

Astro 350
Lecture 3
Jan 24, 2022

Announcements:

- **Discussion Question 1** posted on Canvas due this Wednesday
- **Homework 1** posted today due this Friday
- please turn on video

Last time: naked-eye cosmology

Q: How are the Sun, Planets, Stars arranged in the sky?

Q: How do they move in the sky each day?

Q: How do the planets move on the celestial sphere?

stars: on sky – “fixed” on 2D celestial sphere
which appears to spin once daily: $P = 1$ day

Sun: on celestial sphere – moves in great circle (ecliptic)
with uniform speed, constellations visited: zodiac
implies Earth-Sun motion is in a *plane*

planets: on celestial sphere – in zodiac, near ecliptic
usually move in same direction as Sun
but speed on sky not is uniform
and sometimes briefly reverse direction: retrograde
www: retrograde animation

~ Sun and planet motion in celestial sphere: www: SOHO/LASCO

These Patterns Cry Out For Explanation

you may have noticed—I've heaped a lot of facts on you.

Do you have to memorize them? Do *I* have them memorized?

No! There's a simpler way of remembering.

→ build a **model** of the solar system's geometry and dynamics
organize, explain all of this data!

Crucial point:

when making model for motions of planets

have to explain *all* observed features;

turns out the retrograde motion, in all its detail,

gave people the hardest time...

Classical Greek Cosmology: Geocentric

Classical Greek Cosmology

Pythagoras (Mr. Triangle!) and followers believed:
the world follows underlying rules: **cosmos** = order
universe founded on **geometry**, which is perfected in *spheres*

- Earth: spherical shape

Eratosthenes (276-195 BC) calculated size of Earth
got very close to the correct answer!

...as you will see in HW1

- Moon, Sun, planets, stars fixed on spheres
spinning around us in uniform circular motion

Aristotle (284-322 BC)

Two realms, where different physical principles apply

	heavenly	terrestrial
realm	above moon	below moon
status	“incorruptible” unchanging, perfect	“corruptible” changeable, imperfect
natural motion in realm	uniform circular rotation	earth, air, water, fire: toward natural place in universe earth lowest, then water, air, fire

Geocentrism

Ancient Greeks: **Earth is center of universe** (“geocentric”)

★ rise & set of sun/moon/planets can be explained Q: *how?*

★ we don't *feel* Earth is spinning

would mean we move at 900 mph w.r.t. Earth center

→ why aren't we flung off?

★ apparent lack of **stellar parallax**

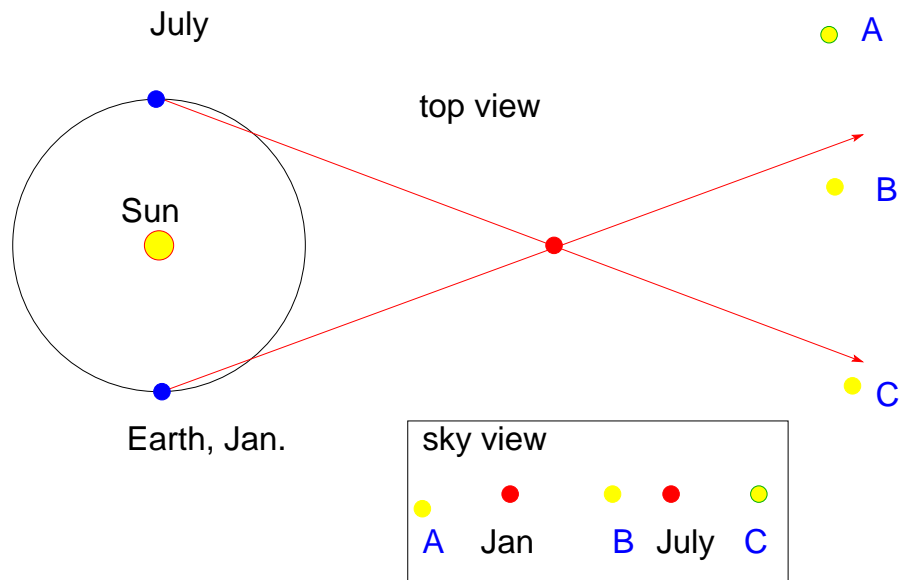
Proof by contradiction: *what if* earth orbits sun?

