Lunatic Fringe:

The Science and Math of the Moon

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webpage with images and links:

`http://www.astro.uiuc.edu/~bdfields/mste_aims07.html`

- The geometric Moon:
  - Lunar phases and the Moon's orbit
  - eclipses of the Sun and Moon
- The dynamic Moon:
  gravity, tides, the receding Moon and lengthening day
- The statistical Moon:
  counting craters on the Moon for solar aystem archaeology
- The physical Moon
  first-person accounts, lessons from moonrocks

Introductions

Please allow me to introduce myself...

Q: anybody teach any astro?
Q: if so, what? do you use math?

Today's schtick based on my conviction:

Astronomy and Math/Science teaching
are two great tastes that taste great together!

Astronomy can serve math & science by:
illustrating, motivating, and enriching subjects you are *already teaching*

Today's strategy: I'll provide the Astronomy
but you know best how build your lessons!

The Geometric Moon: Orbit, Phases, Eclipses

The Moon's Motion on the Sky

as seen by earthling, Moon moves in the sky
several patterns emerge

daily motion:
Moon rises in the eastern horizon,
sets in the westerns horizon
period $P_{\text{horizon}} = 1$ day

monthly ("Moonthly") motion:
Moon moves among the stars *Q: what does this mean?*
path is circle–in fact, a great circle
travels in Zodiac (same constellations as Sun)
period $P_{\text{thru stars}} = 1$ month

Q: what do these patterns tell us about the Moon's motion in 3-D space?

Lessons from Lunar Motions

- Daily Motion
  Moon rises in E, sets in W; Sun, stars do same
  Earth-centered ("geocentric" or egocentric!) interpretation
  $\rightarrow$ we are fixed, all orbit us once daily!
  not crazy! ancient Greeks believed this!
  Sun-centered ("heliocentric" or democratic) interpretation
  our Earth spins $\rightarrow$ earthlings see spinning sky
  infer $P_{\text{spin,Earth}} = 1$ day!

- Monthly Motion
  on 2-D sky: Moon moves among (and in front of!) stars
  in 3-D space: stars are (more or less) fixed
  $\rightarrow$ Moon and Earth must move relative to each other!
  $\rightarrow$ Moon orbits Earth, in a plane,
  with a nearly circular path
  infer $P_{\text{orbit,Moon}} = 1$ day!

Interlude: The Flat Sky

The motion of the Moon is one example of
a general problem in astronomy (and all science!)
have to connect
(a) what you can actually *observe/measure: data*
(b) with what is "really" going on–*models/theory*

In astronomy: observe objects in sky
can measure shapes, positions on sky

but sky gives *no* direct information about distance
$\longrightarrow$ observed sky flattens the 3-dimensional arrangements
down to 2-D sphere projection: "cosmic roadkill"

Geometry problem: have to always go between

- observed 2-D sky view
- underlying 3-D space distribution

For the Moon

in 3-D space: a sphere orbiting Earth,
itself spinning on its own axis, and orbiting Sun

on 2-D sky as seen by earthling: a circular disk, none/some/all illuminated

Other "flattening" issues in astronomy...

Exercise in geometry, spatial visualization.

A Sense of Scale

How do sizes of the Earth and Moon compare?
If Earth represented by globe $\approx$ basketball size
What would correctly represent the Moon's size?
i.e., when is $r_{\text{ball}}/r_{\text{globe}} = R_{\text{Moon}}/R_{\text{Earth}}$?
(a) another basketball
(b) tennis ball
(c) golfball
(d) marble

How does the orbit compare to the object sizes?
If Earth represented by globe and Moon by ball
Where does the "moonball" need to travel?
(a) arm's length
(b) front row
(c) middle of room
(d) back of room
(e) outside of the building

