The Search for Intelligent Life in the Universe
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Properties and Types of Stars

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.
## Spectral Types

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Initial Mass (M☉)</th>
<th>M-S Lum. L☉</th>
<th>M-S $T_{surface}$ °K</th>
<th>M-S Life (years)</th>
<th>M-S Radius (R☉)</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>
M-S Properties Related

- A star’s physical properties on the Main Sequence (M-S) are related: \( T_{center} \propto M/R \); \( R \propto M^{1/2} \)
- A star radiates like a blackbody, so \( L \propto R^2 T^4 \)
- Approximately \( T_{center} \propto T_{surface} = T \).
- 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 $Z$.
- $z(\text{element symbol})^A$ 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

![Periodic Table Image](image)

Bosphorus

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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)

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

$\nu_e$ 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 $\text{He}$. 
In the red giant phase, helium is converted into heavier elements by

\[ 3(2\text{He}^4) \rightarrow 6\text{C}^{12} \]
\[ 6\text{C}^{12} + 2\text{He}^4 \rightarrow 8\text{O}^{16} \]

- There are no stable elements of mass 5 or 8.
- Therefore the reactions involving the most abundant isotopes \(2\text{He}^4 + 1\text{H}^1\) or \(2\text{He}^4 + 2\text{He}^4\) are not allowed.
- A very-rare three-body collision is required to generate heavy elements.
- The Big Bang can’t produce many nuclei heavier than helium, because it is expanding and cooling too rapidly.
- 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. This occurs 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 stellar portions expand away (planetary nebula) and core cools and dies as a white dwarf.
Normal stars are composed of gas supported by thermal pressure, where $P \propto \rho T$.

Ordinary solid matter at room temperature, like rock, has essentially zero pressure.

As the temperature is lowered, gas pressure tends to zero. So when a star dies and subsequently cools off, little pressure exists to support it against gravity even if it crystallizes (freezes).

However, quantum mechanics predicts, because of the Pauli Exclusion Principle, that it is difficult to squeeze electrons or nucleons into too small a volume. This additional source of pressure, which exists even at zero temperature, is called degeneracy pressure.
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. S. Chandrasekhar showed that an upper limit to the white dwarf mass is about $1.4 \, M_{\odot}$ (called the Chandrasekhar limit). Larger masses would collapse and become neutron stars.

Typical white dwarfs have masses within $0.1 - 1.2 \, M_{\odot}$, and radii $3 \, R_{\oplus} \simeq 0.01 \, R_{\odot}$.

The density in a white dwarf is about $10^6 \, g \, cm^{-3}$, a million times that of water (a teaspoon of a white dwarf would weigh as much as an elephant on the Earth).
The Sun’s Evolution in the H-R Diagram

- Double shell-burning core
- Inert carbon
- Helium-burning shell
- Hydrogen-burning shell

- Helium-burning shell
- Helium burning
- Subgiant star core
- Inert helium
- Hydrogen-burning shell

- Subgiant/red giant core

- Planetary nebula
- Double shell-burning red giant
- Red giant
- Helium-burning star
- Helium-burning star core
- Sun
- White dwarf

Surface temperature (Kelvin)

Luminosity (solar units)
Proof of Evolution

- Cluster Main Sequence
- WD → Blue Stragglers
- Horizontal Branch
- Asymptotic Giant Branch

M55

James Lattimer
AST 248, Lecture 4
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 is converted into Fe (iron), the most bound element, nuclear burning ceases to produce energy and the star collapses to form a neutron star or black hole, a violent event accompanied by a supernova explosion (called Type II supernova).
Supernovae within a few thousand lt.-yrs. would be lethal to Earth life.

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

Until supernovae occurred, gas from which stars and planets were made contained virtually no elements heavier than helium.
Advanced Evolution in Binaries

- Stars in binaries may evolve significantly different than single stars if mass can be transferred when a star becomes a red giant or supergiant.

- White dwarfs in close binaries may accrete matter from a normal stellar companion. If they grow to exceed 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 collapse leads to a thermonuclear explosion, converting these elements into iron, in a Type I supernova.
We conveniently subdivided supernovae into two types, Type I and Type II.

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.

But there are significant differences between these two types of supernovae:
Type I supernovae: 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 less powerful than Type II supernovae.
- Their energy comes from thermonuclear energy (the conversion of carbon and oxygen nuclei into iron nuclei).
- 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 so similar to each other they can be used as standard candles to measure cosmological distances, which 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 many neutrinos, and are 100 times more powerful than Type I supernovae.
- 99% of the released energy appears as neutrinos.
- Their energy comes from gravitational potential energy (also called binding energy) due to the gravitational contraction of the collapsing stellar core into a neutron star or black hole.
- The explosion occurs when the iron core of a massive star grows into a mass larger than the Chandrasekhar limit ($1.4M_\odot$).
- They leave behind both an expanding gaseous remnant and either a neutron star or black hole.
Neutrinos and Supernovae

- Beyond C, O burning, more energy is wasted as neutrinos than as useful thermal support. Neutrinos escape rather than giving up their energy inside the star.
- Neutrino interactions with matter are so weak, that to have a 50% chance of stopping a solar neutrino, a lead shield would have to be 100 lt.-yrs. thick.
- The production of neutrinos increases in the gravitational collapse leading to a Type II supernova, reaching, for a few seconds, the power output of all the stars in all the 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.

• To date, no neutron star is visible within the remnant, suggesting that a black hole might have later 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.
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 favored that the source of r-process elements (which includes gold, platinum, and uranium) is supernovae of Type II.

However, models show that matter ejected from supernovae is not rich enough in neutrons and an alternative site, compact binary mergers of neutron stars with neutron stars or black holes, is now beginning to be favored.
Neutron Stars

- If matter is forced to even higher densities than in a white dwarf, $10^6$ times that of water, it collapses but could stabilize to form a neutron star with aid of additional pressure from nucleon degeneracy and the strong nuclear force.

- Observed neutron stars have masses 1.2–2.0 $M_\odot$ and radii of about 12 km, only 3–4 times the radius of the same mass black hole.

- The upper mass limit to a neutron star is not well known, but has to be less than about 3 $M_\odot$. 
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 $c$.

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

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."