Imagine the Earth were moving around the Sun

Q: *how would this change the observed pattern of stars?*

Stellar Parallax: Take One

if earth moves \rightarrow star positions change on celestial sphere



foreground star should appear to *shift* w.r.t. background stars

∞ but parallax effect *not* observed!

Q: *why?*

Q: *if you are Aristotle, what do you conclude?*

Aside: the Modern View

Of course we will soon conclude the Earth *does* move
So why is there seemingly no parallax?

eye cannot resolve angles $\lesssim 1' = 1 \text{ arc min} = 60 \text{ arc sec}$
it turns out—typical star shift on sky: $\sim 1'' = 1 \text{ arc sec}$
a very small effect!
parallax not detected until $\sim 1830(!)$

Aristotle explained data available at the time
and gave strong evidence **against** Sun-centered picture!

Poll: The Geocentric Celestial Sphere

Consider the geocentric picture of Aristotle and Ptolemy, in which the celestial sphere is literally a sphere.

What is the motion of this sphere?

- A no motion; at rest
 - B uniform rotation with period = 1 year
 - C uniform rotation with period = 1 day
 - D nonuniform rotation, period = 1 year, tilted by $\pm 23.5^\circ$
-

Q: What does the geocentric model (described thus far) explain? what not?

In Defense of Geocentrism

Geocentric framework not a crazy idea!
explained data available at the time
and gave strong evidence **against** Sun-centered picture!

also note—*based on everyday experience*:

- not obvious that any objects in sky are larger than Earth!
lunar eclipses show Moon smaller than Earth!
need accurate distances to know Sun is larger
- not obvious that planets and stars have any size at all!
so perhaps Earth is the largest object in the Universe!?!?
and thus, of course it should be at the center!

≠ but one element of naked-eye motion not yet explained
Q: what are we missing so far? what's the fix?

Retrograde Motion and Epicycles

theory has to explain *all* data

if contradicted by some data, either:

- improve theory
- dump it and get a new one

Tricky balance: don't want to be too hasty

Q: why not immediately abandon theory if new data contradicts?

but also don't want to stubbornly cling to sinking ship

any cosmology must explain **Retrograde motion**

Greeks: deferent and epicycle

www: epicycle animation

Claudius Ptolemy ~ 125 AD

Constructed complete geocentric model of the known cosmos
every planet had epicycles—in fact, epicycles on top of epicycles!
complicated/elaborate model, but also sophisticated

Ptolemy accounted for

- non-uniform motion
- retrograde motion
- Venus and Mercury never in opposition
center of epicycles always on line
connecting earth and sun

Errors generally < 5 deg: not bad but observable!

↳ remained in use for ~1400 years!!

Newton has not done as well! ...yet

Poll: Ptolemy & Science

Vote your conscience!

Is Ptolemy's system a **scientific** model for the naked-eye sky?

- A yes
- B no
- C maybe

Science

science is a human activity → actual real-life practice
very interesting and very complicated
will see complexity through examples, but for starters:

science is a systematic, logical set of ideas about Nature
and the test of all scientific knowledge is **observation**.
→ **Experiment** is the final judge of scientific truth.

If experiment is the Judge, then the Court is the
Scientific Method:

observation & experiment → tentative model → predictions
→ further experiment → refined model → repeat ↑
end product: **theory**

Scientific Models must:

- explain *all* existing observations
- predict future observations
- *change* or even be *abandoned*
if in conflict with *any* observations

sounds simple—but surprisingly complex in practice

this process has forced us, kicking and screaming,
to take seriously ideas like dark matter, dark energy

Cosmologist Richard Feynman

The scientific method is a way of *finding what works*

The first principle is that you must not fool yourself
–and you are the easiest person to fool.

Cosmologist Henri Poincaré:

Science is built up with facts, as a house is with stones.
But a collection of facts is no more a science
than a heap of stones is a house.