Earth radius: $R_{\text{Earth}} \approx 6400$ km

Moon: $R_{\text{Moon}}/R_{\text{Earth}} \approx 1/4$

$\star$ if Earth $\rightarrow$ basketball, Moon $\approx$ tennis ball

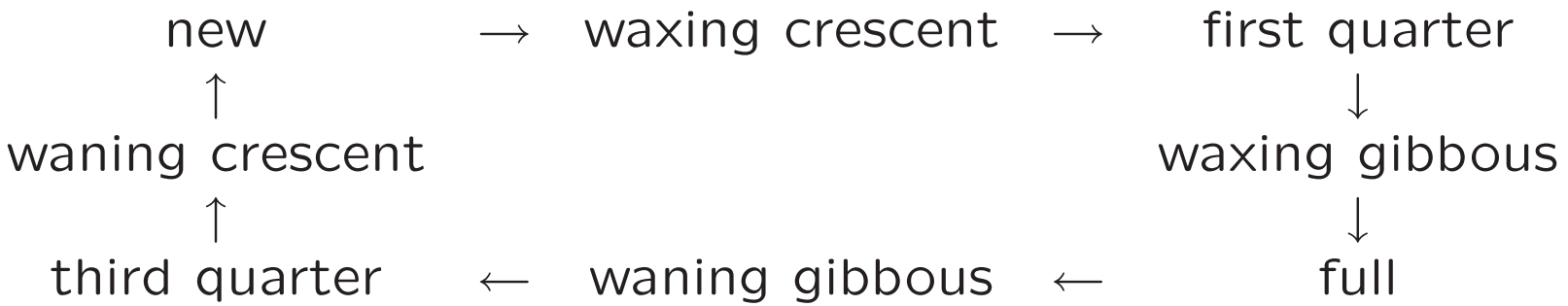
Moon orbit: $d_{\text{Moon}} \approx 60 R_{\text{Earth}}$

$\star$ if Earth $\rightarrow$ basketball, Moon $\approx$ 10 meter $\approx$ 30 ft away!

surprisingly far! key to remember regarding phases

Phases of the Moon

another monthly lunar pattern: cycle of phases



`www: lunar phase images`

Q: what is basic physical origin of phases?
Why do we sometimes see only part of the Moon illuminated?
What does the monthly period imply?

phases simple but beautiful

basic effect: **see illuminated moon from different angles**

phases **not** due to Earth blocking sunlight

i.e., phases are not eclipses!

Phases Take 1: a gut feeling for the effect

Demo: Be the Earth and Moon yourself!

- use flashlight/bright lightbulb for Sun
- make fist (or use ball) for Moon
- Earth = your head!

spin slowly $\rightarrow$ Moon orbit, watch phases on fist/ball/Moon change

Phases Take 2: analyzing the geometry

diagram: top view, sky views

excellent exercise in translating situation in 3-D space
to 2-D projection on sky
for each Sun-Earth-Moon position, ask:
Q: how much of Moon's surface is illuminated by the Sun?
Q: how much of the illuminated portion can we see from Earth?
Q: what does this look like in the sky?

Hint: to check you answers, redo flashlight Sun experiment

Note: each phase rises and sets at a specific time of day

Q: when 1st Quarter moonrise?

my suggestion: do it! practice!
when moon up, point to moon, sun, look at angle!

Eclipses

lunar eclipse: moon in earth's shadow

diagram: Sun, Earth, Moon

`www: lunar eclipses`

note: can still see Moon even when totally in Earth's shadow!

appears much dimmer, and red

Q: what's going on? why the red color?

note that *direct* sunlight is totally blocked
so light must be indirect, in fact:
scattered light from earth's atm.
red b/c blue is scattered more strongly, so only red is left
in other words:
  glow is from all the sunrises and sunsets on Earth!

solar eclipse: observer in moon's shadow
Note: Earth larger than Moon
Q: what does this immediately imply for solar eclipses?

