "model" of sun which matches all properties very well:

The Rules:
• **Pressure Balance** ("hydrostatic equilibrium"). At every depth, the weight of the overlying material is exactly balanced by the gas pressure. (Otherwise the material would be rapidly accelerated, collapsing or blowing up the star in a few days)

• **Equation of State.** This tells how the gas pressure depends on its composition, temperature, and density:

  "Perfect Gas": in the sun (and in the Earth's atmosphere) the pressure (P) is proportional to the temperature (T) and particle number density (N). k is a constant ("Boltzmann's constant"). N, particles/cm³, includes all free particles, like atoms, free electrons, molecules, etc, each counted once. (There are other, more exotic equations of state, governing stars more exotic than the Sun)

  \[ P = N k T \]

This already illustrates the basic principle: *The sun does not collapse under its own gravity because it is hot enough inside that the pressure balances gravity.* But how hot is it?

• **Temperature Balance** ("thermal equilibrium"). At every depth, the loss of heat due to cooling is exactly balanced by heating from the inside. (Otherwise the material would heat up or cool down, which would mess up the pressure balance in a few thousand to a million years).

• **Energy Transport** (how good is the insulation) This tells how easily the heat flows from the inside to the outside. Depending on conditions, 
  Conduction. Hot atoms run into cool atoms, speeding them up (e.g. touching hot stove).  

**Convection.** Hot gas is light, cool gas heavy. If gas "turns over", it carries heat (e.g. "heat waves" above a hot highway, cumulus clouds).

**Radiation.** Hot gas emits light, which is absorbed by cool material. (e.g. how sun heats up earth).

- **Energy Generation** This tells how energy lost to the outside (the star's luminosity!) is replaced. In the sun, this is the "proton-proton" variety of hydrogen fusion. Depends very sensitively on temperature. (There are other varieties active in other stars.)

So the bottom line is,

*as long as fusion continues in the center of the sun, it replaces the heat lost to the outside, keeping the temperature high enough that it does not collapse under its own gravity.*

---

**Interior Structure of the Sun**

Can calculate physical state of interior of Sun based on these principles:

**Center:**
- Temperature 15.8×10^6 K
- Density 162 gm/cm^3 (162x water)
- % H: 34% (down 2x from start at 70%)
- %He: 64%

**“Core”:**
- ½ of nuclear fusion (mostly proton-proton) takes place within inner 10% of radius

**“Envelope”**
- Radiative heat transport out to 70% of radius
- Convective heat transport in outer envelope

"**Atmosphere**"
- Photosphere, Chromosphere, Corona

**Verification:**

**Helioseismology.** Can see “ringing” of sun as sound waves propagate through it!
- Brightness variations
- Velocity variations (Doppler effect shifting of absorption lines)

**Neutrino Flux**
- The relative number of neutrinoes from the different branches of the p-p cycle is
very sensitive to core temperature and density. This must be almost right

**HR Diagram**
- The radius of the Sun (and so its position on the Main Sequence) comes out right:
Lecture 16. The Main Sequence; Stellar Evolution

The Sun is a Main Sequence star. Let's apply what we have learned to the other Main Sequence Stars:

**What is the Main Sequence?**

**Properties of the Main Sequence**

For Main Sequence stars (90% of observed stars), there is a unique relationship among Mass, Luminosity, and Radius (Surface Temperature):

<table>
<thead>
<tr>
<th>Mass</th>
<th>Luminosity</th>
<th>Radius</th>
<th>Surf Temp</th>
<th>Spec</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>5x10^5</td>
<td>18</td>
<td>40,000</td>
<td>O5</td>
<td>zeta Pup</td>
</tr>
<tr>
<td>3.2</td>
<td>80</td>
<td>2.5</td>
<td>9900</td>
<td>A0</td>
<td>Vega</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5800</td>
<td>G2</td>
<td>Sun</td>
</tr>
<tr>
<td>0.1</td>
<td>8x10^-4</td>
<td>0.13</td>
<td>2400</td>
<td>M7</td>
<td>Wolf 359</td>
</tr>
</tbody>
</table>

So the most massive Main Sequence Stars are the most luminous (by a lot) and the largest. Recall that the least luminous, and thus the least massive main sequence stars, are the most common.

For Supergiants, Giants, and White dwarfs, there is no obvious relation between mass and position on the HR diagram.

Hypothesis: the other Main Sequence stars are just like the Sun, with different masses. More precisely

Main Sequence: stars supported against self-gravity by a Perfect Gas heated by Hydrogen Fusion in the core.

This is verified in a number of indirect ways (we can't see neutrinos from stars other than the Sun)
For one, it works theoretically: The main sequence radii and luminosities are exactly what you get if you assume all these stars are just like the sun, but with different masses:

- Why does the main sequence luminosity increase so rapidly with mass? 
  *The central temperature of more massive stars must be higher to support additional material. The Hydrogen fusion rate is very sensitive to the star's central temperature.*

- Main sequence stars are especially stable because of the Perfect Gas thermostat mechanism: if fusion rate increases slightly, heats core, causing star to expand and cool, which brings fusion rate down again. This is also why main sequence stars fall in a pretty small range of sizes.

- Why aren't there any main sequence stars outside of the mass range $0.1 < M/M_{\odot} < 50$?
  $> 50 M_{\odot}$: luminosity so high that the pressure of the light itself blows it apart again!
  $< 0.1 M_{\odot}$: required core temperature so low that H fusion does not turn on. Should gradually collapse into "brown dwarf" (these have just been seen!)

**Differences along the Main Sequence**

Because of the increasing core temperature of the more massive MS stars, there are differences in stellar structure along the MS

- H Fusion process:
  $< 1.25 M_{\odot}$: proton-proton reaction (like the Sun)
  These stars have radiative cores and convective envelopes
  
  $> 1.25 M_{\odot}$: CNO cycle this is a catalytic reaction which uses existing trace carbon, nitrogen, and oxygen to help along the first step:

  \[
  \begin{align*}
  C^{12} + H^1 & \rightarrow N^{13} + \gamma \\
  N^{13} & \rightarrow C^{13} + e^+ + \nu \\
  C^{13} + H^1 & \rightarrow N^{14} + \gamma \\
  N^{14} + H^1 & \rightarrow O^{15} + \gamma \\
  O^{15} & \rightarrow N^{15} + e^+ + \nu \\
  N^{15} + H^1 & \rightarrow C^{12} + He^4 
  \end{align*}
  \]
Result:
\[ 4 \text{H}^1 \rightarrow \text{He}^4 \] (the C\textsuperscript{12} is returned as a catalyst)

These is even more sensitive to temperature than the proton-proton reaction

*Important: Even though it is called the CNO cycle, it still fuses H to Helium*

These stars have convective cores and radiative envelopes

• Convection/radiation boundary: Moves outward as the mass increases.

