Astro 350

Lecture 18

March 2, 2022

Announcements:

- **Discussion 4 due Wednesday**
- **Homework 5 due Friday**
- Office hours after class today

Last time: whirlwind tour of star life cycles

most spectacular: massive stars ($M > 8M_{\text{Sun}}$)

"celebrities of the cosmos" – rare but extravagant

Q: what are their lifestyles like?

Massive Star Lifestyles

High-mass stars are rare
less than 1% of all stars have ($M > 8M_{\text{Sun}}$)
but play a critical role role in galaxies

live fast: high mass $\rightarrow$ huge L, short lifespan

die young: form ever heavier elements in core
until core is iron: when this grows too large it's unstable
star implodes, core crushed to ultra-high density ball of neutrons
infalling star "bounces" off ultradense core, ejected
supernova explosion!

leave a beautiful corpse:
- most of stars mass and newly formed elements ejected to space
- ultradense "cinder" left behind: neutron star or black hole

The Legacy of Supernovae

Supernovae have a major impact on their environment

- gas ejected: contains newly-formed heavy elements
  around 90% of initial star mass
  high-mass stars major source of oxygen up to uranium

- explosion heats, stirs up interstellar gas

- leftover cinder: **neutron star or black hole**
  neutron stars: masses $(1.4 - 3)M_{\text{Sun}}$
  black hole masses: we will see!

Origin of the Elements: Nucleosynthesis

Stars are nuclear reactors during their lives
eject reaction products when die
$\Rightarrow$ *stars are element factories*

We will see:
the big bang also produces elements
but only the lightest two: H and He and a tiny amount of lithium
$\rightarrow$ all heavier elements made in stars!

intermediate mass stars $0.8 M_{\text{sun}}$ to $8 M_{\text{sun}}$

- make most carbon, also helium
  the carbon your DNA came from planetary nebulae!

high-mass stars $> 8 M_{\text{Sun}}$

- make oxygen, iron, & many other heavy elements
  the iron in your blood comes from supernova explosions!

Cosmologist Carl Sagan

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We are made of star-stuff.
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Cosmologist Joni Mitchell

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We are stardust
We are golden
We are billion year old carbon
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Stars: Overview of Outcomes and Outputs

Mass	Compact Remnant	Main Elements Ejected
$< 0.08 M_{\text{Sun}}$ brown dwarfs	the object itself inert, cools forever	none no nuclear fusion
$(0.08 - 0.8) M_{\text{Sun}}$ red dwarfs	the star itself lives "forever"	none very low L
$(0.8 - 8) M_{\text{Sun}}$ intermediate mass	white dwarf cools forever	carbon, helium. ejected in planetary nebula
$> 8 M_{\text{Sun}}$ high mass	neutron star or black hole	oxygen, silicon, iron ejected in supernova explosion

Relativity

Space/Time: Gut Reactions and Common Sense

Relativity is a theory of space, time, and matter

Go with your gut:

Q: what is the nature of space?

e.g.: dimensionality? size? distances between points?
properties here vs elsewhere?

Still go with your gut:

Q: what is the nature of time?

e.g.: when are goings-on "simultaneous"?
properties of time here vs elsewhere?

Space

Gut expectations from everyday life

Space is:

- three dimensional–i.e., extends in 3 independent directions
  points described with 3 coordinates, e.g., (x, y, z)
- geometry according to Euclid (i.e., as learnt in high school)
  circle circumference/diameter$=\pi$
  triangle internal angles sum to 180°
- infinite in size, volume
  e.g., (x, y, z) Cartesian grid extends without limit

Before the end of the semester
all of the above will be called into question!

Space: Wit and Wisdom

Absolute space, in its own nature,
without relation to anything external,
remains always similar and immovable.
Relative space is some movable dimension or measure
of the absolute spaces ...

– Cosmologist Sir Isaac Newton

Q: What's Ike talking about?
what's absolute vs relative? examples?

Time: Bigwigs Weigh In

What then is time?
If no one asks me, I know what it is.
If I wish to explain it to him who asks,
I do not know.

– Cosmologist St. Augustine

Absolute, true and mathematical time,
of itself, and from its own nature,
flows equally, without relation to anything external.

– Cosmologist Sir Isaac Newton

Time: Commonsense Expectations

Time: Gut Expectations

- universal–"flows at same rate" everywhere
  e.g., as 1 hour passes here, 1 hour also passes
  in Chicago, North Pole, the Moon, M31 galaxy, ...
  don't need new watch when travel out of state

- simultaneous=clocks all read the same
  since time universal, can coordinate all clocks to read same
  and once set, will always stay synchronized

By the end of the week: will find these ideas untenable!

