Chapter 02: Light and Matter

Notes and Sketches

2.1: Information From the Skies

Light and Radiation

- Radiation is a method of energy transfer
- What we call "light" is a small part of a much larger phenomenon
- A light wave is energy transported from one place to another, without the need for a physical medium

Wave Motion

- A wave is an oscillation in time propagated through space
- Water wave: Water molecules vibrate up and down. Wave propagates forward as energy is transferred directly from one molecule to the next.
- Sound wave: Air molecules vibrate back and forth. Wave propagates forward as energy is passed from one molecule to the next by collisions.
- The wave is not the water, or the air. It is the pattern created by the transfer of energy.

Parts of a Wave

- Period (P): Time for a wave to complete one full cycle of oscillation
- Frequency (f): Number of complete wave cycles per second ($f = 1/P$)
- Wavelength (λ): Literally the length of the wave. Measure how long before the pattern repeats.
- Amplitude (A): Maximum displacement from equilibrium ("height" of wave crest or "depth of trough)
- Speed (v): Wave speed $v = \lambda f$

2.2: Waves in What?

Wave Behavior

- Straight line propagation
- Diffraction: Wave front bends as a result of obstacle or aperture
- Interference: Two (or more) waves occupy the same space at the same time

Interactions Between Charged Particles

- Protons are (+), electrons are (—)
- Charged particles exert forces on each other
- This is a LOT like gravity, with one important difference: charges can attract (+ attracts —) or repel (+ repels + or — repels —) other charges
- Electric field is a representation of the effect a charge is going to have on everything around it
- Stationary charge creates a constant, unchanging E field
- Moving a charge causes the E field to change

Electromagnetism

- Charge exists: This automatically means it has an E field
- Charge moves: E field changes and this creates a magnetic (B) field
- E and B are perpendicular to each other

Oscillating Fields

- Charged particle oscillates, the E and B fields also oscillate
- Propagation of field through space is the wave
- Energy is transported: Speed of light $c = 3 \times 10^5$ km/s

2.3: The Electromagnetic Spectrum

Components of Visible Light

- ROY G BIV: White light separated into spectrum of colors
- Red: Longest wavelength (650–700nm), lowest frequency, lowest energy
- Violet: Shortest wavelength (400–450 nm), highest frequency, highest energy
- Measure wavelength in nanometers (1 nm = 10^{-9}m)

The Full Range of Radiation

- ROY G BIV is a very small part of much larger electromagnetic (e-m) spectrum
- All forms of e-m radiation are exactly the same phenomenon: Vibrating charge creates oscillating E and B fields
- Difference between radio waves and X-rays is only the frequency of the oscillation
- Low frequency: Long wavelength, low energy, no danger from exposure (radio, microwave, infrared (IR))
- Mid-frequency: Shorter wavelength, higher energy (IR, visible, ultraviolet (UV))
- High frequency: Shortest wavelength, highest energy, exposure is dangerous (UV, X-rays, gamma rays)

Atmospheric Windows

- Astronomical objects emit radiation across the spectrum (not just visible)
- Not all frequencies are capable of penetrating atmosphere
- Some frequencies are reflected off the surface of atmosphere (very long wavelength radio waves)
- Some frequencies are absorbed/scattered by the molecules in the atmosphere (microwave, IR, far UV, x-ray, gamma)
- This explains both why we have eyes that see only visible light, and why we need space telescopes

2.4: Thermal Radiation

Everything Radiates

- If an object is made up of atoms, then it radiates
- Radiation is the result of vibrating particles: More energy means higher frequency of vibration
- You are radiating, just not in the visible (you are not glowing...you radiate IR)

The Blackbody Spectrum

What Exactly is a Blackbody?

- A blackbody is a construct: Imagine an object that absorbs absolutely all radiation that hits it (nothing is reflected)
- To keep a constant temperature, the object must emit as much energy as it absorbs
- The energy emitted (radiation) is not all at a single frequency: There is a distribution of emitted frequencies

What Exactly is a Blackbody Curve?

- Plot the intensity as a function of frequency
- Intensity: How much energy emitted at a specific frequency
- Graph will look like a camel hump: Intensity increases with increasing frequency to some maximum value, then decreases as frequency continues to increase
- This curve can tell you about the temperature of the object

The Kelvin Temperature Scale

- Temperature measures the average energy per molecule of an object
- Higher energy per molecule, higher temperature = hotter object
- Related to Celsius temperature scale: Same size degrees
- 0 K ≠ 0°C: Celsius scale is relative (references freezing and boiling of water), Kelvin scale is absolute
- 0 K is as cold as anything could possibly get (all molecular/atomic motion stops)

The Radiation Laws

Wien's Law

- Temperature is directly proportional to frequency: Higher frequency, higher temperature

Notes and Sketches

- An object with blackbody peak in the UV or X-ray spectrum is hotter than an object with a peak in the visible
- Temperature is inversely proportional to wavelength
- An object with peak in long wavelength radio spectrum is cooler than object with peak in the visible

Stefan's Law

- Total energy is proportional to $(\text{temperature})^4$
- Total energy means energy per area per second
- T^4: Means that small change in temperature yields a big change in amount of energy radiated
- You only need a 20% increase in temperature to double the radiation output

Astronomical Applications

- Spectrum reveals temperature
- Temperature reveals type of object

2.5: Spectroscopy

Continuous Spectrum

- Use a prism to separate white light into ROY G BIV
- You will see colors blend, no gaps, no spaces: Continuous spectrum
- A spectrum that is not continuous is telling you something

Emission Lines

- Instead of continuous spectrum, you see very narrow lines widely separated
- Source does not emit all frequencies, only very specific frequencies
- Different sources will emit different frequencies

