Most stars are Main Sequence (M-S) stars, which burn H into He in their cores. Other groups are red giants, which have exhausted H fuel and “burn” He into C and O, supergiants which are burning even heavier elements, and white dwarfs (dead low-mass stars). M-S stars can be divided into spectral types O, B, A, F, G, K and M based on temperature or color. Note that there are diagonal lines of constant radius.
<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Initial Mass ($M_\odot$)</th>
<th>Initial Lum. ($L_\odot$)</th>
<th>$T_{\text{surface}}$ ($°$ K)</th>
<th>M-S Life (years)</th>
<th>M-S Radius ($R_\odot$)</th>
<th># in Galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>60</td>
<td>800,000</td>
<td>50,000</td>
<td>$1 \cdot 10^6$</td>
<td>12</td>
<td>$5.5 \cdot 10^4$</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>800</td>
<td>15,000</td>
<td>$1 \cdot 10^8$</td>
<td>3.9</td>
<td>$3.6 \cdot 10^8$</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
<td>14</td>
<td>8000</td>
<td>$2 \cdot 10^9$</td>
<td>1.7</td>
<td>$2.4 \cdot 10^9$</td>
</tr>
<tr>
<td>F</td>
<td>1.3</td>
<td>3.2</td>
<td>6500</td>
<td>$6 \cdot 10^9$</td>
<td>1.3</td>
<td>$1.2 \cdot 10^{10}$</td>
</tr>
<tr>
<td>G</td>
<td>0.9</td>
<td>0.8</td>
<td>5500</td>
<td>$1.3 \cdot 10^{10}$</td>
<td>0.92</td>
<td>$2.8 \cdot 10^{10}$</td>
</tr>
<tr>
<td>K</td>
<td>0.7</td>
<td>0.2</td>
<td>4000</td>
<td>$4 \cdot 10^{10}$</td>
<td>0.72</td>
<td>$6 \cdot 10^{10}$</td>
</tr>
<tr>
<td>M</td>
<td>0.2</td>
<td>0.01</td>
<td>3000</td>
<td>$2.5 \cdot 10^{11}$</td>
<td>0.3</td>
<td>$3 \cdot 10^{11}$</td>
</tr>
</tbody>
</table>
A star’s physical properties on the Main Sequence (M-S) are related: $T_{\text{center}} \propto M/R$; $R \propto M^{1/2}$

A star radiates like a blackbody, so $L \propto R^2 T^4$

Approximately $T_{\text{center}} \propto T_{\text{surface}} = T$.

Combining the above, $L \propto M^3$

A star’s Main Sequence lifetime can be estimated by considering the amount of fuel and dividing by the rate at which the fuel is burned:

$\tau \propto M/L \propto M/M^3 = M^{-2}; \quad \tau = M/L \tau_\odot$

Massive stars burn out too quickly for life to form.

But low-mass stars have a smaller habitable zone, whose volume $V \propto M^4 \propto L^{4/3}$. 
Nuclear Nomenclature

- An atom is composed of a nucleus and 1 or more electrons.
- The nucleus has 1/100,000 the radius of the atom, but nearly all its mass.
- Nuclei are composed of neutrons and plus-charged protons.
- Elements are distinguished by the atomic (proton) number $Z$.
- $Z$ (element symbol)$^A$ refers to a nucleus or an atom of atomic number $Z$ and atomic weight $A = Z + N$.
- Isotopes have the same $Z$ but different neutron numbers $N$ and are nearly chemically identical.
- Radioactive nuclei are unstable and decay into others.
Periodic Table of Rejected Elements

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James Lattimer  AST 248, Lecture 4
Nuclear Energy Generation

- In general, fusion in stars goes from the lightest elements to heavier ones, because Coulomb repulsion is proportional to $Z_1 Z_2$

- Fusion of hydrogen nuclei to helium nuclei (proton-proton cycle)

\[
\begin{align*}
1^1H + 1^1H &\rightarrow 1^2H + e^+ + \nu_e; \\
1^1H + 1^1H &\rightarrow 2^3He + \gamma; \\
2^3He + 2^3He &\rightarrow 2^4He + 1^1H + 1^1H.
\end{align*}
\]

$\nu_e$ is the neutrino, a massless nearly invisible particle.

- R. Davis (Brookhaven Nat’l Lab) first detected neutrinos from the Sun using a tank of 100,000 gallons of carbon tetrachloride ($C_2Cl_4$, cleaning fluid) in the Homestake Gold Mine in Lead, South Dakota in the 1970’s. The observation of neutrinos from the Sun proves that energy is generated by the fusion of H into He.
In the red giant phase, helium is converted into heavier elements by

\[
3(\text{He}_4) \rightarrow \text{C}^{12}_6
\]

\[
\text{C}^{12}_6 + \text{He}_4 \rightarrow \text{O}^{16}_8
\]

There are no stable elements of atomic weight 5 or 8.