Space, Time, and Motion

motion links space and time
and so depends on nature of space and time

Pre-Relativity: Aristotle

Aristotle: Ancient Greece
ideas based on everyday experience, common sense
(paraphrased here to anticipate where we are going)

natural state of motion: rest
e.g., oxcarts, arrows, anchors come to rest on Earth's surface
$\rightarrow$ absolute space exists, defined by "frame" or viewpoint
in which objects naturally at rest
and absolute time exists too:
time "flow" is same always, everywhere, for everyone

Aristotleian Space: Description

to completely specify the *address* or *location*
of any point in space
need to give *three numbers*
thus we say $\Rightarrow$ space is **three dimensional**

examples of 3-numbered addresses:
- in city: 1. street, 2. number on street, 3. floor of building
- on GPS device: 1. latitude, 2. longitude, 3. altitude

Why? Space has 3 independent directions
left-right, up-down, back-front
need to give location in all three direction (dimensions)
to completely specify a point

If label points with 3-D (x, y, z) Cartesian grid
- Aristotelian space: set of all possible (x, y, z) addresses
- fixed "stage" for goings-on in time t

iClicker Poll: Aristotle and Simultaneity

In an Aristotelian world:

is it meaningful for events to be "simultaneous" = at the same time?

A yes

B no

Q: if not, why not? what's the problem?

Q: if so, how do you tell?

Life According to Aristotle

consider two "events": localized in space and time
firecracker 1: (x_1, y_1, z_1, t_1)
firecracker 2: (x_2, y_2, z_2, t_2)

Q: What is spatial distance between events?
Q: What is duration/elapsed time between events?
Q: How to tell if events simultaneous?

two events:
firecracker 1: (x_1, y_1, z_1, t_1)
firecracker 2: (x_2, y_2, z_2, t_2)

spatial distance ℓ between events:

$$\ell^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 \tag{1}$$

- à la Pythagoras
- result indep of time coordinates
  $\rightarrow$ encodes idea of "absolute space"

elapsed time between events: $t_2 - t_1$
simultaneous: no elapsed time $\rightarrow t_2 = t_1$ (same time coord)
- indep of place in space (i.e., coordinates)
  $\rightarrow$ encodes idea of "absolute time"

The Principle of Relativity

existed (in part) even before Einstein:
Galileo knew it, and so did Newton:

> "The motions of bodies included in a given space are the same among themselves, whether the space is at rest or moves uniformly forward in a straight line"
>
> –Cosmologist Sir Ike Newton

Q: what's Ike going on about?

Galilean Relativity Principle

- the motion of a *system of bodies* (matter)
  relative to each other
  is *the same* for any constant-velocity ("inertial")
  motion of the entire system
  e.g., planet motion vs SS motion

- which means: there is *no experiment* that can detect the
  absolute motion of matter; can only measure
  motion of particles *relative* to each other

$\Rightarrow$ in closed non-accelerating room: can't tell if you're moving!
Contrary to Aristotle!

- T-Shirt/Bumper Sticker/Text Message/Twitter version:
  "only relative motion counts" (for matter)

But how does *light* weigh in?
Can you use light to tell if a closed room is moving?

The Ether

Consider a moving lightbulb

Newton, Galileo say: if emitter has speed v

then bystander sees light move at speed $c + v$

sped up ahead, slowed down behind

In Newton/Galileo framework:

- light defines (& requires!) a special universal "rest frame"
- in viewpoint where light is wave
  needs medium to wave in (e.g., water waves need water)
- late 19th century: **"luminiferous ether"**
  invisible, neutral, massless substance
  defines absolute cosmic rest frame

Something's Gotta Give

Michelson & Morley experiment (1890s, done in Chicago!)

setup: measure *difference* in speed of light
  in two perpendicular directions
  repeat for different directions

result: *never see a difference in speeds!*

but: the Earth is moving around Sun
  if ether exists, Earth orbit moves us relative to it
  light should be slower in direction of Earth motion
  yet never seen, so conclude

⋆ no experiment can detect ether or it effects–doesn't exist!

⋆ speed of light *constant:* c, *universal*, and
  independent of motion of observer

Q: which means in practice?

Universal speed of light means:
everyone always measures light speed to be same value

$$c_{\text{anybody}} = c_{\text{universal}} = 3 \times 10^8 \text{ m/s} = 186,000 \text{ miles/sec} \quad (2)$$

regardless of motion of emitter, observer

Leads to counter-intuitive (=bizarre) circumstances!

consider "ultrabullet" train
goes at 100,000 miles/sec, shines headlights
★ passengers measure headlight beam speed = 186,000 miles/sec
but also
★ trackside bystanders measure beam = 186,000 miles/sec too!
not Galileo result 286,000 miles/sec!

This is (some of) the weirdness of relativity

Paradigm Shift: Special Relativity

How to cope with lightspeed universality & ether non-existence?

One approach: "separate but equal"
matter and light are fundamentally different
special rules for light
logically possible but lousy idea–if lotsa exceptions
get more general rule

Einstein's approach: "radical democracy"
Upgrade principle of relativity: *no* absolute rest, motion
for *anything* – matter or light
(or anything else you dream up)!
relative motions are all that ever counts!
Special Theory of Relativity a.k.a. "special relativity"
does not yet include gravity! will do this soon, but
will require generalized, modified relativity

A Train in a Thunderstorm

Experiment:

- Train, car length L, moving at some speed v past bystander
- two lightning bolts strike front, back of train
- trackside bystander (Brad) stands at midpoint of burn marks sees flashes simultaneously
- everyone sees light moving at same speed c