What are the stars not on the main sequence? *They must be stars using some other fuel and/or supported in some other way.* Theory of *Stellar Evolution* tries to explain them as stages of star lifetime before and after a main sequence stage.

**Bottom line:** each stage lasts as long as the fuel lasts. Gravity wins eventually, resulting in the partial disruption of the star and a collapsed remnant.
**Stellar Evolution**

Stellar lifetime consists of

1) Formation: time before H fusion stars in the core. Sometimes called "pre-Main Sequence"

2) Fusion lifetime: energy supplied by various fusion processes, starting with "Zero-Age Main Sequence" (moment H fusion starts in core). Age is counted from here. This can be a life with complex stages, called "Stellar Evolution"

3) Remnant: after fusion runs out, (usually) an inert remnant is left, lasts indefinitely.

We will do 2 and 3. leave 1 for later...

Fusion life: What happens after star starts core H fusion?
Eventually fuel runs out and gravity wins.
How fast and in what stages depends almost entirely on the initial mass.

**Theoretical stellar evolution:** Can predict how star evolves by looking in detail at interior of model (T, P at different depths), while allowing composition to change as fusion proceeds. For each starting mass, star will occupy a succession of positions on HR diagram as it evolves; called "Evolutionary Track"

**Observational stellar evolution:** Star clusters are very useful in study of stellar evolution:
All the stars are born from the same composition gas
All the stars have the same age
The only stellar differences are the mass, and how the mass affects the star's appearance at the cluster's age. So the HR diagram for a cluster is a snapshot of what stars of different masses look like after some time (called an "isochrone"). Try to match these with theoretical clusters.
Lecture 17. H Fusion: Main Sequence and Red Giant

**Hydrogen Fusion Stages of Stellar Evolution**

**Main Sequence**: Perfect gas + fusing H in core

**Evolution timescale**.

To estimate the duration of any stage that depends on an energy source:

Energy available = Mass × Efficiency
Rate of energy use = Luminosity (Watts)
Lifetime = (Energy Available)/(Rate of Use)

\[ \text{Lifetime} = \text{Efficiency} \times \frac{\text{Mass}}{\text{Luminosity}} \]

For the sun, we find M.S. lifetime = \(10 \times 10^9\) yrs ("10 Gyr")
For the rest of the main sequence, can do ratio with sun:

**M.S Lifetime/Solar M.S. Lifetime** = \(\frac{M}{M_{\text{sun}}} / \frac{L}{L_{\text{sun}}}\)

So can complete our table for main sequence stars:

<table>
<thead>
<tr>
<th>Mass</th>
<th>Luminosity</th>
<th>Rad</th>
<th>Surf Temp</th>
<th>Sp</th>
<th>MS-Life</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>5x10^5</td>
<td>18</td>
<td>40,000 °K</td>
<td>O5</td>
<td>8x10^6 yr</td>
<td>zeta Pup</td>
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<td>2400</td>
<td>M7</td>
<td>10^12</td>
<td>Wolf 359</td>
</tr>
</tbody>
</table>

- more massive stars last a much shorter time!
Evolution on the Main Sequence

While on Main Sequence, there are slow changes:

Zero-Age Main Sequence: first ignition of H in core.

Evolution: As 4H -> He in core, the number of gas particles is reduced. For a "perfect gas" it takes a higher core temperature to maintain the same pressure. As core temperature rises, fusion rate rises, so luminosity increases somewhat. (This is very important for understanding origin of life on earth. Sun's luminosity has grown at least 50% since birth of Earth. Planetary scientists having difficult time understanding why Earth was not in permanent ice age then!)

Then What?

After the Main Sequence: Red Giants and Supergiants

When H runs out in core (core is about 10% of mass), core starts contracting, heats up, starts H fusion in "shell" around core. Outer layers to bloat out and cool off:

Red Giant: Perfect Gas + fusing H in shell
Core: He ash, not fusing

M < 1.25 M\text{sun}: happens gradually
M > 1.25 M\text{sun}: sudden adjustment, since CNO fusion caused core to be convective and fully mixed.

Star moves to right in HR diagram: Red Giant Branch

M < 2 M\text{sun} (about): stars first move gradually to the right in HR. These are the Subgiants
M > 2 M\text{sun}: stars move quickly to the right. Few stars found here. This is the "Hertzsprung Gap" (observed!)
M > 10 M\text{sun}: stars move toward the top of the Red Giant Branch: these are Red Supergiants
It checks! Next most numerous stars to main sequence are **Red Giants**: correspond nicely to this stage. Duration of stage, 20% of Main Sequence lifetime.

For sun, (in about 5 billion years)
- Radius -> 1 AU (incinerating Mercury, Venus, and Earth)
- Surface Temp -> 3500 K (very red)

**Why is the star adjusting in this way?**

There are at least three things happening simultaneously!
1) Overall composition change -> luminosity increase (as above)
2) Composition becomes increasingly inhomogeneous: core has heavy particles; envelope has light particles. Pressure and thermal balance makes core shrink while envelope expands -> size increase + surface temperature decrease
3) Shift from core fusion to shell fusion -> inert core collapse + envelope expansion

(1) would happen regardless. Moving to the right in HR depends on (2) and (3). If one artificially constructs stellar models in which the fusion products are mixed throughout the star as they are produced, the stars actually move to the left. This is not observed, so stars must not be fully mixed.
Lecture 18. Stellar Age; He Fusion and Degeneracy

Dating Stars

As a cluster ages, the most massive stars run out of core Hydrogen first, moving to Red Giant stage: The point where stars are just leaving the Main Sequence is called "main sequence turnoff" point.

The age of a cluster is just the main sequence lifetime of the stars at the main sequence turnoff

This is about the only way astronomers have to date objects outside the solar system!

Even fancier: can construct "Theoretical Cluster HR diagrams" by aging (in the computer) stars of a range of masses to the age of an observed cluster: allows for checking models of later stages of stellar evolution.

Some observed cluster facts:

! Young clusters are always found near active star formation sites. (Seems logical)
! Middle-age clusters are usually "open" clusters: 100-1000 stars loosely bound together by gravity.
! The oldest observed clusters are 13 billion years old. They are globular clusters: Tight assemblages of 100's of thousands of stars.

Timescales (for the sun: the times are faster for more massive stars)

! H core fusion: Main sequence lifetime
! H shell fusion alone: few million years: "subgiant -&gt; red giant or supergiant". Subgiant is very fast for high mass stars, produces "Hertzsprung Gap" in the H-R diagram
Summary: let's summarize the life stages for various stellar masses in a "Fate vs Mass Diagram". Here is the story so far:

**Helium Fusion Stages of Stellar Evolution**

What happens next? Pretty complicated, but a few general things are clear:

- Stellar core staves off collapse for a while by fusion of heavier elements
- Some of stellar envelope ejected, either gradually or explosively
- Some kind of collapsed "remnant" left behind.

