Atoms and Star Formation
What are the characteristics of an atom?

- Atoms have a nucleus of protons and neutrons about which electrons orbit.

<table>
<thead>
<tr>
<th>neutrons</th>
<th>protons</th>
<th>electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 charge</td>
<td>+1 charge</td>
<td>-1 charge</td>
</tr>
<tr>
<td>$1.67 \times 10^{-27}$ kg</td>
<td>$1.67 \times 10^{-27}$ kg</td>
<td>$9.1 \times 10^{-31}$ kg</td>
</tr>
</tbody>
</table>
Atomic Structure

• An atom consists of an atomic nucleus (protons and neutrons) and a cloud of electrons surrounding it.

• Almost all of the mass is contained in the nucleus, while almost all of the space is occupied by the electron cloud.
If you could fill a teaspoon just with material as dense as the matter in an atomic nucleus, it would weigh ~2 billion tons!!
What makes each element unique is the number of protons.

A regular atom has equal numbers of protons, neutrons, and electrons.

<table>
<thead>
<tr>
<th>Ion</th>
<th>O⁻</th>
<th>Electrons lost or gained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
<td>$^3_2\text{He}$</td>
<td>Different number of neutrons</td>
</tr>
<tr>
<td>Molecule</td>
<td>H₂O</td>
<td>Atoms in a chemical bond</td>
</tr>
</tbody>
</table>
Different Kinds of Atoms

- The kind of atom depends on the number of protons in the nucleus.

- Most abundant: Hydrogen (H), with one proton (+ 1 electron)

- Next: Helium (He), with 2 protons (and 2 neutrons + 2 electrons)
Where does it all come from and how does this all happen?
Clouds and nebula

• The interstellar medium is not uniform, but varies by large factors in density and temperature.
• The clumps in the interstellar medium are clouds or nebulae (one nebula, two nebulae).
• Three types of nebulae:
  – Emission nebulae
  – Reflection nebulae
  – Dark nebulae
Emission nebulae emit their own light because luminous ultraviolet stars (spectral type O,B) ionize gas in the nebula. The gas then emits light as the electrons return to lower energy levels. In this image Red = Hydrogen, Green = Oxygen, Blue = Sulfur.
Reflection nebulae do not emit their own light. Dust scatters and reflects light from nearby stars.
Dark nebula are so opaque that the dust grains block any starlight from the far side from getting through.
Molecular clouds

- Dark nebula are usually molecular clouds.
- Molecular clouds are relatively dense and are very cold, often only 10 K.
- Giant molecular clouds can contain as much as $10^4$ solar masses ($M_\odot$) of gas and be 10 light years across.
- Molecular clouds are the primary sites for star formation.
Eagle nebula
Eagle nebula in infrared
Star birth can begin in giant molecular clouds
Protoplanetary Disks
Orion Nebula

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA
• Gas in the cloud keeps falling onto the protostar.
• The collapsing gas tends to start rotating around the protostar as it falls in forming a disk and a jet.
• Eventually, the protostar develops a wind, like the solar wind but much stronger. This out flowing wind stops the in falling matter.
• The protostar keeps contracting under it own gravity. The protostar is powered by gravity via contraction - not by fusion.
• The protostar becomes a star when it has contracted so much that it is dense and hot enough to begin nuclear fusion.
During the birth process, stars both gain and lose mass.

