ASTR 390 Lecture #4 and #5
Chemistry of the Universe

What I’m Going to Talk About
- The chemical abundance of elements in the universe.
- The chemical abundance of elements in the solar system.
- The structure of the atom.
- The laws of chemical combinations.
- The First Law of Thermodynamics.
- The Second Law of Thermodynamics.
- The life cycle of stars.
- The nucleosynthesis that takes place in stars.

Elements after Big Bang

Chemical Abundance of Elements in the Solar System

Chemical Abundance of Elements in the Solar System

iClicker Question
- The fraction of the Sun that is comprised of hydrogen and helium is roughly
  - A 98%
  - B 90%
  - C 50%
  - D 10%
  - E 2%
Neutrino Factoids

- The earth receives about 40 billion neutrinos per second per cm$^2$ from the sun.
- About 100 times that amount are passing through us from the big bang.
  - This works out to about 330 neutrinos in every cm$^2$ of the universe!
  - By comparison there are about 0.0000005 protons per cm$^2$ in the universe.
- Our body emits about 340 million neutrinos per day from $^4$K.
- Neutrinos don’t do much when passing through matter.
- Remember, it is very difficult to observe neutrinos.

Neutrino Detection

- The neutrino is observed by detecting the product of its interaction with matter.

### Neutrino Factoids

- **Structure of the Atom**
  - Neutrinos are produced in the “Weak Interaction”, for example
  - Neutrinos from the earth
    - natural radioactivity
    - “Man-made” neutrinos
      - accelerators, nuclear power plants.
  - Astrophysical neutrinos
    - Solar neutrinos
    - Atmospheric neutrinos
    - Relic neutrinos
      - left over from the big bang.

- **Neutrino Detection**
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### Neutrino Factoids

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  - Remember, it is very difficult to observe neutrinos.
Neutrinos reveal information about the Sun’s core—and have surprises of their own

- Neutrinos emitted in thermonuclear reactions in the Sun’s core have been detected, but in smaller numbers than expected
- Recent neutrino experiments explain why this is so

iClicker Question

Which of the following are most likely to get to Earth from the core of the Sun, before any of the others?

- A protons
- B electrons
- C photons
- D neutrinos
- E all of the above will arrive at about the same time

Chemistry Law of Definite Proportions

Clues to an invisible world

What is an element?

A substance which can’t be separated or divided into a different substance by normal chemical means.

Each has characteristic properties. Humans have been learning about the elements for a long time.

Famous guys in the history of chemistry

Hammurabi – 1700 BC Babylonian king wrote of metals and heavenly bodies (but was most famous for his “code” of laws)

Democritus – 450 BC Ancient Greek said atoms are the simplest form of matter

Aristotle – 300 BC Ancient Greek philosopher wrote of 4 elements—earth, fire, water, air. (Did not believe in atoms)

In the early 1800s, chemists began to combine elements to form new substances; they especially noted the quantities of elements combining together.

Dalton observed:

- 8 lbs Oxygen combined with 1 lb Hydrogen → 9 lbs water
- 5 lbs Nitrogen combined with 1 lb Hydrogen → 6 lbs Ammonia

He concluded that elements combined in mass ratios.
Famous guys in the history of chemistry, continued

Gay-Lussac observed that:
- Hydrogen combined with Oxygen in a ratio of 2:1 by VOLUME → to form Water (now known as H2O)
- Nitrogen and Oxygen combined in a ratio of 1:1 by VOLUME → to form Nitrous Oxide (NO, used in anesthesia)

He concluded that elements combine in volume ratios.

Joseph Proust — 100 lbs of copper combined with acid and carbonates always yielded → 180 pounds of green carbonate.

In 1799 he proposed the Law of Definite Proportions: elements combine in definite ratios when forming compounds.

He also proved that grape sugar is the same as the sugar in honey.

**iClicker Question**

1. The first guy to come up with the idea of atoms was:
   A) Aristotle B) John Dalton C) Democritus D) Joseph Proust

   C) Democritus

2. The first guy to notice elements combining in ratios by mass was:
   A) Aristotle B) John Dalton C) Democritus D) Joseph Proust

   John Dalton
   He noticed that 9 pounds of water was made of 8 pounds of oxygen and 1 pound of hydrogen

**iClicker Question**

3. The first guy to notice elements combined in ratios by volume was:
   A) Aristotle B) John Dalton C) Democritus D) Gay-Lussac

   Gay-Lussac
   He noticed that hydrogen and oxygen always combined in a ratio of 2:1 by volume to make water

