

ASTRONOMY 9: HISTORY OF COSMOLOGY

Handout #18

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Physics Before the Twentieth Century

I. The Nature of Light: Electromagnetism

- Cosmology depends on *observations*: light tells us about the universe
- Important to understand something about the nature of light
- How fast does it move?
 - Before 1650: infinite speed?
 - Ole Romer (1656)
 - * Jupiter's moons seemed 11 minutes "ahead of schedule" when Earth is closer to Jupiter, "behind schedule" when farther
 - Aberration of starlight (see previous lecture notes)
 - From 1850: lab measurements by Fizeau, Michelson, and others using rotating wheels and mirrors
 - Note: today we can't measure the speed of light any more!
 - * It is *defined* to be $c = 299,792,458$ m/s
 - * Note 1 second is defined using the frequency of a specific atomic transition ("atomic clock")
 - * Thus, c really defines the *meter*
 - * Before 1960s, meter was a rod in Paris! Kilogram is still a lump of stuff there
 - * Connection between French Revolution and metric units (1790s)
 - Implication of *finite* speed of light: looking out into space is looking back in time!
- What is light "made of"?
 - Newton: "corpuscles" (particles)
 - Huygens, Hooke, Halley: waves
 - 1803: Thomas Young double-slit experiment
 - * Pass light through two narrow slits in a plate
 - * Get *interference* pattern
 - * Seems to prove that light is a wave...
 - Electric Fields
 - * 1789: Charles Coulomb shows two electric charges exert a force on each other:

$$F \propto \frac{q_1 q_2}{r^2}$$

- * Like gravity ($1/r^2$), but charges can either *attract* or *repel*
- * Opposite (+/−) charges attract, like charges repel
- * Michael **Faraday** (1791–1867) suggests idea of **field**
- * Charges "disturb" space around them so that other charges feel a force
- * Direction of field lines = direction of force
- * Force is stronger when field lines close together
- Magnetic Fields
 - * Magnetism also attractive or repulsive: poles (N/S) instead of charges
 - * Unlike electric charges, magnetic poles always seem to come in *pairs*: no one has found a **magnetic monopole**
 - * Can also describe using concept of fields
 - * Compass needle lines up with field lines
 - * Magnetism and electricity seem like separate phenomena, but they are not!
- Electromagnetism
 - * 1820: Oersted discovers moving charges create magnetic field!

- * 1831: Faraday discovers moving magnets create electricity!
- * Electric and magnetic fields related by *motion*
- * 1862: James Clerk **Maxwell** unites electricity and magnetism together as **electromagnetism**
- * Maxwell predicts accelerating charges produce electric and magnetic fields
- * This pair of fields travels together through empty space at speed of light!
- * Light is therefore an *electromagnetic wave*
- Properties of waves
 - **Amplitude**: height of peak above midpoint
 - **Wavelength** (λ): distance between peaks (or troughs)
 - **Frequency** (ν): Sit at a point and count the number of waves that go by per second
 - $\lambda = c/\nu$ (just like dist = speed \times time)
 - **Doppler Effect** (1842, Christian Doppler, Austria)
 - * Waves from a source moving towards or away from you change wavelength
 - * Example: Pitch of train whistle higher when approaching than when receding
 - * Approaching sources have shorter λ (higher ν), receding have longer λ (lower ν)
 - * In *Newtonian* physics,

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

$\Delta\lambda$ is the *change* in wavelength, λ is the wavelength when the source is not moving, v is the speed of the source, and c is the speed of the waves (could be sound, light, or whatever)

- Most waves require a *medium* to propagate through (e.g., sound in air, waves in water)
- Light was thought to travel though some unknown “ether”
- Maxwell shows that light waves can actually propagate through empty space!