Therefore, the reactions \(2\text{He}_4 + \text{H}_1\) or \(2\text{He}_4 + 2\text{He}_4\) involving the most abundant isotopes do not proceed.

Extremely rare three-body collisions \(2\text{He}_4 + 2\text{He}_4 + 2\text{He}_4\) are required to generate heavy elements.

Nuclei heavier than helium cannot be produced during the Big Bang because the universe expands and cools too rapidly for three-body collisions to occur.

As a result, heavy elements can only be produced by stars.
Low-mass stars \(< 8M_\odot\) evolve into a red giant phase in which their surfaces greatly expand and cool, but their interiors shrink and heat when the H fuel in the star’s core is depleted. A red giant burns He into C and O. When He is eventually exhausted, the outer parts of the star escape to form planetary nebula, and the core cools and dies as a white dwarf.
What Happens When Nuclear Fuel Runs Out?

- Normal stars are supported by gaseous thermal pressure, with $P \propto \rho T$.
- When nuclear fuel is exhausted, the temperature and pressure can only be maintained by compressing the core.
- But as its density increases, another kind of pressure due to the quantum mechanical Pauli Exclusion Principle takes over. Matter resists squeezing electrons into too-small a volume.
- This additional source of pressure, called degeneracy pressure, exists even at zero temperature.
- Ordinary solid matter at low temperatures, like rock, is also difficult to compress.
- As a stellar core dies, it finally stops compressing but continues to radiate energy. It eventually freezes as its nuclei form a rock-like crystal lattice.
White Dwarfs

- A star, as it cools off, eventually replaces thermal pressure with degeneracy pressure and becomes a white dwarf.
- Degeneracy pressure is large, but not infinite. Chandrasekhar showed that the upper limit to the white dwarf mass, now called the Chandrasekhar mass, is about $1.4 \, M_\odot$. Larger masses must collapse and become neutron stars.
- Typical white dwarfs have masses between $0.1 \, M_\odot$ and $1.2 \, M_\odot$ and radii about equal to $R_\oplus \simeq 0.01 \, R_\odot$.
- The density in a white dwarf is about $10^6 \, g \, cm^{-3}$, a million times higher than water (a teaspoonful on the Earth would weigh as much as an elephant).
The Sun’s Evolution in the H-R Diagram
Proof of Evolution

- Cluster Main Sequence
- Blue Stragglers
- Horizontal Branch
- Asymptotic Giant Branch
- Red Giant Branch

M55

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Advanced Evolution of High-Mass Stars

- High-mass stars ($M > 8M_\odot$) evolve into both red and blue giants and supergiants as their cores burn heavier elements: C, O $\rightarrow$ Ne $\rightarrow$ Mg, Si $\rightarrow$ S, Ca $\rightarrow$ Fe, Ni

- After the core converts to Fe (iron), the most bound element, nuclear burning no longer releases energy. Its core collapses to form a neutron star or black hole, a violent event accompanied by a supernova explosion (a so-called Type II) that expels the rest of the star.
Supernovae within a few thousand light-years would be lethal to Earth life.

Yet life could not exist without supernovae, because supernovae eject necessary heavy elements into space.

Until supernovae occur, gas from which stars and planets are made contain virtually no elements heavier than He.
Advanced Evolution in Binaries

- Stars in close binaries may evolve in a significantly different way than single stars since mass can be exchanged when one star becomes a red giant or supergiant.

- White dwarfs in close binaries may also accrete (gain) matter from their normal companion. If they grow beyond the Chandrasekhar mass limit (\( \approx 1.4 \, M_\odot \)), they begin to collapse. However, white dwarfs consist of nuclear fuel (e.g., C, O), so this triggers thermonuclear fusion, converting these elements into iron, and causing a Type I supernova explosion.
Types of Supernovae

We conveniently subdivided supernovae into two types, Type I (thermonuclear) and Type II (gravitational collapse).

They have approximately equal luminosities in visible radiation and kinetic energies of their expanding gaseous remnants.

They both produce and eject heavy elements (like carbon, nitrogen, oxygen and iron) into the interstellar medium, where these elements can then be used in the formation of newer stars and their planets.

They are thus both essential for the origin of life, but can also cause its catastrophic demise if too near.

But there are significant differences between these two types of supernovae:
Type I supernovae: from white dwarfs evolved from low-mass stars \((M \lesssim 5M_\odot)\) in binary systems.