The next fusion process: Helium fusion

As Hydrogen "shell" fusion continues, helium "ash" left behind in core continues to collapse and heat up. If \( M > 0.4 \, M_{\odot} \), the core temp gets to about 100 million \( K \) (!) and the He begins to fuse to still heavier elements \( C, O \)

\[
^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} \quad \text{(Beryllium)}
\]

\[
^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C} \quad \text{(Carbon)}
\]

Since Helium nuclei are known to physicists as "alpha particles" this is called the "triple-alpha process". Also get Oxygen from

\[
^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O}
\]
On H-R: reversion to a core fusion source causes star to become less bloated when He ignites in the core (smaller, higher surface temperature) but still to right of main sequence.

Low mass stars (get to this stage in very old globular clusters): "Horizontal Branch"
Higher mass stars (seen in younger open clusters): "Blue Loop stars"

He core fusion plus H shell: 20% M.S. lifetime

Running Out Again!

After Helium in core exhausted: Just as when Hydrogen ran out in core, core (now carbon) shrinks, heats up, star envelope expands, cools. Becomes Red Giant/Supergiant again, radius > 2 $R_{\odot}$ (there goes Mars!). Start fusing Helium and Hydrogen in separate shells. (current models say this is unsteady, in "shell flashes", which stir up insides)

Star returns to the Red Giant Branch, now renamed:

Asymptotic Giant Branch: Perfect Gas + He and H fusing in shells
Carbon inert core
Advanced Stages of Stellar Evolution

The details of the rest of the story quite uncertain - the subject of current research!

What happens next depends on mass of star, again:

**Low Mass (< about 8 M$_{sun}$) Fate (eg, Sun)**

Carbon core (ashes of helium fusion) shrinks, never gets hot enough for Carbon fusion.

Outer envelope (maybe 50% of stellar mass) gets so distended that part of it drifts off into space, giving "Planetary Nebula". This uncovers hot compact "degenerate C" core, which is now to left of Main Sequence ("hot subdwarf"). Short stage, but many are seen.

Nebula drifts off in maybe 50,000 years, core cools into "white dwarf".

**Degeneracy**

Things get peculiar here, because of the onset of an odd property of very dense gases called degeneracy. This is a new "equation of state" replacing "perfect gas"

**perfect gases**
Atomic particles (electrons, nuclei) are separated by much vacuum, behave much like billiard balls. The higher the temperature (speed of particles), the higher the pressure. The gas is "thermostated": if you heat it up, it tends to expand and cool back to its old value (this is why main sequence stars are stable)

**degenerate gases**
At very high densities (and if temperature not too high), degeneracy is a quantum mechanical equivalent of "size", which keeps particles apart regardless of temperature.

In a degenerate gas, pressure does not depend on temperature.
As you compress an ionized gas, the electrons become degenerate first, called **electron degeneracy**. Degenerate gases are not thermostated, since if you heat them up they don't expand, until it gets so hot that the gas reverts to "perfect". (The Helium core of lower mass stars ($< 3 \, M_{\text{sun}}$) is actually electron degenerate: when it gets hot enough for Helium fusion it happens explosively ("**helium flash""), suddenly rearranging star into a **Horizontal Branch** star. Common in globular clusters (the only clusters which are old enough to have such low mass stars evolved).
Lecture 19. White Dwarfs; Supernovae

Remnants of low-mass stars:

**Supported against gravity entirely by electron degeneracy.** Density is extremely high: ≈ $10^6 \times$ water! Radius: approximately radius of Earth ($0.009 R_{\text{sun}}$)

No energy sources at all. Luminosity due to remnant heat. Since surface area very small, even the hottest (10000 to 30000 K) have very small luminosity $10^{-4}$ to $10^{-2} M_{\text{sun}}$. So it takes a long time to cool off.

The higher the mass, the smaller the radius!

<table>
<thead>
<tr>
<th>$M/M_{\text{sun}}$</th>
<th>$R/R_{\text{sun}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.013</td>
</tr>
<tr>
<td>1.0</td>
<td>0.008</td>
</tr>
<tr>
<td>1.4</td>
<td>$\rightarrow 0!$</td>
</tr>
</tbody>
</table>

In fact, White Dwarfs are not possible for masses $> 1.4 M_{\text{sun}}$. This is called the "Chandrasekhar Limit". Physically what happens for would-be white dwarfs above the C. Limit is that the electrons approach the speed of light and the star is no longer stable: it would collapse. (Later we will encounter WD's that are pushed into this situation by mass transferred onto them from a nearby companion.)

Ultimate fate: white dwarf cools off to undetectable "black dwarf" in a few 100 billion years. Since radius does not depend on temperature, cooling is along line of constant radius: defines where White Dwarfs are on H-R diagram. Material (mostly carbon) becomes "crystalline". **This is the ultimate fate of Sun.**

**Known White Dwarfs:**

100's of stars nicely matching these properties are found within about 50 pc of Sun. (e.g. Sirius B). Some of the more luminous ones (the youger, hotter ones) have been seen in globular clusters.

Here is the story so far:
How massive can a star be to still make it to the white dwarf? Stars do lose mass (especially the less stable, more massive ones) at each stage change. White dwarfs have been found in the Pleiades cluster (M45, age 50 Myr), where stars of 8 $M_{\odot}$ (B5 stars) are just leaving the main sequence.
But what happens to stars that start out with more than 8 $M_{\text{sun}}$? ....

**High Mass (> 8 $M_{\text{sun}}$) Fate (eg, Betelgeuse)**

Impending Doom! No matter what the details, the core will be more massive than the Chandrasekhar Limit, so some violent event must intervene. **In the process, most of the elements below Iron are formed.**

The picture, as now understood (this might change!):
- After core helium runs out -> Red Supergiant, as before

- Start helium fusion in shell, core collapses. The following happens too fast for a Planetary Nebula to be ejected:
  - For $M$ (main sequence) $> 8 M_{\text{sun}}$, temperature $\rightarrow$ 600 million K, starting core Carbon fusion:
    \[ ^{12}\text{C} + ^{12}\text{C} \rightarrow \text{Neon, Magnesium, Oxygen} \]
    For $M < 9 M_{\text{sun}}$, this should occur when the core is degenerate, giving "C detonation". This may or may not disrupt some stars.
  - After carbon runs out in the core, start carbon shell fusion, core collapses.
  - For $M > 9 M_{\text{sun}}$, temperature $\rightarrow$ 1 billion K, start core Neon fusion:
    \[ ^{20}\text{Ne} \rightarrow \text{Oxygen, Magnesium} \]
  - After this runs out, start neon shell fusion, core collapses.