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Also note: scientific theory \neq offhand idea or wacky notion!
despite common usage...

from *Webster's Collegiate Dictionary*

theory

1 : the analysis of a set of facts in their relation to one another

2 : abstract thought : SPECULATION

6 (a) : a hypothesis assumed for the sake of
argument or investigation

(b) : an unproved assumption : CONJECTURE

18 *Not* how we will use the term!

In Praise of Ptolemy

It is science? I'd say: **Yes!**

- ★ gives a logical way of organizing, picturing, and understanding the world
- ★ explains a large set of data both qualitatively and quantitatively
Q: which is to say?
- ★ based on a set of physical principles

Shortcomings:

- weak on predictions—no idea when/where will need new epicycle
- good but not perfect agreement with observations available at the time

Give Claudius his due:

given the data *available to him*

Ptolemy did a well as, or better than, all contenders

⇒ remained in use for ~1400 years!

(Newton/Einstein can't touch that!)

Indeed, at the time big problems with sun-centered model

(where's the parallax?)

Today, geocentric has numerous problems:

we know more physics, and have better observations

But: if naked eyes are what you have, Ptolemy is legit

Renaissance Cosmology: Revolution!

Nicolaus Copernicus 1473–1543 Polish

adopted *heliocentric* cosmological model:

Note: motivation was *not* Ptolemaic disagreement with data but rather aesthetic – i.e., intuitive sense of beauty

www: Copernican model

- Mercury & Venus closer to Sun \Rightarrow always seen near Sun
- earth spins \Rightarrow daily motion of celestial objects
- earth orbits sun \Rightarrow apparent sun motion in ecliptic
- retrograde motion: during earth–planet passing

www: retro animation

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But: have to explain *all* data

Q: how would Nick account for non-observation of star parallax?

Copernicus Bonus: calculated relative distances of planets!

recall: Venus never seen too far from Sun

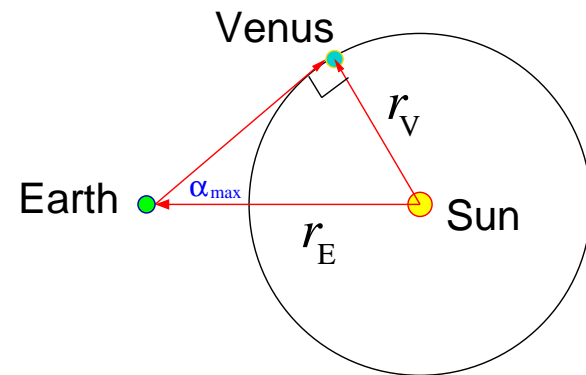
largest angle from Sun: maximum “elongation” $\alpha_{\text{Venus}} = 46 \text{ deg}$

in heliocentric model:

max elongation when sightline is
tangent to Venus orbit

from diagram: $\sin \alpha_{\text{max}} = r_V / r_E$

and so $r_V = r_E \sin \alpha_{\text{max}} = 0.72 r_E$



New unit of distance/length:

“astronomical unit” = average Earth-Sun distance

$$1 \text{ au} \equiv r_E = 1.50 \times 10^8 \text{ km} = 93 \text{ million miles}$$

- Earth (average) orbit radius: 1 au
- Venus orbit: 0.72 au

Copernicus: What's New and What's Not

- planets still on spheres
- Copernicus still used epicycles!
- predictions *not* better than in Ptolemy's model
→ geometrically equivalent Q: *meaning?*
- Copernicus' model not generally accepted
and Ptolemaic–Copernican disagreement though to be metaphysical, *unanswerable* question

Q: *so how do we decide which is right?*

Tycho Brahe 1546-1601: Danish Astronomy Extraordinaire

in youth: observed “nova stella” (supernova) www: Tycho sketch
→ change observed in heavens → corruptible!
observed Sun, Moon, planets for 20 years: careful, accurate data
but not a good number cruncher
→ like any good professor: made grad student do the work!