- These have no H observed in their spectra.
- They do not emit many neutrinos, and are intrinsically less powerful than Type II supernovae.
- Their energy source is thermonuclear (the conversion of carbon and oxygen into iron).
- The explosion occurs when mass from a companion star accumulates (or accretes) onto the white dwarf, pushing its mass above the Chandrasekhar limit \((1.4M_\odot)\).
- They leave behind only an expanding gaseous remnant.
- They are relatively similar to each other they can be used as standard candles to measure cosmological distances. This realization led to the discovery of dark energy.
Type II supernovae are explosions of massive stars ($M \gtrsim 5M_\odot$) at the ends of their lives.

- These sometimes have H observed in their spectra.
- These emit copious neutrinos, and are 100 times more powerful than Type I supernovae.
- But 99% of the released energy appears as neutrinos, so their light output and kinetic energies are similar to Type I supernovae.
- Their energy source is gravitational potential energy (also called binding energy) released when massive stellar cores contract into a neutron star or black hole.
- The explosion occurs when the iron core of a massive star grows larger than the Chandrasekhar limit ($1.4M_\odot$).
- They leave behind both an expanding gaseous remnant and a collapsed remnant, either a neutron star or a black hole.
Neutrinos and Supernovae

- Beyond C and O burning, more energy is emitted as neutrinos than converted to useful thermal support. Neutrinos readily escape from inside the star.
- Neutrino interactions with matter are so weak, that to have a 50% chance of stopping a solar neutrino, a water shield would have to be a light-year thick.
- The release of neutrinos increases as massive stars evolve, culminating during the gravitational collapse leading to a Type II supernova. For a few seconds, the power output exceeds that of all stars in all galaxies of the visible universe! The total supernova neutrino energy is more than 300 times the solar output during its entire life!
- The production of neutrinos and the nucleosynthesis and ejection of heavy nuclei in Type II supernovae was confirmed by SN 1987a in the Large Magellanic Cloud, a nearby galaxy, on February 23, 1987.
• Neutrino detectors in Ohio and Japan simultaneously detected a total of about 20 neutrinos even though this supernova was 180,000 lt.-yrs. from the Earth.
• Radioactive Ni, Co and Ti nuclei were also observed in the ejecta.
• In late 2019, an hot dust blob was found that appears to hide the neutron star that was formed.
Nucleosynthesis

- After the Big Bang, matter in the universe consisted almost entirely of only H and He.
- Heavy elements are synthesized only in stars.
- Because of Coulomb repulsion, the abundance of elements decreases with $Z$.
- Elements made of multiples of $\alpha$—particles (He nuclei) are more abundant than average.
- Elements with even numbers of protons are more abundant than odd-$Z$ elements.

[Relative Abundance of the Chemical Elements in the Solar System](www.greenspirit.org.uk/Resources/ElementAbundance.htm)
Most of the lighter heavy elements (i.e., up to iron) and half of heavier elements (called s-process or slow neutron capture process) are synthesized in stars and are mostly dispersed through supernova explosions, of both Type I and Type II.

Some C, N, O and Ne are also ejected from stars in stellar winds and in novae (when H is accreted, burned, and ejected from the surface of a white dwarf in a close binary).

Fe and Ni are the most bound elements, so the other half of heavier elements (called r-process or rapid neutron capture process) can be created only in rare explosive events.

It has long been thought the source of r-process elements (includes gold, platinum, and uranium) are Type II supernovae.

However, the binary neutron star merger GW170817 observed in gravitational waves, as a gamma-ray burst, and as a kilonova (powered by radioactive decay of extremely neutron-rich nuclei), indicates that the primary source of r-process elements are binary neutron star or black hole-neutron star mergers.
Neutron Stars

- If matter is forced to higher than white dwarf densities ($10^6$ times water), it collapses to form a neutron star, stabilized with aid of additional pressure from the strong nuclear force.

- Observed neutron stars have an average mass $1.4 M_\odot$ and radius about 12 km, only 3–4 times larger than the same mass black hole.

- The most massive known neutron star is about $2 M_\odot$. The upper mass limit is uncertain but believed to be less than about $M_{\text{max}} = 2.3 M_\odot$.

- Further addition of mass causes collapse to a black hole.
Black Holes

• Without degeneracy pressure, a cold star would eventually collapse into a black hole, first predicted by John Michell in 1783, but termed *corps obscura* by Laplace in 1795.

• A black hole occurs when the size of the object becomes small enough that the escape velocity becomes equal to c.

\[ v_{\text{escape}} = \sqrt{\frac{2GM}{R}}, \Rightarrow R = \frac{2GM}{c^2} \approx 3\left(\frac{M}{M_\odot}\right) \text{ km} \]

• Cold objects of larger mass than the maximum neutron star mass must be black holes. Many black holes are known to exist, with masses ranging from about 6 \( M_\odot \) to millions of solar masses.

• Masses of white dwarfs, neutron stars and black holes have been precisely measured in binary systems using Kepler’s Laws with general relativistic refinements.

"It's black, and it looks like a hole. I'd say it's a black hole."