- Next, get similar steps of
  - 1.5 billion K: Oxygen fusion $\rightarrow$ Silicon, Phosphorus, Sulfur, Magnesium
  - 3 billion K: Silicon fusion $\rightarrow$ hundreds of isotopes, including Iron ($^{56}\text{Fe}$)

This is the end: **There is no energy available from Iron, since it is the most stable element.**
**Timescale:** These happen with increasing speed, since each successive step yields less energy. For 25 M$_{\odot}$ star:

<table>
<thead>
<tr>
<th>Element</th>
<th>Fusion Stage</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>fusion</td>
<td>600 years</td>
</tr>
<tr>
<td>Neon</td>
<td>&quot;</td>
<td>1 year</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&quot;</td>
<td>6 months</td>
</tr>
<tr>
<td>Silicon</td>
<td>&quot;</td>
<td>1 day</td>
</tr>
</tbody>
</table>

HR evolutionary track. This is very hard to calculate, because:
- The star is continuously losing mass, at a rate which is not yet understood
- The fusion stages change more rapidly than the star can adjust thermally (the envelope does not find out about core changes, so position on HR changes only sluggishly)

For less massive stars, stages take longer, since pressure (temperature required) is much lower.

**Sample star:** Betelgeuse! (alpha Ori). M = 10 M$_{\odot}$. Probably in carbon core fusion stage, maybe lasting 100,000 years.

- Next: Burned-out core collapses into something very compact (is beyond Chandra Limit), (somehow) releasing enough energy to expel the envelope (with its heavy elements) in **Supernova**

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**Supernova Scenario**

Current ideas on what happens in a supernova (actually "Type II" supernova - there are others)

More than 1.4 M$_{\odot}$ of fusion ash accumulates: electron degeneracy fails and core collapses (in 0.25 sec!)

When core temperature reaches 5 billion K, electron + proton $\rightarrow$ neutron + neutrino
All electrons are turned into neutrons

**Neutrinos almost all escape star, carrying away most of remaining energy**

Core neutrons collapse to a density $4 \times 10^{14}$ gm/cm$^3$, the density inside an atomic nucleus (core is few 10's of km across). **Collapse halts under**

---

23
nuclear forces.

Rest of inside of star crashes down on core generating shock wave, which (in some models) escapes the star, **blowing off envelope. This causes the visible explosion.** Leaves expanding **gaseous remnant.** (note: a very difficult calculation. But it must happen, since we see the explosion!).

**Core settles into a collapsed remnant.** Either:

a) **Neutron star.** Supported by neutron degeneracy. Radius 10 km. Like white dwarfs, there is an upper mass limit, maybe 3 $M_{\odot}$. Above this, get a

b) **Black hole.** Surface gravity so large that light can't escape. Disappears except for gravity.

The final picture:
Lecture 20. Observed Supernovae; Pulsars

Supernovae of the Past

There have been three supernovae in modern history that have been visible to the naked eye:

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cas (Tycho's)</td>
<td>1572</td>
<td>-4.1</td>
</tr>
<tr>
<td>Oph (Kepler's)</td>
<td>1572</td>
<td>-2.2</td>
</tr>
<tr>
<td>SN 1987A</td>
<td>1987</td>
<td>3.0</td>
</tr>
</tbody>
</table>

(Five others, in AD 185, 396, 827, 1006, and 1054 have been reported by historians).

SN 1987A. The only naked-eye SN observed with modern techniques:

- Location: in Large Magellanic Cloud ("LMC"), a nearby galaxy
- Light Curve: peaked at 3 mag after 85 days; now fainter than 15th.
- Pre-SN star. The star that exploded has been identified in old photographs and surveys of LMC. It was Sk -69 202, a 13th mag B3I supergiant (10^5 L☉).
- Theoreticians best estimates: on MS was 20 M☉. Shed mass by mass loss. Just before SN, had maybe 5 M☉ Hydrogen in envelope, and 6M☉ Helium, 2 M☉ heavier elements, including 1.5 M☉ iron in core.
- Neutrinos. For 0.1 sec, power calculated to be 10^{47} Watts. In fact, SN1987A was the first (except for sun) astronomical object seen in neutrinos! 3 hours before reported in visible light, approx 10 neutrinos seen in Japan and US. Just the right amount and timing!
(Gaseous) Supernova Remnants (SNR's)

Supernovae are visible for tens of thousands of years through visible and radio light emitted by ejected gas. The emission lines from the nebula are often very rich in lines from heavy elements, as expected.

The time of an SN can be estimated from the current expansion of nebula (using doppler shift of emission lines). Some are identifiable with historical SN's:

- Cas A - Kepler’s SN
- Crab Neb - SN 1054
- "Echo" remnant of SN1987A (old ejected gas lit up by explosion)

Origin of the Heavy Elements. All identified SNR’s are rich in heavy elements CNO .. Fe .. presumably produced in the fusion leading up to the explosion. By a rough count of SN’s/year, these account for most of the elements heavier than Helium in the universe.

=> We are made of supernova remnants!

What else is left? Collapsed remnants: neutron star, black hole

Collapsed Stellar Remnants: Pulsars and Black Holes

Neutron Stars

Neutron stars: degenerate gas stars, but electrons and protons are combined into neutrons. Recall for White dwarfs: electron degeneracy works up to $M < 1.4 M_{\text{sun}}$ (“Chandrasekhar Limit”)

Neutron Stars: neutron degeneracy works up to $M < (\text{roughly!}) 3 M_{\text{sun}}$

The supernova scenario suggests neutron-degenerate objects may be formed in the evolution of the most massive stars. They would be very exotic objects. For instance
- Mass 1.3 $M_{\text{sun}}$
- Radius: 16 km. Surface area small: thermal radiation too tiny to observe (until recently).
Central Density: $4 \times 10^{14}$ gm/cm$^3$ (the density of an atomic nucleus)
Escape velocity: $1/2$ speed of light

How to observe such objects? Accidental discovery: radio pulsars
Lecture 21. Pulsars; Black Holes and General Relativity

Pulsars

First discovered (1967) pulsar:
CP 1919+21 (in Vulpecula, just south of Cygnus).
All of radio power concentrated in pulses 25 ms long with period P=1.3373011 sec, regular to 8 decimal places.

The first rule to apply to any rapidly variable phenomenon:

Any variable object must be smaller than the distance light travels in its observed variability time:

\[ R < R(var) = c \cdot t(var) \]

This is because any actual variability that might be faster is smeared out when we observe it by the delay between the light reaching us from the front and back part.