since Moon smaller than earth, whole earth cannot be in shadow
in fact, only a small region, ~ 100 mi, at a given time
"eclipse path"

interesting coincidence: Moon and Sun *appear* to have
  almost identical *angular* size on the sky
  i.e., one can "cover" the other nearly exactly
and what's more: Moon's distance changes (not circular orbit)
`www: moon perigee/apogee comparison`

together this means: two kinds of solar eclipses
`www: annular eclipse`
`www: total eclipse`
`www: looking back on Earth's shadow`

Note: there is *not* a solar eclipse every month!
Q: why? What does this imply for lunar motion in 3-D?

if Moon's orbit plane around Earth
were same as Earth's around the Sun (i.e., the ecliptic)
then *would* have eclipses monthly

the fact that we *don't* means that
the two orbits are *not* coplanar!

⋆ moon's orbit plane slightly tilted w.r.t. ecliptic
so moon is typically below or above ecliptic
Transp: *eclipse diagram*
only eclipse when Moon orbit crosses ecliptic plane
happens twice a year → "season of eclipses"

A Spinning Moon?

`www: lunation animation: always same face!`

`www: far side`

Always same side faces us!

demo: lunar globe

Q: in one orbit period, is there spin?

Q: how many periods?

Moon has $P_{\text{orbit}} = P_{\text{spin}}$ exactly!
"corotation"

Sounds too good to be true!
Better be a good reason for this!

...and there is...

ENOUGH ALREADY–TAKE A BREAK!

The Dynamic Moon: Gravity, Tides, and the Lengthening Day

Earth–Moon System: Tides

`www: high/low comparison photo`

ocean tides are due (mostly) to Moon

Q: why "mostly"? Other actor(s)?

ocean tides are periodic

Q: what is tide period: high to high/low to low?

`www: tide data`

Q: how does the Moon raise tides on Earth?

Why the observed periodicity?

Tide Warmup: Gravity in a Nutshell

Isaac Newton:
gravity initmately linked to *mass*

- all objects with mass exert force: gravity
- all objects with mass feel gravity forces
  from all other massive objects

in fact: more mass $\longrightarrow$ more gravity
but: gravity forces *decrease* as distance *incresaes*
$\longrightarrow$ *inverse* relationship with distance

General rule: two objecs of mass m_1, m_1
separated by distance d
each feel attractive gravity force F due to the other

- $F \propto m_1$
- $F \propto m_2$
- $F \propto 1/d^2$

together:

$$F_{\text{grav}} \propto \frac{m_1 m_2}{d^2} \tag{1}$$

"inverse square law"
$\rightarrow$ double distance: F_{grav} is 4 times smaller!
$\rightarrow$ to lose weight, go upstairs!

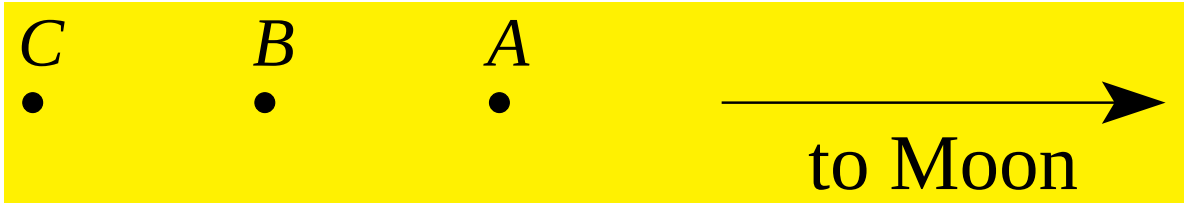
Q: effect of Earth's gravity on Moon?
Q: effect of Moon's gravity on Earth? where strongest? weakest?

Earth's gravity keeps Moon in orbit
otherwise it would fly away!

Moon's gravity pulls on every particle on Earth
but: gravity force *decreases* with distance from Moon

- strongest pull at closest point "underneath" Moon
- weakest pull at farthest point, opposite closes
- medium pull at center of Earth

An illustrative simplified problem:
three identical mass balls A, B, C in a line
freely floating except for Moon's gravity



if Moon's gravity force *did not* change with distance
but were the *same* on all three
Q: how would the set of particles move relative to the Moon?
Q: how would the particles move relative to each other?

