Radiation, Matter and Energy
What is light?
Light is an electromagnetic wave.

Wavelength is the distance between adjacent peaks of the electric field.

Frequency is the number of times each second that the electric field peaks at any point.

All light travels with speed $c = 300,000 \text{ km/s}$.
Light is an electromagnetic wave.

- **Wavelength = 1 cm, frequency = 30 GHz**
- **Wavelength = \(\frac{1}{2}\) cm, frequency = \(2 \times 30\) GHz = 60 GHz**
- **Wavelength = \(\frac{1}{4}\) cm, frequency = \(4 \times 30\) GHz = 120 GHz**

**Longer wavelength means lower frequency.**

**Shorter wavelength means higher frequency.**
Photons: “pieces” of light, each with precise wavelength, frequency, and energy. Think of photons as tiny bullets

Energy is proportional to frequency

Within the visible spectrum, blue light has higher energy than red light

Within the electromagnetic spectrum, X-rays have the highest energy, followed by UV, visible light, IR, and radio

Remember: Light is just one form of electromagnetic wave of energy, the kind we can detect with our eyes.
What is matter?

Atomic structure:

Ten billion atoms could fit end to end across this dot.

The nucleus is nearly 100,000 times smaller than the atom but contains nearly all of its mass.

Atom: Electrons are “smeared out” in a cloud around the nucleus.

Nucleus: Contains positively charged protons (red) and neutral neutrons (gray).
Atomic Terminology

• **Atomic Number** = # of protons in nucleus
• **Atomic Mass Number** = # of protons + neutrons
Atomic Terminology

- **Isotope**: same # of protons but different # of neutrons. ($^4\text{He}$, $^3\text{He}$)

Different isotopes of a given element contain the same number of protons but different numbers of neutrons.

**Isotopes of Carbon**

- **carbon-12**
  - $^{12}\text{C}$
  - (6 protons + 6 neutrons)

- **carbon-13**
  - $^{13}\text{C}$
  - (6 protons + 7 neutrons)

- **carbon-14**
  - $^{14}\text{C}$
  - (6 protons + 8 neutrons)
Atomic Terminology

- Molecules: consist of two or more atoms (H_2O, CO_2)

- Organic molecules contain carbon (and usually also contain hydrogen).
- Compounds are molecules made from atoms of two or more different elements.
- Molecules consist of two or more atoms.
What is energy?

Energy is a very broad concept, basically it’s anything that can make matter move or change.

Energy changes forms but is not created or destroyed: this is a law of physics.

Life mostly uses light energy (the Sun) and potential (chemical) energy from molecules.
In all matter, anywhere in the universe, atoms and molecules in constant, microscopic motion

**Temperature** is a measure of the *average* kinetic energy of the many particles in a substance.

 Longer arrows mean higher average speed.
All atoms and molecules in the universe are in constant microscopic motion or vibration:

**Thermal energy**

As a result, every substance emits a smooth spectrum of radiation, mostly at invisible infrared wavelengths:

**Thermal radiation**

**Gas Phase**
Atoms or molecules move essentially unconstrained.

**Liquid Phase**
Atoms or molecules remain together but move relatively freely.

**Solid Phase**
Atoms or molecules are held tightly in place.
Temperature Scales

Stars are thousands of degrees

Terrestrial planets

Outer gas Planets

Most of the universe
How does light tell us the temperatures of planets and stars?

Thermal Radiation

• Nearly all large or dense objects emit thermal radiation, including stars, planets, you, me…
• Thermal radiation has a smooth and broad spectrum, like the Sun’s rainbow of color
• An object’s thermal radiation spectrum depends on only one property: its temperature
Two Properties of Thermal Radiation:

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.
How do light and matter interact?

- Emission
- Absorption
- Transmission
- Reflection or Scattering

Terminology:
- Transparent: transmits light
- Opaque: blocks (absorbs) light

Everything we know about the universe is a result of these effects.
Interactions of light and matter

Applied to a distant object like a planet, this can give us important physical information **remote sensing**
Example: the Sun’s Spectrum
Chemical Fingerprints

• Every atom, ion, and molecule has a unique spectral “fingerprint”
• We can identify the chemicals in gas by their fingerprints in the spectrum.
• With additional physics, we can figure out abundances of the chemicals, and often the temperature, pressure, and much more.
Two Fundamentally Different Spectral Mechanisms

**Spectral lines:**
- narrow, sharp features
- pattern unique to each element
- gives chemical composition
- emission (hot, diffuse gas)
- absorption (cool, diffuse gas)

**Thermal radiation:**
- broad, smooth continuum
- peak emission gives temperature
- higher temp, shorter wavelength
- no information on composition
- everything emits thermally
What types of light spectra can we observe?
“Normal matter” that we can detect is < 5% of composition of Universe
Fritz Zwicky – provided initial evidence for dark matter in universe
M/L Ratio in Galaxy Clusters

Typical clusters have $\frac{M}{L} > \sim 100$
Galaxy Rotation Curves

M33 rotation curve
(fig. 1)
Gravitational Lensing By a Galaxy Cluster
A Couple of Possibilities for DM Properties

Scenario 1: ‘New’ Gravity - mass follows gas
A Couple of Possibilities for DM Properties

Scenario II: Collisionless DM
Observation of 2 Galaxy Clusters Colliding: Collisionless DM

Dark matter mass distribution

hot gas
The Nature of Dark Matter

Why are astronomers so confident that dark matter really exists?

Because the law of gravity has passed so many tests, and if we put dark matter into computer simulations, we evolve structure that looks just like the universe.

So far, we can only rule items out:

<table>
<thead>
<tr>
<th>Item</th>
<th>(description)</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stars</td>
<td>(normal matter)</td>
<td>census of stars does not allow it</td>
</tr>
<tr>
<td>MACHOs</td>
<td>(sub-stars &amp; planets)</td>
<td>gravitational lensing rules it out</td>
</tr>
<tr>
<td>Black holes</td>
<td>(dark, collapsed stars)</td>
<td>no sign of preceding supernovae</td>
</tr>
<tr>
<td>Dust</td>
<td>(dust to rocks)</td>
<td>re-radiation in infrared not seen</td>
</tr>
</tbody>
</table>
Composition of the Cosmos

- Dark matter: 22%
- Dark energy: 73%
- Heavy elements: 0.03% - 0.1%
- Ghostly neutrinos: 0.3%
- Stars: 0.5%
- Free hydrogen and helium: 4%
- Dark matter: 22%
- Dark energy: 73%
The Discovery of Acceleration of the Universe

Brian Schmidt – UofA alumnus and Nobel Prize winner in Physics
The Nature of Dark Energy

Dark energy is much more mysterious than even dark matter. It’s existence rests on the unexpectedly faint distant supernovae, and a few less direct arguments. Direct detection of dark energy is very challenging.

Dark energy is a repulsive force that counter gravity. It does not change its strength with time (Einstein’s gravitational constant “blunder”)

Physics provides no assistance. The vacuum of space could have energy in quantum theory, but it would be $10^{80}$ times larger than is observed!

The density of dark energy and dark matter are roughly equal, this is the only time in the history of the universe that is true: is this a coincidence?