In this case \( t(var) = 25 \) ms, so \( R(var) < 7500 \) km. This is comparable with the size of a white dwarf, so some early ideas used them (but the regularity is very hard to attain!)

Then (1968): NP 0531+21 clinches neutron star hypothesis:
Pulse length = 1.9 ms (\( R(var) < 600 \) km!)
Period = .0330976 s
Right in middle of Crab nebula, known SN remnant!
Visible star found, seen entirely in 33 ms pulses!

Explanation for rapid pulses: lighthouse beam effect

Pulse periodicity due to very rapid spin (also explains repeatability): Collapse to neutron star preserves angular momentum (spin period proportional to \( 1/\text{size}^2 \)): if spins like sun \( P \sim 1 \text{ mo}/10^8 \sim 1 \text{ ms} \)
Pulse mechanism is particle acceleration: Collapse to neutron star preserves magnetic field (field also proportional to $1/\text{size}^2$): get $10^{10} - 10^{12}$ gauss. Particles accelerated in beam from magnetic pole, emits flash of radiation (radio, visible, X-ray when pointed at us).

This mechanism is verified by the observation that pulsar periods are very gradually growing longer. (The particle acceleration energy is extracted from the energy of rotation!). A pulsar will slow down and fade in $10^5$ yr.

Will SN 1987A make a pulsar after gaseous remnant has cleared?? Stay tuned!
Lecture 22. Special and General Relativity

Neutron stars are already very close to \( v(\text{escape}) = c \). If mass > 3 \( M_{\text{sun}} \), nothing can stop it collapsing beyond that point. Then get "\textbf{black hole}". Description requires physics beyond Newton's classical mechanics:

**Relativistic Mechanics:** Einstein special and general relativity

Whenever speeds approach speed of light:

**Special Relativity.** Applies to uniform motions (no acceleration):

Experiments show there is a special speed in Physics: \( \text{light appears to travel at the same speed for any observer, regardless of relative motion.} \)

\[ \Rightarrow \text{There is no absolute motion - only relative.} \]

Light is used to make measurements of size (comparing meter stick with object), and time (comparison of arrival of light from event with clock).

\[ \Rightarrow \text{Measurements of size and time are affected by motion of observer.} \]

Einstein Special Theory of Relativity shows how to make the corrections:

**Time Dilation.** Clocks in relative motion appear to slow down. (Verified! Unstable particles moving at \( v \sim c \) appear to last longer.)

**Lorentz (length) Contraction.** Moving meter sticks appear to be shorter in direction of travel.

**Mass (inertia in Newton's second Law) of a moving particle increases.** Approaches infinity as \( v \to c \) => practically, \( \text{YOU CAN'T TRAVEL FASTER THAN LIGHT.} \)

Special Relativity pretty simple, well verified.

**General Relativity.** Applies to accelerated motion:

Special relativity alterations of \textbf{space} measurements + non-uniform motion =>
Euclid's geometry no longer works ("space is curved")!

Special relativity alterations of time measurements + non-uniform motion $\Rightarrow$ space and time can no longer be treated as separate ("space-time continuum")

Gravity now enters as a special force: recall that gravity is proportional to mass, so that all masses are accelerated the same. Einstein postulated:

**Equivalence Principle:** you cannot distinguish between being at rest in a gravitational field and being accelerated in a gravity-free environment.

In Einstein's view: Mass causes curvature of space-time which looks like acceleration.

Best way of visualizing this: "toy" universe with only 2 space dimensions instead of 3. In absence of mass, space is a flat sheet, and objects travel in straight line from one edge to another. With mass present, sheet is depressed around mass. Objects travel along trajectory which is shortest distance between two points (called a "geodesic"). Near the mass, the trajectory is bent towards mass.

**Consequences of General Relativity**

1) **Kepler's First Law** (elliptical orbits) is slightly wrong. Curvature of space near mass $\Rightarrow$ circumference of orbit slightly less than $2\pi \times$Radius. **Verified:** accounts nicely for anomaly in Mercury's orbit.

2) **Gravitational lensing.** Light passing near a mass is deflected by curvature of space. Predicted light beam just grazing sun's surface deflected 1.75 arcsec. **Verified** in 1919 during solar eclipse + many recent examples.

3) **Gravitational redshift.** Clocks in high gravitational field appear to run slower than clocks in free space. One observable clock is the frequency of known absorption lines in stars. **Verified:** Extra redshift of lines in white dwarfs.

4) **Gravitational Radiation.** Objects accelerated when traveling near light speeds cause "ripples in space" which travel at the speed of light.

**Not yet observed directly** ("LIGO" the Laser Interferometer Gravitational-Wave Observatory now starting development, will operate near year 2000).
**Has been observed indirectly.** Pulsar/neutron star binary with period 7.8 hours has been found. Orbital velocity about 0.1 c, so gravitational radiation should be emitted, carrying away orbital energy, causing orbit to shrink and period to speed up. Pulsar allows very accurate period change measurement - Verified!
Lecture 23. Black holes; Binary Stars

5) **Black Holes.** (any object with \( v_{\text{esc}} > c \)). Einstein's general relativity has been solved for all possible "static solutions" of black holes. (Forming stellar-mass BH's probably settle into these very "rapidly" after radiating copious gravitational radiation).

**There are only three physical properties which define a static black hole:** 
**mass, electric charge, and angular momentum.** All other internal properties (magnetic field, composition, etc) have no effect on the outside. ("Black holes have no hair").

- **Mass**

If object is electrically neutral and non-rotating, it can be described by a single number: "**Schwarzschild Radius**". The radius of a sphere around a mass \( M \) at which the escape velocity is the speed of light. The Schwarzschild radius of a black hole is proportional to its mass.

\[
R(\text{Sch}) = \frac{2GM}{c^2}
\]

Doing ratios with sun,

\[
R(\text{Sch}) = 3 \text{ km} \times \frac{M}{M_{\text{sun}}}
\]

A **(nonrotating) black hole is observable only by its gravity**. Everything happening inside the Schwarzschild radius is unobservable by us. For this reason, the surface defined by the Schwarzschild Radius sometimes called the "**event horizon**".

Note: theoretically, **you can have a black hole of any mass, if you can somehow compress it within its Schwarzschild Radius**. The massive-star evolution scenario leads us to look for BH's of Mass 3 - 30 \( M_{\text{sun}} \).

Near the event horizon (Schwarzschild radius):
- Weird time effects due to general relativity
- In stellar-mass BH's: very large "tides" so that solid material is shredded.
Far from event horizon ( > 100 R_{Sch} ~ 3000 km )
  Looks just like gravity from an ordinary star of same mass =>
  **BH's can be detected in binary systems with ordinary stars**

! **Charge**
Theoretically this makes a difference, but electric force from a charged BH will
quickly suck in enough opposite charged particles to neutralize it.