In reality, Moon's gravity strength *decreases* with distance
in this case:
Q: how would the set of particles move relative to the Moon?
Q: how would the particles move relative to each other?

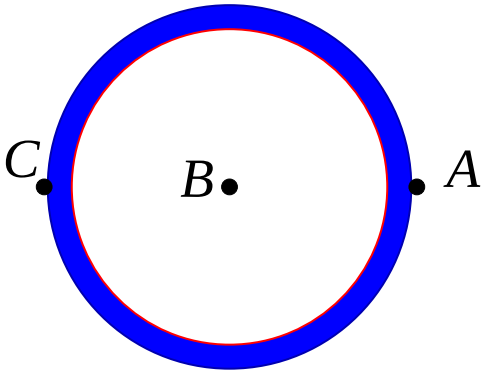
If gravity were (unrealistically) *constant* with distance:

- all three particles feel the same force
  so the whole ABC system falls toward (or around) the Moon
- but they would *not* move relative to each other
  i.e., not pulled apart or together

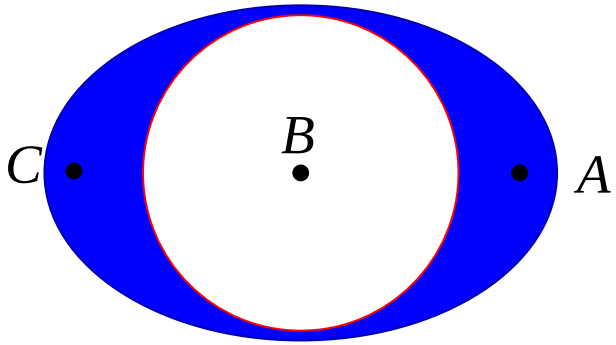
But gravity really *weakens* with distance:

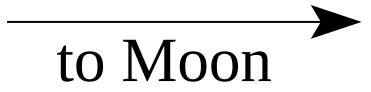
- all particles still feel *some* attraction
  so the whole ABC system still falls
  toward (or around) the Moon, but...
- the farther particles feel progressively less force
  A pulled away from B, and B pulled away from C
  $\Rightarrow$ entire ABC system is internally stretched!
  relative to midpoint (B), edges pulled away!

Given the realistic results
Q: What is the Moon's effect on oceans?



Earth in isolation





Earth in field of Moon

A attracted more than average (B), C less

$\rightarrow$ tides rise symmetrically along axis towards moon

i.e., tides high in region nearest and farthest from Moon

$\rightarrow$ high-tide to high-tide period twice daily

`www: tide animation`

What about the rocks on the Moon, and the Earth?

Q: how do changing gravity forces affect them?

Tidal stresses on Moon → Moon surface constantly deformed
Deformed Moon non-spherical: tidal bulges
Earth gravity on bulges → twists Moon! (torque)

- if Moon spins faster than orbit → decreases Moon spin
- also decreases Moon orbit speed → moves Moon outward!
  measured! the Moon moves away about 3.8 cm/year!

repeated stretching/compression → friction, heating
dissipation → evolve to frictionless state:
reduces Moon spin rate until
$P_{\text{spin}} = P_{\text{orbit}}$: corotation!

Note: may take long time!
complete for Moon, not for Earth!
measured! Earth spin period increasing!
→ day getting longer by about 0.0016 sec/century!

ENOUGH ALREADY–TAKE A BREAK!

The Statistical Sky: Solar System History from Lunar Craters

Craters on the Moon and Earth

Compare pictures of Earth and Moon

`www: global Earth`

`www: global Moon`

Q: similarities? differences?

Note craters:

Q: how are they made?

Q: why differences in Earth vs Moon cratering?