Absorption Lines

- You see a continuous spectrum with missing pieces: narrow black lines interrupt continuity
- Original source may be emitting continuous spectrum, but something is absorbing certain very specific frequencies
- A different "something" will absorb different frequencies

Kirchhoff's Laws

- Solids, liquids, and dense gases emit a continuous spectrum
- Low-density hot gas: Emission spectrum. Lines depend on the composition of gas
- Low-density cool gas: Absorption spectrum. Absorption lines depend on composition
- Same composition, same lines: Hot gas will form emission lines at same frequencies as cool gas will form absorption lines

Astronomical Applications

- Composition: What is it made of?
- Abundance: How much (by comparison) of this and that?
- Discovery: Once you have identified all the lines you know for sure, what's left over? New patterns reveal new compositions (elements, compounds)

2.6: Formation of Spectral Lines

Atomic Structure

Bohr Model

- Nucleus (protons & neutrons) at center, electrons (e^-) orbit like tiny planets in circles around nucleus
- The rules for electron orbits are very strict: How may e^- per orbit are allowed, exactly where orbit can exist
- Electrons can move (jump) from one orbit to another, but cannot exist anywhere in between
- This model is not rigorously correct, but a useful visual tool for examining spectra formation non-mathematically

Notes and Sketches

Orbits and Energy

- To move from one orbit to another, an e^- needs energy
- To move from a low energy (closer) orbit to a higher one, e^- must absorb some energy
- To move from high (far) to lower energy orbit, e^- will give up energy
- The amount of energy is very, very, very precise: You need the exact quantum of energy to jump
- What this amount of energy is depends on what type of atom you have and what jump the e^- wants to make

The Particle Nature of Radiation

A Photon is a Particle of Light

- Photons are massless particles of light which have a specific frequency (and hence a specific energy)
- The quantum of energy carried by a photon is proportional to frequency: $E = hf$
- Frequency also determines wavelength, and hence the color of the photon

Photons In

- A continuous spectrum of e-m radiation strikes a cloud of low density, cool gas
- The individual electrons of the individual atoms grab a convenient passing photon
- The photons grabbed will only correspond to exactly the frequency/energy to jump the e^- to a higher orbit
- Some e^- will jump from $0 \to 1$, or maybe $0 \to 2$, or maybe $1 \to 2$: depends on what color photon the e^- grabs
- The rest of the light passes through the cloud of gas unimpeded
- Light from source emerges with some specific frequencies missing: Absorption spectrum

Photons Out

- Our cloud of gas has now absorbed energy, so it is hotter than it was (let's turn off our imaginary source from the last example)
- Individual atoms now have electrons that are in excited states: They have jumped up to higher energy orbits
- The electrons won't stay excited: They want to return to lower energy (ground) state
- To jump back down, an e^- will emit a photon having exactly the amount of energy it has to get rid of to return $1 \to 0$ or $2 \to 0$ or $2 \to 1$ or whatever
- Cloud is now emitting radiation of only certain specific frequencies: Emission spectrum

The Spectrum of Hydrogen

- Hydrogen atom = one proton + one electron
- You would think that an atom with only one electron would not have much of a spectrum
- A single electron may absorb and emit multiple photons
- One electron: Absorb a single photon to jump from ground (0) to second excited state (2)
- Emission can be a single photon having the original amount of energy to go back $2 \to 0$
- Emission can be multiple (cascade): Emit one photon to drop $2 \to 1$, emit another photon to drop $1 \to 0$

More Complex Spectra

- Different atoms require different amounts of energy to transition
- Hydrogen $0 \to 1$ transition absorbs 121.6nm photon
- Helium $0 \to 1$ transition absorbs 164nm photon
- Why would a helium electron need less energy? Because there's another e- in that 0 orbit with it already...
- Every single element has a unique atomic structure, which means that the transitions will require unique amounts of energy

Notes and Sketches

- There may be coincidences where two different elements have two different transitions which require almost identical energy

2.7: The Doppler Effect

Motion Affects Perception

- If source does not move, and observer is also stationary, then there is no change in perception
- Introduce motion: Either source and observer get closer together, or they get farther apart
- Does not matter which thing moves (maybe both are moving), just what happens to their separation

Doppler Effect

- If there is relative motion, the observer perceives a change in frequency of the wave
- This happens with any kind of wave: Sound wave, e-m wave, whatever
- The source does not change the frequency it is emitting; the effect is purely one of perception

Red Shift

- If the source and observer get farther apart, observer perceives decrease in frequency
- Lower frequency means longer wavelength (so visible light would be shifted toward red)
- All frequencies are equally affected, not just visible

Blue Shift

- Source and observer get closer together, observer perceives an increase in frequency
- Higher frequency means shorter wavelength
- All frequencies are equally affected, not just visible

Using Doppler to Measure Speed

- Ratio of frequencies related to ratio of velocities
- (true f)/(perceived f) = 1+ (relative speed)/(wave speed)
- Relative speed will be (+) when object recedes from observer (distance increases)
- Relative speed will be (—) when object approaches observer (distance decreases)
- Direction of relative speed is always radial (directly toward or away)
- Doppler does not measure transverse (sideways) velocities

2.8: Spectral-Line Analysis

What Spectra Tell You

- Composition: Specific lines always associated with specific atoms or molecules
- Abundance: Compare quantities of atom A with atom B by comparing intensities of lines
- Temperature: Blackbody curve
- Radial Velocity: Doppler shift
- Rotation Rate: A more complex look at Doppler
- Pressure: Causes broadening of spectral lines
- Magnetic Field: A strong field can cause lines to split

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