Johannes Kepler 1571–1630: Harmony of the Worlds

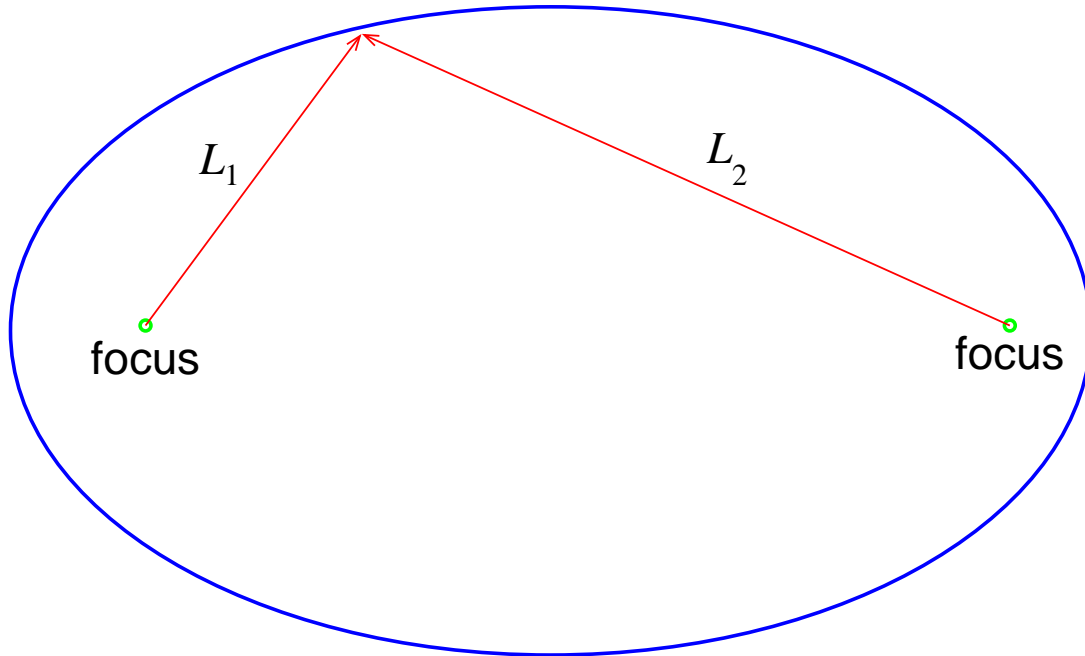
Analyzed Tycho’s data for **20 years**(!), especially Mars motions
used heliocentric model with circles
but observations didn’t quite agree
a small error (few arc min!) remained...took seriously
→ after trial & error:
completely & accurately described planet orbits

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Q: Kepler’s Laws?