**Atoms in Combination**

Great Idea: Atoms bind together in chemical reactions by the rearrangement of electrons
Electron Shells, the Periodic Table, and Chemical Bonds

- **Chemical Bond**
  - Valence electrons
- **Stable configuration**
  - To fill outer shell
    - Give electrons
    - Accept electrons
    - Share electrons

iClicker Question

- The term “valence electron” describes:
  - A all electrons
  - B inner electrons
  - C outer electrons

Ionic Bonds

- **Bond of electrostatic attraction**
  - Donate or accept electron(s)

Example: Na and Cl
Fiery reaction results in stable crystal

Metallic Bonds

- **Share electrons**

  - Characteristics
    - Shiny, conduct electricity, malleable

Covalent Bonds

- **Share electrons**
  - Molecules share

Carbon
- Single bond, double bond
Polarization and Hydrogen Bonds

- Polar molecules
- Hydrogen Bond
  - Weak bond

Van der Waals Forces

- Weak bonds between molecules
- Example:
  - Clay
  - Stack of paper

iClicker Question

- Covalent bonds involve:
  - C shared electrons
  - B loss and gain of electrons to form charged particles
  - C no electrons at all

States of Matter

- States of Matter
  - Gas
  - Liquid
  - Solid
  - Plasma

Gases, Plasma, and Liquids

- Gas
  - No volume or shape
  - Expands to fill container
- Plasma
  - Positive nuclei in sea of electrons
  - Properties
- Liquids
  - Fixed volume, no shape
  - Surface tension

Solids

- Solids
  - Fixed shape and volume
- Crystals
  - Regular repeating sequence
- Glasses
  - No predictable arrangement
- Polymers
  - Chains of molecules
  - Plastics
Changes of State

- Transitions
  - Freezing, melting
  - Boiling, condensation
  - Sublimation, deposition
- No temperature change during phase change

The Phase Diagram

iClicker Question

- One difference between solids and liquids is:
  - A particles in liquids are much further apart than particles in solids
  - B in liquids, particles are able to slide past one another
  - C in liquids, particles are much smaller

iClicker Question

- A plasma is:
  - A a state of matter formed only at extremely low temperatures
  - B a state of matter where all the atoms are given extra subatomic particles
  - C a state of matter where electrons have been stripped off of atoms

Chemical Reactions and the Formation of Chemical Bonds

- Chemical reactions
  - Interaction of molecules
  - Reactants → products
  - Reactants must balance
- Example
  - $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$

Chemical Reactions and Energy: Rolling Down the Chemical Hill

- Energy of an electron
  - Kinetic and potential
- Energy changes with bonding
  - Exothermic
  - Endothermic
Common Chemical Reactions

- Oxidation
  - Transfer electrons
- Reduction
  - Accepts electrons
- Precipitation-Solution Reactions
- Acid-Base Reactions
  - Acid produces H⁺
  - Base produces OH⁻
  - pH scale

<table>
<thead>
<tr>
<th>Substance</th>
<th>pH Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomach acid</td>
<td>0.0-2.0</td>
</tr>
<tr>
<td>Mean of Stomach luke, 1975</td>
<td>0.5</td>
</tr>
<tr>
<td>Normal saline</td>
<td>5.6</td>
</tr>
<tr>
<td>Mean of Stomach luke, 1990</td>
<td>5.5</td>
</tr>
<tr>
<td>Pure water</td>
<td>7.0</td>
</tr>
<tr>
<td>Human blood</td>
<td>7.3-7.5</td>
</tr>
<tr>
<td>Household ceramics</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Common Chemical Reactions cont.

- Polymerization
  - Condensation Reaction

Forms of Polymers

- Linear polymer
- Branched polymer
- Cross-linked polymer

Building Molecules: The Hydrocarbons

- Hydrocarbons
  - Composed of H and C atoms
  - Chain length
  - Isomers

iClicker Question

- Chemical reactions involve:
  - A rearrangement of atoms in elements and compounds
  - B rearrangement of electrons to form chemical bonds
  - C both a and b
iClicker Question

- A reaction that must have energy supplied to proceed is:
  - A exothermic
  - B endothermic
  - C enerphoric

First Law of Thermodynamics

- Energy cannot be created nor destroyed.
- Therefore, the total energy of the universe is a constant.
- Energy can, however, be converted from one form to another or transferred from a system to the surroundings or vice versa.

Spontaneous Processes

- Spontaneous processes are those that can proceed without any outside intervention.
- The gas in vessel B will spontaneously effuse into vessel A, but once the gas is in both vessels, it will not spontaneously effuse.