! **Angular Momentum**
Since neutron stars are formed with rapid spins (pulsars) this seems likely.
  Solution called a "Kerr black hole". Spacetime outside event horizon is
  "dragged around" by rotation. It is theoretically possible to extract energy from
  the rotation.

**Observing Black Holes**

Only practical way so far involves observing the gravitational effect of a BH on its
surroundings:

**Close binaries with X-rays from unseen compact object**
In 1970, first X-Ray Satellite "Uhuru" found the **brightest X-Ray sources**
  **associated with close binary stars**. Some X-Rays pulsed.

**Scenario**: in close binaries, one star evolves so that it spills matter onto neighbor.
What if the neighbor is a compact remnant? Let's step back and revisit binary
stars...
**Studying Close Binaries**

**Eclipsing Binaries**: An excellent way of studying close binaries: some have plane of orbit near line of sight, get mutual eclipses of stars twice/period. Total Flux varies with binary "phase" in "light curve".

Get
- Radii of stars
- Structure of transfer stream and accretion disk.

**Spectroscopic Binaries** The stars quite close to each other; their images are merged, but their spectra are different since rapid orbital motion plus the Doppler Effect causes the absorption lines in each to be shifted by different amount $\Delta \lambda$ during orbit. Radial velocity $v_{\text{rad}} = \Delta \lambda / \lambda \times c$ of each star varies with binary phase in the "velocity curve".

Get
- Period $P$ = time for spectroscopic shifts to repeat.
- Orbital Speeds $v_1, v_2$ from largest Doppler Shift. (Except need correction for inclination)
- Speeds $\times$ Period $= 2 \pi$ (Orbit radii), $A_1$ and $A_2$ (for circular orbits, ellipses a bit more complicated)

$\Rightarrow$ Mass ratio from $M_2 / M_1 = A_1 / A_2 = v_1 / v_2$
- Sum of Masses from Kepler's third

We actually have more masses from spectroscopic binaries than from visual binaries where you actually see the orbit
Lecture 24. Close Binary Evolution

Close binary stars an important place to look to test ideas of stellar evolution:

! Can get masses of stars
! Evolution of most advanced star in pair is interrupted when it becomes so big that it loses mass to companion.

**Inner Lagrangian point**: point between stars where gravity just balanced

**Roche Lobe**: shape of star (like a teardrop) when it just reaches the inner Lagrangian Point

**Detached Binary**: neither star "fills its Roche Lobe"

**Contact Binary**: both do. May coalesce into one (very peculiar) star. e.g. W UMa

**Semi-Detached Binary**: one does. It loses mass via:
- Stellar wind. e.g. β Per (Algol)
- Mass Transfer Stream onto **Accretion Disk**. e.g. β Lyr

In many cases, the mass loser (big star) is less massive than the small star. How can this be? The big star must have run out of H first, so must have been more massive of pair! ("the Algol paradox")

Current idea: the mass loser has lost so much of its mass to the companion that the companion is now more massive. Will get "leapfrog" evolution with very weird results depending on whether the mass transferred is processed, etc.

Here are the stats for a binary star (circular orbits for simplicity)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Masses</td>
<td>(M_1, M_2)</td>
<td>(M = M_1 + M_2), the total mass</td>
</tr>
<tr>
<td>Orbital radii</td>
<td>(A_1, A_2)</td>
<td>(A = A_1 + A_2), the total orbital radius</td>
</tr>
<tr>
<td>Orbital velocities</td>
<td>(v_1, v_2)</td>
<td></td>
</tr>
</tbody>
</table>

Note: \(v_1 = 2\pi A_1 / P\) and \(v_2 = 2\pi A_2 / P\), so
\[
\frac{v_1}{v_2} = \frac{A_1}{A_2} = \frac{M_2}{M_1}
\]

As we transfer mass from one to the other, we assume:

Mass conservation: \(M_1 + M_2 = M = \text{const}\) (just transfer mass from one to other)
Angular Momentum: \[ M_1 A_1 v_1 + M_2 A_2 v_2 = J = \text{const} \]

Kepler's Third Law \[ A^3 / P^2 = (G/4\pi^2) M \]

What we find (the algebra is a bit messy):

*If you transfer mass from the more massive to the less massive star, the orbits get smaller*

This leads to a runaway! the closer the stars, the faster the mass transfer happens!

Current idea (subject of current research!)

- Once mass transfer starts, the stars' envelopes (but not the cores) quickly merge in a "common envelope"

- Stars emerge from common envelope phase (which lasts for maybe only 1000 years) with the mass ratio reversed. The more evolved star is now the less massive, as observed!

- Stars continue to exchange mass as the more evolved (now less massive) star continues to evolve (the core has still run out of fuel - it continues to Red Giant phase). The orbits widen (period lengthens) until mass transfer stops. These are Algol stars ("after the first mass transfer")

eg β Lyr. Just emerged from common envelope phase

- Semi-Detached; Eclipsing (Inclination ~83°); P = 12.91 days
- Distance 270 ± 30 pc
- Active Mass Transfer (W Serpentis type Algol)
  \[ \frac{dP}{dt} = 18 \text{ s/ yr} \quad \text{(period growing longer as orbit grows)} \]
  \[ \frac{dM}{dt} = 3 \times 10^{-5} \text{ M}_\odot / \text{yr} \quad \text{(if system conserves M, J)} \]

- Loser (Primary): B6IIp ~2 M_\odot. Originally 12 M_\odot?
- Gainer: B0V 12 M_\odot, occulted ~2 mag by:
- Accretion Disk: edge is ~A8II. ~6 R_\odot thick
Binary Star Fate

This is subject of current research because of what must happen next. The story depends on
   Initial Orbital radius A (is it close enough that one or both stars exceed their Roche lobe)
   \( M_1 \) (low or high mass evolution)
   \( M_2 \) (low or high mass evolution)

=> each binary star is an individual!

Here is a scenario (low mass - high mass)

   MS-MS
   MS-Giant (active mass transfer) -> Algol Binary ->
   pMS-SN (runaway MS?) ->
   pMS- NS or BH ->
   Giant- NS or BH (active mass transfer) -> X-Ray binary
   SN or PN - NS or BH (runaway NS?) ->
   compact-compact -> merger???