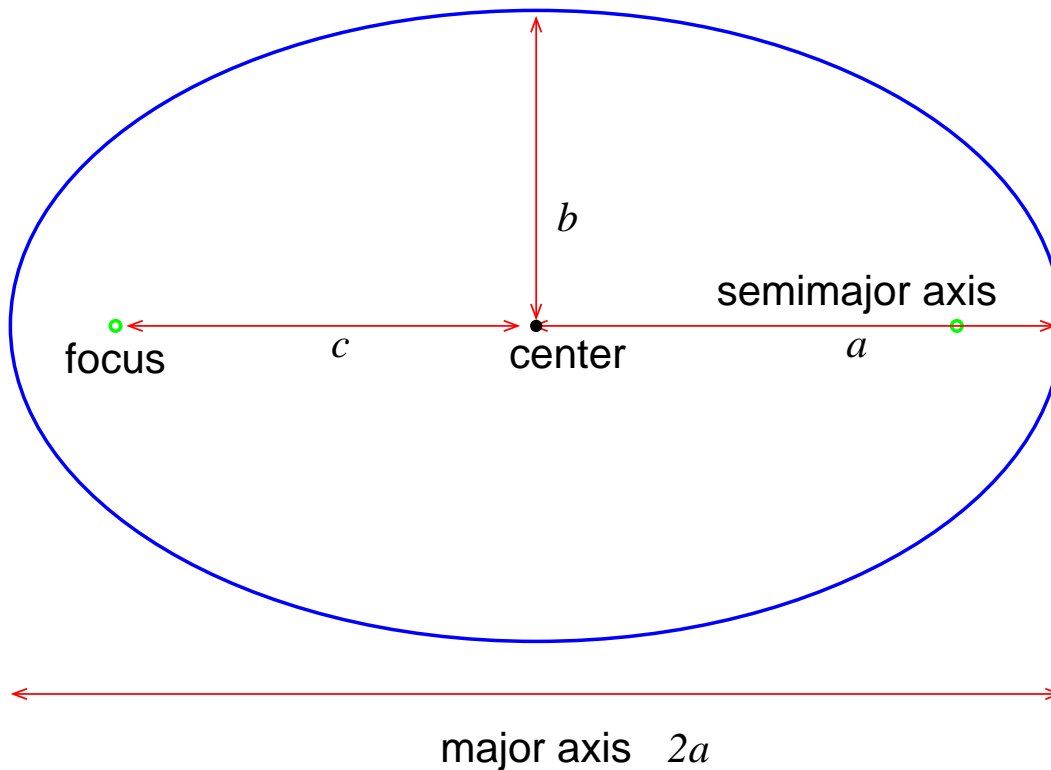
Kepler I: Law of Ellipses

each planet's orbit is an **ellipse**
with the **sun at one focus**



$$L_1 + L_2 = \text{constant}$$

Ellipse Anatomy



- two foci
- semi-major axis a
- focal length c
- semi-minor axis
 $b = \sqrt{a^2 - c^2}$

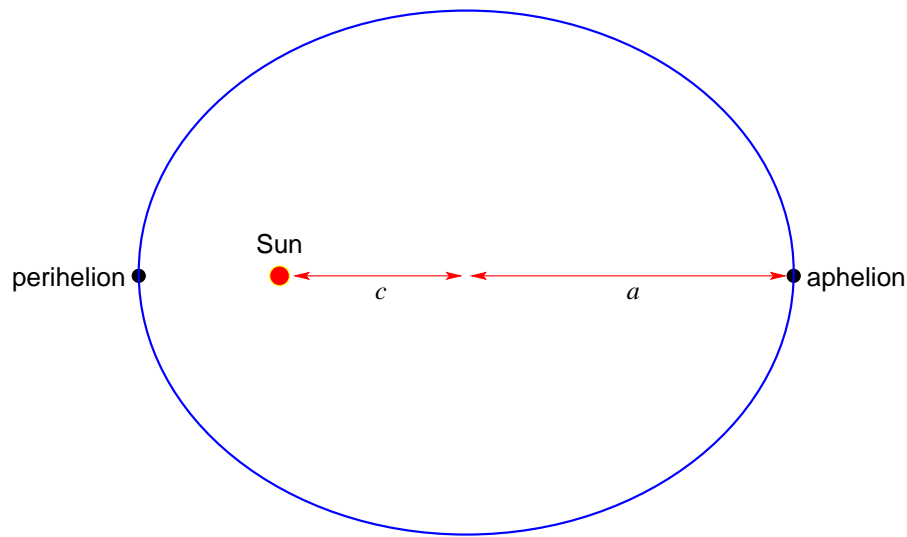
any ellipse fully characterized by:

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a and eccentricity $e = c/a$

Q: what do we get for $e = 0$? $e = 1$?

Kepler I: orbit is **ellipse** with **sun at one focus**



Orbit anatomy

aphelion: farthest point from Sun

perihelion: closest point to Sun

Q: what is aphelion distance in terms of a and e ?

$$r_{\text{ap}} = a + c = a + a \frac{c}{a} = (1 + e)a \quad (1)$$

Q: If the Sun's at one focus, what's in the other focus?

Q: What does Kepler I not say about orbits?

At the other focus: nothing! (sorry!)

Note: Kepler I only gives orbit *shape*
but says *nothing* about how orbit evolves in time
→ need more info to fully describe orbit, hence...

Kepler II: Law of Equal Areas

a straight line from the planet to the sun
sweeps out equal areas in equal times

diagram: sketch areas

note that this amounts to telling about speed of planet

Q: where fastest? slowest?

www: area animation

Q: This still doesn't fully characterize an orbits—why not?