Spontaneous Processes

Processes that are spontaneous in one direction are nonspontaneous in the reverse direction.

Spontaneous Processes

- Processes that are spontaneous at one temperature may be nonspontaneous at other temperatures.
- Above 0°C it is spontaneous for ice to melt.
- Below 0°C the reverse process is spontaneous.

Reversible Processes

In a reversible process the system changes in such a way that the system and surroundings can be put back in their original states by exactly reversing the process.

Changes are infinitesimally small in a reversible process.
Irreversible Processes

- Irreversible processes cannot be undone by exactly reversing the change to the system.
- All **Spontaneous** processes are **irreversible**.
- All **Real** processes are **irreversible**.

Entropy

- **Entropy** ($S$) is a term coined by Rudolph Clausius in the 19th century.
- Clausius was convinced of the significance of the ratio of heat delivered and the temperature at which it is delivered,
  \[
  \frac{q}{T}
  \]

- Entropy can be thought of as a measure of the randomness of a system.
- It is related to the various modes of motion in molecules.

- Like total energy, $E$, and enthalpy, $H$, entropy is a state function.
- Therefore,
  \[
  \Delta S = S_{\text{final}} - S_{\text{initial}}
  \]

Entropy

- For a process occurring at constant temperature (an isothermal process):
  \[
  \Delta S = \frac{q_{\text{rev}}}{T}
  \]
  $q_{\text{rev}}$ is the heat that is transferred when the process is carried out **reversibly** at a constant temperature.
  $T$ = temperature in Kelvin.

Second Law of Thermodynamics

- The entropy of the universe does not change for reversible processes and increases for spontaneous processes.
- Reversible (ideal):
  \[
  \Delta S_{\text{univ}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} = 0
  \]
- Irreversible (real, spontaneous):
  \[
  \Delta S_{\text{univ}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} > 0
  \]
Second Law of Thermodynamics

“You can’t break even”

Reversible (ideal):
\[ \Delta S_{\text{univ}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} = 0 \]

Irreversible (real, spontaneous):
\[ \Delta S_{\text{univ}} = \Delta S_{\text{system}} + \Delta S_{\text{surroundings}} > 0 \]

Entropy on the Molecular Scale

• Ludwig Boltzmann described the concept of entropy on the molecular level.
• Temperature is a measure of the average kinetic energy of the molecules in a sample.

Entropy on the Molecular Scale

• Molecules exhibit several types of motion:
  – Translational: Movement of the entire molecule from one place to another.
  – Vibrational: Periodic motion of atoms within a molecule.
  – Rotational: Rotation of the molecule on about an axis or rotation about \( \sigma \) bonds.

Entropy on the Molecular Scale

• Boltzmann envisioned the motions of a sample of molecules at a particular instant in time.
  – This would be akin to taking a snapshot of all the molecules.
• He referred to this sampling as a microstate of the thermodynamic system.

Entropy on the Molecular Scale

• Each thermodynamic state has a specific number of microstates, \( W \), associated with it.
• Entropy is
\[ S = k \ln W \]
where \( k \) is the Boltzmann constant, \( 1.38 \times 10^{-23} \text{ J/K} \).
Entropy on the Molecular Scale

Implications:

• more particles -> more states -> more entropy
• higher T -> more energy states -> more entropy
• less structure (gas vs solid) -> more states -> more entropy

Entropy on the Molecular Scale

• The number of microstates and, therefore, the entropy tends to increase with increases in
  – Temperature.
  – Volume (gases).
  – The number of independently moving molecules.

Entropy and Physical States

• Entropy increases with the freedom of motion of molecules.
• Therefore,
  \[ S(g) > S(l) > S(s) \]

Entropy Changes

• In general, entropy increases when
  – Gases are formed from liquids and solids.
  – Liquids or solutions are formed from solids.
  – The number of gas molecules increases.
  – The number of moles increases.

Solutions

Dissolution of a solid:
Ions have more entropy (more states)

But,
Some water molecules have less entropy (they are grouped around ions).

Usually, there is an overall increase in S.
(The exception is very highly charged ions that make a lot of water molecules align around them.)

Third Law of Thermodynamics

The entropy of a pure crystalline substance at absolute zero is 0.

\[ S = k \ln W = k \ln 1 = 0 \]
Third Law of Thermodynamics
The entropy of a pure crystalline substance at absolute zero is 0.

\[ S = k \ln W = k \ln 1 = 0 \]

Standard Entropies
- These are molar entropy values of substances in their standard states.
- Standard entropies tend to increase with increasing molar mass.