...more than one reason!

Crater Comparison

Craters made by explosions (including man-made events...)
larger explosion $\rightarrow$ larger crater size
in Solar System: explosions from asteroid/comet collisions

crater existence on a surface in Solar System
$\rightarrow$ encodes info on bombardment history!

Why more craters on Moon?
Moon & Earth share same Solar System real estate
so exposed to same bombardment hazard, but...

- ★ Earth atmosphere burns up all but largest objects
- ★ Earth oceans hide 75% of surface
- ★ Earth erosion "quickly" erases damage
- ★ Earth volcanos hide some
- ★ Earth tectonic activity (plate motions) recycles surface

Craters on the Earth

In fact: large objects *do* survive atmosphere,
hit Earth surface, leave craters for millions of years
today $\sim$ 100 identified around the world!

`www: terrestrial craters`

Largest known crater: Chicxulub, Mexico

`www: Chicxulub crater map`

- 200 km across!
  $\rightarrow$ explosion = 40,000 $\times$ *entire global nuke arsenal*!
- date: created 65 million years ago
- also: dinosaurs wiped out 65 million years ago

$\Rightarrow$ probably due to explosion
fires; tsunamis; dust $\rightarrow$ dark, cold for years

Craters on the Moon

`www:  global Moon`

`www:  Google Moon`

Q: what patterns do you notice–color, terrain, cratering?
Q: are craters equally numerous across Moonscape?
Q: what is this trying to tell us?

Lunar Craters and Solar System History

Lighter-Colored Regions: "Highlands"

- rough, mountainous terrain
- high concentration of craters (Lunar DMV not on the job!)

Darker-Colored Regions: Maria = "Seas"

- smooth plains
- many fewer craters (but still plenty of them)

Since cratering → bombardment history
fewer craters in Maria → younger surface
in fact: moonrocks from Maria are "basalt" = volcanic
⇒ Maria/seas are ancient lava flows → "repaved" part of Moon
⇒ Maria cratering gives bombardment rate since
⇒ early Solar System more collisions: a violent place!
⇒ in fact, Moon itself probably born in collision!
Mars-sized body + Earth → Moon!

ENOUGH ALREADY–TAKE A BREAK!

The Physical Moon: Traveler's Tales, and Lessons from Moonrocks

The Moon: Surface Features

⋆ **highlands**: lighter in color, heavily cratered

`www: Apollo 17 in highlands (mountains made by impacts)`

⋆ **maria** – "seas" (singular: mare): dark plains

`www: Mare Imbrium large scale`

`www: maria/highlands comparison`

smooth: fewer craters, made of volcanic rock *Q: how do we know?*

formed by lava flows

⋆ craters

cover surface

occur in all sizes, $>$ 20km to microscopic

`www: Mare Oriental`

`www: maria--overlapping craters`

★ "soil" **regolith** = "rock blanket"

transp: Niel Armstrong quote–right after first step

`www: footprint`

`www: Real Audio Armstrong--start at 3:35`

dust, rock fragments

accumulated debris from many impacts

★ other tips for tourists:

- no atmosphere → no UV, X-ray protection
- slow rotation → long "days"
  huge day/night temp diff: 370K vs 125 K

The Moon: Origin

Earth & Moon similar in composition of crust, different in core

- Fission model ("sparated at birth") :

moon spun out from rapidly rotating earth

- Binary ("Sister") model

earth and moon formed together as binary system

- Capture model

"vagabond" moon gravitationally captured by earth

- giant impact model

Moon created in collision of Mars-sized object with early Earth

Q: pros, cons of each?

• Fission model ("sparated at birth") :
unlikely: ang mom problem–Earth wouldn't rotate fast enough

• Binary ("Sister") model
unlikely: where do differences come from?

• Capture model
unlikely: where do similarities come from?

• giant impact model
"least unlikely"–accounts for both differences and similarities
$\rightarrow$ eary solar system a violent place!