Astronomy 9: History of Cosmology

Handout #19

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Special Relativity (1905)

- Albert Einstein (1879–1955)
  - Like Aristotle and Newton, created new conceptual foundation for physics
  - Worked on wide variety of problems (mechanics, gravitation, quantum and statistical physics)
  - Born Ulm, Germany; emigrated to U.S. in 1933; died Princeton, NJ
  - Detached childhood, strong distrust of all authority, but not an untalented student
  - "Person of the Century" (*Time*), socially engaged
  - Used his great celebrity to speak out on pacifism, democracy, Zionism; offered presidency of Israel
  - Science as path to self-transcendence; deep belief in Nature as a mystical riddle
- Motivation for Special Relativity
  - At age 16, Einstein thinks about "riding on a light beam"
  - If you catch up, light should appear to stop moving
  - But Maxwell's theory says light *always* moves: no stationary EM waves allowed!
  - Ideas of length contraction and time dilation previously suggested by Lorentz and Fitzgerald to explain Michelson-Morley result, but did not understand why
- Postulates of Special Relativity
  - I. **Laws of physics are the *same* for all observers moving with constant velocities**
    - This is the old idea of (Galilean/Newtonian) relativity
    - Motion at constant velocity is *relative*
    - No experiment inside a train with closed windows can determine if it is moving at constant velocity
  - II. **The speed of light in empty space is always measured to be the *same*, regardless of motion of the source or observer!**
    - Very counter-intuitive: simple addition of velocities doesn't work!
    - Maxwell is right, Newton wrong!
    - c is *absolute* (not everything is relative!)
  - From these simple postulates, all bizarre implications of relativity follow (thought experiments)
  - Effects are only noticeable when speeds approach $c = 300,000$ km/s, *far* removed from our everyday world
- Fun Implications of Special Relativity
  - I. **Simultaneity** is *relative*!
    - If two observers are moving relative to each other, two events that look simultaneous to one will *not* look simultaneous to the other!
    - Example: passenger stands in middle of moving train car and shines light forwards and backwards
      - Both passenger and station observer measure c
      - To passenger, hits front and back simultaneously
      - To station observer, hits back of car first!
  - II. Time is relative: **time dilation**!
    - Moving observers will *not* agree that clocks tick at the same rate
    - Demolishes Newtonian idea of absolute time
    - Example: "light clock" in a moving train
      - Tick/tock is light bouncing vertically off mirrors separated by height H

        - For observer moving with clock, tick/tock time is H/c
        - For station observer, the light has to go farther, so time is $> H/c$!
        - **Moving clocks run slower!** Factor is $\gamma = 1/\sqrt{1-(v/c)^2}$ ("boost factor")
        - Note reciprocity: observer on train will see that *station observer's* clock runs slow
        - The fastest-running clock ("**proper time**") is always the one that is moving with the observer
        - Note: you always perceive your *own* time "flowing" at the same "rate"

  III. Space is relative: **length contraction**!
    - Moving rulers become shorter along the direction of their motion!
    - As with time dilation, factor is $\gamma = 1/\sqrt{1-(v/c)^2}$
    - Demolishes Newtonian idea of absolute space
    - Example: decaying subatomic particles at speed close to c
        - Typical half-life time τ for particle at rest
        - Particles can live much *longer* when moving due to time dilation (observed all the time using *cosmic rays*)
        - This means they can travel much *farther* than you would expect before decaying
        - But imagine you are Superman, flying along with the particle
        - Since particle is at rest in your frame, it decays in its usual short time
        - But it *did* manage to cover the longer distance—how?
        - Must be that space *contracted* along the direction of motion!

  IV. Velocities do not simply add
    - Throw a ball forward with speed u from a train moving with speed v
    - Newton and Galileo: observer on ground sees speed $u + v$
    - Einstein: observer on ground sees speed

$$\frac{u+v}{1+uv/c^2}$$

    - Note this is always $< c$, even if u and v are very close to c!
    - Doppler shift is also more complicated:

$$\frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \sqrt{\frac{1+v/c}{1-v/c}}$$

  V. Speed of light is the ultimate speed limit!
    - In a second 1905 paper, $E = mc^2$
    - Mass is a form of energy! Can convert from one to the other, for example:
        - Nuclear fission (first uranium atomic bombs)
        - Nuclear fusion (hydrogen bomb, powers the Sun)
        - Even chemical reactions that give off energy result in a (tiny) change in mass
    - Even when matter is at rest, still has some energy
    - Speed something up, it has more energy, and therefore more mass: $m \propto \gamma$
    - $v = c$ would lead to infinite mass, requiring infinite energy, so cannot be reached
    - Any particle traveling at c must have zero "rest mass"
    - Note: this is not simply a problem of engineering (like sound speed), but a fundamental physical principle!

- Twin "Paradox"
  - Send one twin off to α Centauri and back
  - Earth-bound will see the twin's clock run slower, so when she gets back she will have aged less!
  - But the traveler will see Earth's clock run slower, so she will expect the Earth-bound traveler will have aged less
  - Who is right?
  - In fact the traveling twin ages less. Why?

  - Only Earth-bound twin was in an inertial frame; in order to come back, traveler had to *decelerate*, turn around, and *accelerate*
  - But Earth-bound *will* always see traveler's clock run slow, so it is true that traveler ages less upon return
  - Have to be careful to account for the acceleration when talking about what traveler will see

- Absolute Newtonian space and time are replaced by four-dimensional **spacetime**
  - Space and time not just a background arena, but active physical entities
  - Plot ct (time) vs. x (one dimension of 3-d space)
  - Particles at rest in this frame follow vertical lines
  - Particles in inertial (uniform velocity) frames follow *straight lines*
  - Light follows 45° diagonals
  - **Spacetime interval:** $\Delta s^2 = c^2 \Delta t^2 - \Delta x^2$
    * Note – sign makes this very different from Euclidean geometry!
    * This interval is *invariant*: all observers will measure the same value for Δs (though different Δt and Δx)
  - Events outside the 45° **light cone** are "elsewhere" and cannot be in causal contact

- Remaining problem: how does gravity fit in with all this?
  - Need for a General Theory!