Magnetic field lines are pulled toward the protostar as material is attracted to the protostar. The swirling motions of the disk material distort the field into helical shapes and some of in-falling disk material is channeled outward along these lines.
Jets, disks form in protostars
Disk and jet of a protostar
Protostar jet and Herbig Haro objects.
Globules

Bok globules:

~ 10 to 1000 solar masses;

Contracting to form protostars
Globules

Evaporating Gaseous Globules ("EGGs"): Newly forming stars exposed by the ionizing radiation from nearby massive stars.
Nuclear Fusion

• **1905:**
  Einstein demonstrates that Mass and Energy are equivalent: $E=mc^2$

• **1920s:**
  Eddington noted that 4 protons have 0.7% more mass than 1 Helium nucleus ($2p+2n$).
  If 4 protons fuse into 1 Helium nucleus, the remaining 0.7% of mass is converted to energy.
Fusion Energy

• Fuse 1 gram of Hydrogen into 0.993 grams of Helium.
• Leftover 0.007 grams converted into Energy:
  • \[ E = mc^2 = 6.3 \times 10^{18} \text{ ergs} \]
• Enough energy to lift 64,000 Tons of rock to a height of 1 km.
The Source of Stellar Energy

Recall from our discussion of the Sun:

• Stars produce energy by nuclear fusion of hydrogen into helium.

• In the Sun, this happens primarily through the proton-proton (PP) chain.
Gravity & Pressure in Equilibrium
Luminosity radiates away heat & Pressure
*Drops*
Balance tips in favor of gravity, Sun shrinks.
Contraction makes core heat up, increasing the internal Pressure.
Balance restored, but with higher gravity, pressure & temperature than before...

Starts the cycle all over again...
Hydrostatic Equilibrium

- Outward pressure force must exactly balance the weight of all layers above everywhere in the star.

- This condition uniquely determines the interior structure of the star.
Energy Transport

Energy generated in the star’s center must be transported to the surface.

Inner layers of the Sun:

Radiative energy transport

Outer layers of the Sun (including photosphere):

Convection
Stellar Structure

- Temperature, density, and pressure decreasing
- Energy generation via nuclear fusion
- Energy transport via radiation
- Energy transport via convection

Flow of energy

- Basically the same structure for all stars with approximately 1 solar mass or less.

Sun

Convective zone
Radiative zone

Temperature, density and pressure decreasing
Hydrogen Exhaustion

• **Inside**: He core collapses & starts to heat up. H burning zone shoved into a *shell*.
  Collapsing core heats the H shell above it, driving the fusion faster.
  More fusion, more heating, so Pressure > Gravity

• **Outside**: Envelope expands and cools
  Star gets *brighter* and *redder*.
  • Becomes a *Red Giant Star*
Red Giant Star

H Burning Shell

Inert He Core

Cool, Extended Envelope
The CNO Cycle

In stars slightly more massive than the Sun, a more powerful energy generation mechanism than the PP chain takes over:

The CNO Cycle
Asymptotic Giant Branch Star

- H Burning Shell
- He Burning Shell
- Cool, Extended Envelope
- Inert C-O Core
Core-Envelope Separation

- Rapid Process: takes $\sim 10^5$ years
- Outer envelope gets slowly ejected (fast wind)
- C-O core continues to contract:
  - with weight of envelope taken off, heats up less
  - never reaches Carbon ignition temperature of 600 Million K
- Core and Envelope go their separate ways.
Planetary Nebula Phase

- Expanding envelope forms a ring nebula around the contracting C-O core.
  - Ionized and heated by the hot central core.
  - Expands away to nothing in $\sim10^4$ years.

- Planetary Nebula

- Hot C-O core is exposed, moves to the left on the H-R Diagram
Core Collapse to White Dwarf

- Contracting C-O core becomes so dense that a new gas law takes over.
- **Degenerate Electron Gas:**
  - Pressure becomes independent of Temperature
  - \( P \) grows rapidly & soon counteracts Gravity
- Collapse halts when \( R \sim 0.01 \ R_{\text{sun}} \) (\( \sim R_{\text{earth}} \))
  - **White Dwarf Star**
Evolution of White Dwarfs

• White dwarfs only shine by leftover heat.
  – No sources of new energy (no fusion, nothing)
  – Cools off and fades away slowly.

• Ultimate State: A “Black Dwarf”:
  – Old, cold white dwarf
  – Takes ~ 10 Tyr to cool off
  – Galaxy is not old enough to see Black Dwarfs.