The interesting parts are where there is active mass transfer.
   Accretion power from a disk
   Explosions from compact gainer

1) Accretion power.
In close binary with mass transfer, gas spills into orbiting accretion disk around gainer.
Falling gas is heated up by friction with the material that it runs into:

\[
\text{thermal energy} = \text{kinetic energy} \\
kT = \frac{1}{2} m v_{esc}^2 = \frac{GM}{r}
\]

• It heats up as it falls toward gainer star. Temperature proportional to 1/radius to which it falls:
  If Main Sequence: radiates visible
  If white dwarf: " visible, UV
  If neutron star or BH: " X-Ray
• Accretion onto very small objects can be a more efficient energy source than fusion!

Fusion Energy \( \sim 0.007 \, \text{m} \, \text{c}^2 \)
Accretion Energy \( \sim \frac{1}{2} \, \text{m} \, \text{(infall velocity)}^2 \)
  but infall velocity = escape velocity \( \sim 0.5 \, \text{c} \)

Accretion Energy \( \approx 0.25 \, \text{m} \, \text{c}^2 \)

All the really luminous objects in the universe are probably fueled this way:
  Supernovae \( \text{accretion energy of forming NS or BH} \)
  QSO's \( \text{accretion energy of matter falling into galactic BH} \)

And
Lecture 25. X-Ray Binaries; Binary Star Explosions

In 1970, first X-Ray Satellite "Uhuru" found the brightest X-Ray sources associated with close binary stars with compact companions. Some X-Rays pulsed.

X-Ray Binary Black Hole Candidates

Currently best way of locating black holes: effect of Black Hole in Binary system

Method: process of elimination:

1) Find suspected compact objects in binary systems.

2) Find X-Ray binaries. X-rays evidence of accretion onto object smaller than white dwarf.

3) Eliminate pulsed X-Rays. These come from magnetic fields on spinning neutron stars. Black holes can't have magnetic fields.

4) Look for millisecond X-Ray "flickering": shows X-rays definitely coming from object smaller than white dwarf

5) Solve for sum of masses of two stars from doppler "velocity curve" of "normal" star. Can't get individual masses since only normal star has measurable lines.

6) (Somehow) estimate mass of "normal" star. Best if it is just leaving Main Sequence.

7) If remaining mass > 3 Mʘ, it must be a black hole, since that is too massive for a neutron star

The best cases so far:

Cygnus X-1 = HDE 226868.
A 9th mag single-line 5.6-day spectroscopic binary in Cygnus.
X-rays flicker.
Total mass from velocity curve ~ 30 M⊙.
"Normal" star a B0I supergiant. Evolution folks say M(B0I) < 24 M⊙,
Leaves \( M(\text{compact}) > 6 \, M_{\odot} \)

**LMC X-1.**
Similar, but period 1.7 days.
"Normal" star looks like a B3V main sequence star, so mass estimate more believable.
\( M(\text{compact}) > 9 \, M_{\odot} \)

**Explosions on Collapsed Objects**

When accreted material reaches white dwarf or neutron star:

**White Dwarf:** generates

**a) Nova**

White dwarf around small companion
Large mass transfer from rapid evolution, or from shrinking of orbit due to mass transfer.

Moderate mass transfer: "dwarf nova". Get repetitive accretion bursts of ~ 100 x over months or years

Higher mass transfer: "classical nova" > 1000 x, doesn't repeat in < 100 years.
About 1 of these per year. Light comes from rapid fusion of accumulating hydrogen on surface of white dwarf. Burst Duration: weeks - months.
Lecture 26. Binary Star Explosions; Nucleosynthesis

Eventually, WD can pick up enough matter to exceed its Chandrasekhar Limit (1.4 $M_{\text{sun}}$) =>

b) Type I Supernova

It turns out two types of SN's can be distinguished by light curve and spectrum:

**Type II**: Luminosity peaks at $6 \times 10^8 L_\odot$, drops off in two steps. Spectrum shows Hydrogen lines.

*SN1987A was Type II*, and fits the massive star scenario (hydrogen lines come from unfused material in envelope ejected into space)

**Type I**: Luminosity peaks at $4 \times 10^9 L_\odot$, drops off smoothly. Spectrum does not show Hydrogen lines.

Tycho's and Kepler's were Type I's. What is a Type I ??Scenario:

1) Start with **close binary with massive white dwarf** (nearly 1.4 $M_\odot$, the Chandresekhar limit, carbon core) **plus star now evolving off main sequence**.

2) As evolving star expands past "Roche Lobe", transfers mass onto white dwarf.

3) When white dwarf **nears Chandra Limit, starts collapsing**, heats up. While still degenerate, gets hot enough for carbon fusion. As in "helium flash" low mass star evolution, temperature is not thermostatted, so get "**carbon flash**".

4) This is **violent enough to disrupt whole star** in supernova. No collapsed remnant formed.
Neutron Star:

X-Ray Burster

Light comes from rapid fusion of accumulating He on surface of neutron star. Burst Duration: seconds.

The neutron star is "old", ie spun down, no longer a pulsar. As accreting matter hits it, conservation of angular momentum spins it up, "rejuvenating" it as a pulsar. Pulsars with 1 ms periods seen in globular clusters. Eventually, becomes so luminous that it heats up and destroys (consumes) its companion. - "black widow" pulsar systems.

Unsolved problem: All the neutron stars in binaries have measured masses of 1.4 $M_{\text{sun}}$. Scenarios invited!

Fuel for speculation: if a white dwarf in a nova system eventually makes a supernova when it reaches the Chandrasekhar limit, what does a neutron star in a burster system do when it reaches its limit???
Lecture 27. Nucleosynthesis; Stellar Recycling

A very important byproduct of the lives of stars is the production of the heavier elements. Let's look at elements that are produced in fusion processes that ultimately make it to the surfaces of stars and into their ejecta.

For these purposes, it is important to differentiate between different isotopes of the same element, which are produced in very different reactions.

Convenient plot: "the Z-N plane" a random point in the Z-N plane is a "nuclide"
Vertical: $Z =$ number of protons (element)
Horizontal: $N =$ number of neutrons

$A = Z + N =$ atomic mass, is distance along diagonal

Observe: stable nuclides for $N \sim Z$ up to Ca, then $N > Z$. Called the "stability valley". This is because adding n's provides binding force without adding charge, which is a repulsive force.

