Astronomy 9: History of Cosmology

Handout #21

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Life in the Quantum World

- The Nature of Light Revisited
  - Recall the "ultraviolet catastrophe": classical physics predicts blackbody spectrum keeps rising, infinite energies at high frequencies!
  - Max **Planck** (1900) makes a desperate hypothesis to explain the observed spectra:
  - Matter can only absorb and emit light in discrete (*quantized*) amounts:

$$E = hf$$

  - Light of frequency f comes in indivisible little packets of energy hf
  - $h \approx 6.627 \times 10^{-34}$ Joule sec is Planck's constant
    - Joule is an amount of energy (about enough to lift your textbook a few cm)
    - Small size of h means we don't usually see weird quantum effects in everyday life
  - Einstein (1905) studies *photoelectric effect*
    - Awarded 1921 Nobel prize for this work (not relativity!)
    - Shine light of frequency f on a metal
    - No electrons are ejected for $f < f_0$
    - For $f > f_0$, energy of ejected electrons is $h(f - f_0)$
    - Light is behaving like a *particle* (**photon**)
  - But sometimes light behaves like a wave (eg, it diffracts around corners) ⇒ **wave/particle duality**
- The Nature of Matter: A Brief History of Atomic Theory
  - J. J. Thompson (~1900): "plum pudding" model
    - Electrons are plums
    - Diffuse positively charged pudding
  - Ernest Rutherford (1911)
    - Studies "Rutherford scattering" of charged particles hitting thin metal sheets
    - Almost all are just slightly deflected, but a few bounce straight back
    - Atomic nucleus is small and very dense, most of atom is empty space!
    - Electrons whiz around
  - Niels Bohr (1913)
    - Electron is *accelerating* as it moves around nucleus
    - Maxwell's equations say it should radiate all its energy and collapse to the nucleus!
    - Bohr's solution: electron can only exist in *discrete* atomic levels—atoms are quantized too!
    - Light is emitted or absorbed when electron jumps between levels (a "quantum leap": it doesn't go in between)
    - Each atom has a different set of levels, explains **spectral lines**
  - Louis de Broglie (1924)
    - Just as light can behave like particles, electrons can behave like waves!
    - Electron can exist only in orbits where integer number of waves "fit" around the orbit
    - Explains Bohr's quantization idea
- The Uncertainty Principle
  - Werner Heisenberg (1925)

  - If precisely measure momentum (p) of a particle, its position (x) becomes completely uncertain, and vice versa!
  $$\Delta x\, \Delta p > \frac{\hbar}{2}$$
  where $\hbar = h/2\pi$ and Δ means "uncertainty in"
  - Can also be expressed as relationship between measurements of energy and time: $\Delta E\, \Delta t > \hbar/2$
  - Destroys old Laplacian philosophy of *determinism*!
  - Observer also plays a crucial role: what you choose to measure influences the physical state of the system!

- Max Born and Erwin Schrödinger (1927)
  - Quantum mechanics (QM) only describes *probabilities*
  - The **wavefunction** ψ specifies all there is to know about a system
  - Schrodinger equation determines evolution of wavefunction in time and space
  - The wavefunction of an electron at point x represents the probability of finding it at x: $P \propto |\psi|^2$
  - Particles are "fuzzy"!

- Quantum Statistics
  - Particles have an intrinsic "spin", also quantized: only comes in units of $\hbar/2$
  - Particles aren't really little spheres, spin is not really like our common-sense notion
  - Two types of particles, classified according to spin:
  - **Fermions**: Spins are a half-integer multiple (1/2, 3/2, 5/2, ...) of $\hbar$
    * Named after Enrico Fermi (nuclear physicist)
    * Examples: electron, proton, neutron (normal matter)
    * "Anti-social" particles: obey Pauli's Exclusion Principle
    * No two fermions may be in the same quantum state
  - **Bosons**: Spins are an integer multiple (0, 1, 2, ...) of $\hbar$
    * Named after Satyendranath Bose (Indian physicist)
    * Examples: photon (spin-0), graviton (spin-2, carries gravitational force just like photon carries electromagnetism)
    * Gregarious, "social" particles: all like to enter the same quantum state!
    * Note: spin-2 in a sense means you have to rotate by $2 \times 360° = 720°$ before you look the same! Spin-1/2 means you only have to rotate by 180°

- Interpretation of Quantum Mechanics
  - Quantum mechanics *works* very well, in that it is a great tool for calculating things
  - Problems only arise when you try to *interpret* it in terms of our everyday experience
  - Very disturbing to many founders of quantum physics
  - Recent research is beginning to explore boundary between quantum and classical realms: how does quantum weirdness give way to macroscopic classical normality?

  1. Copenhagen ("standard") interpretation (Bohr and others, 1920s)
     - Act of observation mysteriously "collapses the wavefunction"
     - When you're not looking at it, the electron spreads out all over space, and different outcomes are superposed on top of each other
     - The act of observation somehow localizes things, or selects a particular outcome
     - Einstein objects: do you really think the Moon isn't there when you're not looking at it?
     - Example: Schrodinger's cat
       * Feline in a box with vial of poison, decay of a radioactive atom triggers release of poison
       * QM says the atom enters a "superposition of states", both decayed and non-decayed, until an observation is made
       * But then is the cat also simultaneously dead and not-dead? Implies macroscopic manifestation of quantum weirdness
       * What exactly is the act of "observation"? Does human consciousness play a special physical role? Or do common environmental interactions collapse the wavefunction and prevent the cat from entering superposition?

2. Many-worlds interpretation (Hugh Everett, 1957)
   - *All* possibilities embodied by the wavefunction *actually occur*!
   - Universe constantly forks into a multitude of different versions of itself ("parallel universes")
   - In one universe, Schrodinger's cat is alive; in another it is dead
   - Universes are cut off from each other
3. "Hidden variables" (historically favored by Einstein and others)
   - Idea: QM is a terribly incomplete theory, does not preserve *locality*
   - Example: Einstein-Podolsky-Rosen (EPR) "paradox"
     * Send two particles off in a quantum superposition (eg, spins of each are pointing both up and down at the same time!)
     * Measurement of one particle causes it to choose one state or the other
     * Has instantaneous effect on the other particle, even if it has traveled half-way across the universe! Spooky
     * Note: doesn't violate special relativity, since still can't send a *signal* faster than light
   - Some unknown underlying "variables" affect the system, allow only local effects
   - Experimental evidence does not support this interpretation