Standard Entropies
Larger and more complex molecules have greater entropies.

Practical uses: surroundings & system
Entropy Changes in Surroundings
- Heat that flows into or out of the system also changes the entropy of the surroundings.
- For an isothermal process:

\[ \Delta S_{\text{surr}} = \frac{-q_{\text{sys}}}{T} \]

H-R Diagram
Step 1 to an H-R Diagram. Plot the 20 nearest and brightest stars to Earth.

H-R Diagram
Step 2 to an H-R Diagram. Reversing the y-axis.
H-R Diagram

Now it's looking like an H-R Diagram.

A Standard H-R Diagram

Life Cycle Stages of a Star Like the Sun
- Gas cloud
- Fragmentation
- Protostar
- Kelvin-Helmholtz contraction
- Hayashi track
- Ignition
- Adjustment to Main Sequence
- Hydrogen core depletion
- Helium shell burning
- Helium flash
- Helium core burning
- Helium core depletion
- Helium shell burning
- Helium shell flashes
- Planetary nebula
- White dwarf

The Birth of Stars
- Nebular Hypothesis
  - Laplace

The Main Sequence and the Death of Stars
- Stars much less massive than the sun
  - Brown dwarf
  - Glows 100 billion years
    - No change in size, temperature, energy output
The Main Sequence and the Death of Stars

- Stars about the mass of the sun
  - Hydrogen burning at faster rate
  - Move off main sequence
  - Helium burning
  - Red giant
  - Begin collapse
  - White dwarf

- Very Large Stars
  - Successive collapses and burnings
  - Iron core
  - Catastrophic collapse
    - supernova

Layers of a Massive Star Before Supernova Explosion

- Neutron Star
  - Dense and small
  - High rotation rate
  - Little light

- Pulsar
  - Special neutron star
  - Electromagnetic radiation
  - End state of supernova

Black Holes

- Black Hole
  - Result of collapse large star
  - Nothing escapes from surface
  - Cannot see them
    - See impact on other stars
    - Detect x-rays, gamma rays

iClicker Question

- Compared with other stars, our Sun is:
  - A an unusually large star
  - B not a star at all
  - C a rather ordinary star
iClicker Question
• The outer part of the Sun, the part that actually emits most of the light we see, is called the:
  – A chromosphere
  – B convective zone
  – C photosphere
  – D core
  – E radiative zone

iClicker Question
• The solar wind is composed of:
  – A bits of neutral gas
  – B all kinds of organic substances
  – C air
  – D charged particles including hydrogen and helium ions

iClicker Question
• Northern lights result from interactions of:
  – A the Sun’s magnetic field with Earth’s gravity
  – B UV light from the Sun with Earth’s ozone layer
  – C the solar wind with the Earth’s magnetic field

iClicker Question
• The Sun’s peak output of energy is in:
  – A the ultraviolet portion of the electromagnetic spectrum
  – B the visible portion of the electromagnetic spectrum
  – C the infrared portion of the electromagnetic spectrum

iClicker Question
• What is the Sun’s energy source?
  – A combustion of hydrogen rich chemical fuels
  – B fusion of hydrogen
  – C fission of hydrogen
  – D radioactive decay
  – E gravitational collapse

iClicker Question
• It is estimated that the total lifetime of our Sun is 11 billion years. How far is it through its hydrogen-burning phase now?
  – A 10%
  – B 25%
  – C 50%
  – D 90%
iClicker Question

• *Triangulation and Cepheid variable* are methods to measure:
  – A distances to stars
  – B energy output of stars
  – C lifetime of stars
  – D composition of stars

iClicker Question

• A Hertzsprung-Russell diagram plots a star’s temperature versus its:
  – A energy output
  – B distance
  – C age

iClicker Question

• Large dust and gas clouds are commonly found throughout space. They are called:
  – A red giants
  – B galaxies
  – C nebulae
  – D supernovae
  – E white dwarfs

iClicker Question

• The fusion process in very large stars produces chemical elements up to:
  – A He
  – B C
  – C Fe
  – D U
  – E Pb

iClicker Question

• All natural elements beyond iron are created in:
  – A supernova explosions
  – B fusion of very large stars
  – C the big bang

iClicker Question

• An object that is so dense and massive that nothing, including light can escape from its surface is called:
  – A a supernova
  – B a red giant
  – C a white dwarf
  – D a black hole
  – E a neutron star
iClicker Question

• Are you surprised that the chemical elements about you were made in a supernova?
  – A yes
  – B no

What I Talked About

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