Astro 350

Lecture 17

Oct. 8, 2012

Announcements:

- **Discussion 5** due Wednesday
- **HW 5** due at start of class next Friday
- Exam grading almost done; scores will be posted on Compass

Last time: Special Relativity

Einstein's (special) relativity principle

in a closed room, it is *impossible* to detect absolute motion
by means of *any experiment at all*

- consequence: light speed c same for all observers!
- train + lightning experiment: *Q: lessons?*
- moving clock experiment: *Q: lessons?*

Train: disagreement about whether events are simultaneous

$\rightarrow$ "at the same time" is not a universal concept

$\rightarrow$ "relativity of simultaneity"

$\rightarrow$ "universal time" doesn't exist, depends on motion

Moving clock: disagreement about tick duration

- moving clock appears to run slowly (tick lasts longer)
- "time dilation"
- time does not "flow" at universal rate, depends on motion
- prediction: a clock moving at speed v will tick at rate

$$(\Delta t)_{\text{moving}} = \frac{(\Delta t)_{\text{rest}}}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Q: who's right in all these disagreements?

Everybody's right! that is,

- all observations correctly reported
- real problem is deeper:
  Aristotelian notion of universal space, time are *invalid*

⋆ Space, time depend on state of motion of observers
⋆ but *no* observer *ever* sees her/himself as the wierdo
  i.e., your (nearby, at rest relative to you) clocks & yardsticks
  never appear weird to you
⋆ bizarreness only can arise when looking at things moving fast
  and/or at a distance

More later on what we *can* all agree on...

Note: time dilation guessed from "thought experiments"
(Einstein: "Gedankenexperiment")

Q: how would we test this in the real world?

Time Dilation in the Real World

high energy particles from space ("cosmic rays")
collide with Earth's atmosphere
produce unstable particles: muons μ seen at ground
in lab, at rest: muons decay after $t_{\text{decay}} = 2 \times 10^{-6}$ sec

at top of atmosphere: height $h = 10$ km
muons born with speed $v = 0.9999c$

Do they reach the ground?
Earth bystander: moving μ needs travel time
$t_{\text{moving}} = h/v = 33 \times 10^{-6}$ sec $> t_{\text{decay}} \rightarrow$ too long?!
should never see muons on ground! but we see plenty!
Why? muon "feels" at rest, and trip takes only
$t_{\text{rest}} = \sqrt{1 - v^2/c^2}\ t_{\text{moving}} = 0.5 \times 10^{-6}$ sec $< t_{\text{decay}}$
$\Rightarrow$ muon survive trip due to time dilation!

Relativity and Lengths

Turn light clock on side, use as yardstick:
at rest, clock length L_{rest}
shine light, front-to back roundtrip
$\rightarrow$ travel time $t_{\text{rest}} = 2L_{\text{rest}}/c$

HW5: bystander times light pulse
finds clock length to be

$$L_{\text{moving}} = \sqrt{1 - \frac{v^2}{c^2}} L_{\text{rest}} \quad (1)$$

Q: lesson?

Length Contraction

⋆ moving yardsticks don't appear to have same length as yardsticks at rest

⋆ moving yardsticks appears shorter

⋆ moving objects appear shorter in direction of motion!

⋆ space depends on state of motion! not universal!

iClicker Poll: Special Relativity

Which of these can *all* observers agree on regardless of their state of motion?

I. Albert Einstein was born 133 years ago

II. Chambana and Chicago are 133 miles apart

III. radio signals from spacecraft move at speed c

A I only

B II only

C III only

D all of I, II, and II

E none of I, II, and II

The Special Theory of Relativity

Einstein 1905: realized all of the above

Implications deep and wide
Newton's laws of motion built upon absolute space, time
$\Rightarrow$ no longer valid! have to be rebuilt
to respect principle of relativity

Einstein did all of this as well in 1905
Revamped Newton's laws of motion $\rightarrow$ special relativity

- describes motions at any speed
- includes all wierdo time, space effects
- tested many ways many times, always found to agree with experiment
- e.g., particle accelerators (Fermilab, the LHC) wouldn't work if we did not use relativity!

Energy in Relativity

Einstein revised expressions for energy:
a particle of mass m with speed v has (total) energy

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

Enormously important formula

Q: what is E when $v = 0$? What does this mean?
Q: what is E when $v \ll c$ but not zero? What does this mean?
Q: what is E when $v \to c$? What does this mean?

Mass is Energy

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (3)$$

- if $v = 0$, particle at rest
  yet $E = mc^2$ not zero!
  represents energy due to mere *existence* of particle
  i.e., just due to presence of mass!
  $E_{\text{rest}} = mc^2$ is *rest mass energy*
- energy output if mass m totally converted
  to some other energy form
- can be enormous: $m_{\text{donut}}c^2 = 4 \times 10^{15}$ Joules $= 1$ Mton TNT

So: mass is a form of energy!

Q: so what prevents donuts from exploding?
Q: when and where is mass *converted to energy?*

Mass $\Leftrightarrow$ Energy Interconversion

Implies: can convert mass to energy, *and* energy to mass
in fact—happens every day at Fermilab and the LHC!

energy $\rightarrow$ matter **`www: LHC collision event`**
2 particles with huge KE $\rightarrow$ many particles

but: if mass stays as mass, energy remains "stored"
and harmless (but tasty: mmmmm, donuts...)