Classify nuclides according to reactions that produce them:

• Produced in Big Bang: $^1$H, $^4$He

• $\alpha$ nuclides: produced by adding $^4$He particles ($\alpha$ particles) together:
$Z = N = 2n$, so $A = 4n$ ($n = 1, 2 \ldots$)$^{12}$C, $^{16}$O, $^{20}$Ne ... $^{40}$Ca

Ca is the heaviest stable $\alpha$ nuclide

Since these can be made with just nuclides from the Big Bang, are called "primary nuclides". They are the most common.
• Neutron capture/β decay nuclides: if there are n's around, it is easy to add them, since there is no Coulomb (charge) barrier. This gets you to the right of the stability valley. As nuclei get n-rich, they become unstable and the neutrons split up: this is "β decay"

\[ n \rightarrow p^+ + e^- + \nu \]

eg: neutrons are produced as a side reaction during C fusion, producing Sodium (Na):

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + n \]

The neutrons may then be captured, by, say, an Yttrium - 88:

\[ ^{88}\text{Y} + n \rightarrow ^{89}\text{Y} \]
\[ ^{89}\text{Y} + n \rightarrow ^{90}\text{Y} \]

But \(^{90}\text{Y}\) is unstable, and β decays:

\[ ^{90}\text{Y} \rightarrow ^{90}\text{Zr} + e^- + \nu \]

(converting an n to a p does not change atomic mass, but does boost it up one element)

Which elements you get depends on whether you capture neutrons faster than you can decay:

**s-process** (slow capture of neutrons). Produces heavy elements near the center of the stability valley. Happens during unstable fusion of He and H shells in AGB stars. Carbon and s-process elements are brought to the surface in Carbon Stars

**A Test**: s-process produces Technetium (element 43), the only element below Uranium that has no stable isotopes. It is not seen in the Earth (decay < million years). *It is seen in C stars =>* it must be produced there and brought to the surface in < million years!
**r-process** (fast capture of neutrons). Produces heavy elements to right of valley of stability. Should happen in SN Type II

Test: the r-process and s-process elements should be constant among themselves but the relative amount of r and s could vary over the galaxy depending on the number of SN’s: It works!

A good way of looking for the results of nucleosynthesis is to look at stars that are formed from it:

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**The Interstellar Medium and Star Formation**

Stars are observed to form from collapse of cloud of diffuse matter, called **Interstellar Matter** ("ISM").

! **Interstellar Dust.** Smoke-sized "grains" of solid matter (silicate rock, carbon compounds, ices). Seen in:

- **Interstellar "extinction"**: Star light is absorbed and scattered by dust particles along very long light path. Flux of distant stars appears to be smaller than it ought to be for its luminosity and distance.
- **Interstellar "reddening"**: Dust extinction smaller for red light than blue. Distant stars appear to be redder than they ought to be for their spectral type.
- **Reflection Nebulae**: Dust near bright stars is lit up by scattered light.
- **Diffuse Infrared emission**: Heated dust radiates as blackbody at temperatures 10-100.

! **Interstellar Gas.** Atoms and molecules. Seen in:

- **Interstellar Absorption Lines**: For distant stars, some absorption lines in spectrum are not from atmosphere (tell from doppler shift).
- **Emission lines**: Interstellar gas near hot (O, B main sequence) stars absorbs UV light from stars, emits visible lines. (is mostly ionized hydrogen: "**HII region**"). Cool, neutral atoms, molecules also emit radio lines.
Lecture 28. Stellar Populations; Star Formation:

Stars may be roughly grouped into “populations” by the time of their formation using "enrichment dating". Careful spectral typing finds same spectral types sometimes show different strengths of lines from heavy elements.

Enrichment dating:

Elements in a star's atmosphere are representative of elements in the interstellar gas at the time of its birth. (New ones formed by fusion are hidden in core until after main sequence lifetime)

1) "In the Beginning": "Population III"
H,He interstellar gas -> Stars (first generation, no metal absorption lines)
Stars fuse H,He -> C,N,O,"Metals"
Supergiants, Planetary Nebulae return new fusion products CNO back to the interstellar gas
Supernovae return all elements, including “metals” and “heavies” >Fe back to the interstellar gas

2) Next generation: "Population II"
H,He + some C,N,O,metals -> Stars (weak absorption lines of metals)
This happened about 13 Gyr (1 Gyr = 1"gigayear" = 1 billion years) ago, from looking at the Main Sequence turnoff points of Pop II Globular Clusters
Stars fuse H,He -> C,N,O,"Metals"
Supergiants, Supernovae Planetary Nebulae -> Interstellar gas

Many more generations: "Population I"
H,He + more C,N,O,metals -> Stars (metal absorption lines comparable to Sun)
**Distribution of Populations and the History of the Galaxy**

*Find: the more recent the formation of the star, the more confined it is to the Galactic disk.*

- **Population III**: Only a few candidates found. Age unknown. In halo.
- **Population II**: Old Globular Clusters, many M main sequence stars (10-13 billion years old). In central bulge and halo.
- "**Old Disk Population I"**: (2-8 billion years old). **Sun**, planetary nebula nuclei, etc. Confined within about 500 pc of disk plane (Sun is about 8 pc N of plane).
- "**Extreme Population I"": (formed within last few million years). Up to twice metal line "enrichment" of Sun: interstellar gas, dust clouds, O,B stars, Supernova Remnants, Red Supergiants. All confined within about 100 pc of central plane of Disk.

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**Star Formation**

Earliest formation stage found by looking inside "**dark nebulae**" using infrared and radio astronomy. Dust extinction very small at largest wavelengths, so you can actually see through them.

Forming star ("**protostar**") is collapsing cloud of dust and gas. Is heated by matter falling on it. Dust emits infrared light. Molecules in cloud heated and glow in radio. Takes maybe few 100,000 years.

Current model: spinning cloud settles into hot core plus disk of material in orbit, some of which falls onto hot core. Core does not collapse under gravity because of pressure of gas heated temporarily by falling onto core.

Some place actual "birth" at time it disperses dust/gas "cocoon". Then called "**pre-main sequence**" star. These stars are to right of main sequence (cooler, larger) since they are still contracting.

- Lower masses: "**T-Tauri**" star. The Sun was one of these. Some show massive gas/dust disks, with large winds and "jets" out the poles. Much flare and spot activity stirred up by rapid spin. Takes few million years to "settle onto" main sequence. Are planets (and/or binary companions?) leftovers of the disk??
Higher masses: Collapse very rapidly and reach main sequence before dispersing cocoon. See them bursting out of clouds and forming HII regions.

**Star Cluster Formation**

Many stars are often formed at the same time in a *cluster* in a very large cloud of interstellar matter. The clouds are so cold that all the hydrogen atoms combine into H$_2$ molecules: (Also see complex hydrocarbons).

**Giant Molecular Clouds** ("GMC"):

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>100,000 -2,000,000 $M_{\text{sun}}$</td>
</tr>
<tr>
<td>Diameter</td>
<td>20 -100 pc</td>
</tr>
<tr>
<td>Density</td>
<td>200 H$_2$ molecules/cm$^3$</td>
</tr>
<tr>
<td>Temperature</td>
<td>10-50 K</td>
</tr>
</tbody>
</table>

Star clusters may be formed when collapse of a GMC is triggered by compression from:

- Overall sloshing around of gas ("density waves")
- Nearby stellar explosion