II. Light and Astrophysics

- Newton: white light is a combination of all colors
- Can be split using a *prism*
- In modern astronomical instruments, *diffraction grating* (a flat surface with narrow grooves) replaces prism
- **Spectrum**: visible light is only a very small part! ($\lambda \approx 300\text{--}700$ nm, where nm = nanometer = 10^{-9} m)
- Increasing wavelength: Radio, Infrared, Visible, Ultraviolet, X-ray, Gamma-ray
- Joseph Fraunhofer (1815): spectrum of sunlight has hundreds of narrow dark lines!
- Lines at these specific wavelengths must have been *absorbed*
- Bunsen and Kirchoff (1850s): light from burning different chemical elements produces unique sets of spectral lines (“fingerprint”)
- Allows identification of *chemical composition* of elements in the sun, stars, and nebulae
- Elements are the *same* as those found on Earth!
- **Absorption** spectra: dark lines against bright continuous spectrum
- **Emission** spectra: bright lines against dark
- Relationship between these not well understood until later...
- Using the “fingerprints”, can use Doppler effect to measure speeds at which planets, stars, galaxies, etc. are moving towards or away from us!

III. The Nature of Heat: Thermodynamics (19th Century)

- Tied to problems of Industrial Revolution: production of efficient mechanical engines
- **First Law**: conservation of energy
 - Energy can change into different *forms*, but is never created or destroyed
 - Energy of a *closed system* is constant
- **Second Law**: entropy does not decrease in a closed system
 - **Entropy** is a measure of
 - * The *disorder* of a system

- * Generally, the more *information* something contains (or the more *complex* it is), the lower its entropy is
- * Probability: there are many more ways (“states”) to arrange something in a disordered way than in an ordered way
- * Example: monkeys at a typewriter: you have to wait almost forever (10^{122} years) before they’ll produce the works of Shakespeare!
- No “free lunch”: can’t make a perpetual motion machine to produce energy for free
- Note: only applies to *closed systems*; increasing complexity of life does *not* violate the Second Law
- Connection with **arrow of time**: universe doesn’t look the same if run backwards
- May have implications for (im)possibility of life 100s of billions of years in future
- Somewhat depressing subject; Boltzmann committed suicide!
- **Third Law**: Absolute zero ($0\text{ K} \approx -273^\circ\text{ C} \approx -459^\circ\text{ F}$) results if all thermal motion stops
 - Heat is really the statistical jiggling of particles
 - Faster jiggling means higher temperatures
- Study of **thermal radiation**
 - **Blackbody**: an object that absorbs *all* radiation that hits it
 - * Blackbodies are *perfect absorbers* (no light is reflected)
 - * They are also *perfect emitters*!
 - Spectrum from such an object is very simple: only depends on temperature T (not composition or anything else)
 - Shape is always the same, but higher T means more light of *all* frequencies is emitted
 - Higher T also moves the peak to shorter λ (higher ν or “bluer” color)
 - Need to heat to several thousand degrees to get much *visible* light; room temp. gives *infrared*

IV. Problems at the End of the 19th Century

- Many people claimed interesting problems in physics were all solved, mere details remaining!
- But these “details” led to revolutions in the 20th century...
- A) Maxwell’s electromagnetism inconsistent with Newtonian physics?
 - Equations predict light is an EM wave with velocity c
 - Galilean relativity: velocities simply *add*
 - Imagine light shining forward from a train moving at speed v
 - Observer on the ground would see speed $c + v$
 - Which speed of light to use in Maxwell’s eqns., c or $c + v$??
 - Does “ether” define an absolute rest frame?
- B) Michelson-Morley Experiment (1887)
 - Purpose: find the mysterious “ether” which fills space
 - Idea: if we consider Earth’s motion through ether, light will seem to travel at different speeds in different directions
 - Result: No difference!! Who is wrong: Maxwell or Newton??
- C) The “Ultraviolet Catastrophe”
 - Study thermal radiation coming from a *blackbody*
 - Classical physics predicts it will radiate an infinite amount of energy, most at short wavelengths
 - Obviously absurd, what is going on??
- D) First Cosmological “Age Problem”
 - Lord Kelvin and Helmholtz compute age of Sun is 100 million years
 - Assumed it only gets energy from *gravitational* contraction
 - Didn’t know about nuclear physics (20th century): real source of energy is *nuclear fusion* and age is 5 billion years
 - Geologists dating rocks found Earth is much older than 100 million years
 - Darwin: also need a long time for species to evolve
 - How could Earth be older than Sun?!?