From Ptolemy to Kepler

Astronomy 101
Syracuse University, Fall 2019
Walter Freeman

September 26, 2019

"Nature ... is inexorable and immutable; she never transgresses the laws imposed upon her, or cares a whit whether her abstruse reasons and methods of operation are understandable to humans. For that reason it appears that nothing physical which sense-experience sets before our eyes, or which necessary demonstrations prove to us, ought to be called in question (much less condemned) upon the testimony of biblical passages which may have some different meaning beneath their words. For the Bible is not chained in every expression to conditions as strict as those which govern all physical effects; nor is God any less excellently revealed in Nature's actions than in the sacred statements of the Bible."

–Galileo Galilei, to the Grand Duchess Christina (1615)

"Philosophy is written in this grand book – I mean the universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth."

–Galileo Galilei, *The Assayer* (1623)

Announcements

- Exam papers being returned in lab this week
- In lab, discuss questions with your partners and your TA; you can figure out how you did
- Scores will be posted on Blackboard as soon as they are scanned
- **Doublecheck your score** on Blackboard in case something went wrong
  - If you don't have a score or something else is wrong, don't panic – we'll fix it
- If there is an error, write your lab TA and cc: me
- First paper due Wednesday 5PM
- Take-home lab posted; due early December

Writing assignment

For those who missed it, the first paper is due next Wednesday.

- Potential for significant extra credit
- Some special assignments for particular calendars; read the whole thing

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- If you will be gone Wednesday, get your TA's permission to turn it in late; this is fine, as long as the email is on time

Help with your paper

If you'd like extra help with your paper, you can contact:

- Me (help session Friday 9:30-12:00, or by email/Slack)
- Bethany Marsfelder (bcmarsfe@syr.edu, or search her on Slack)
- Junying Chen (jchen104@syr.edu, or search her on Slack)
- Any of the other coaches!

Where we've come from, and where we're going

We are now able to predict the motions of most of the stuff in the night sky:

- the distant stars
- the Sun
- the Moon
- **not** the planets!

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- There are suggestions that the Australian Aboriginals knew about red-giant pulsation
- Pacific Islanders' talents at celestial navigation allowed them to travel long distances over open ocean

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Instead we're going to focus on the specific narrative that led, ultimately, to modern science – from Alexandria (Egypt), through the Islamic world, to Renaissance Europe.

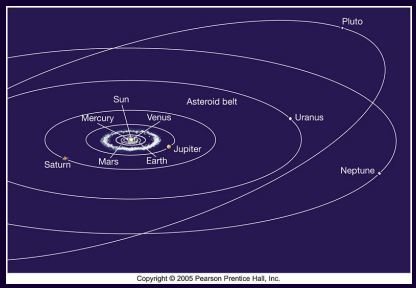
Where we've come from, and where we're going

We've casually mixed together ancient and modern perspectives:

The celestial sphere model

- Heavenly bodies stuck to spheres
- Spheres all turn around Earth
- Planets, Sun, and Moon all have their own spheres
- "Epicycles" needed to get planets right

The heliocentric model



- Earth is one of many planets, all orbiting the Sun
- The Earth rotates on its axis
- The stars are very far away and don't move
- Modern perspective

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... and what else did we learn about the sky in the process?

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- proposed models for things in nature
- used mathematics in these models
- recognized that any model had to agree with observation

The Greeks realized that images of the Moon during an eclipse looked like this.

What might they learn from this?

A: The Earth is round
B: The Moon is about 400,000 km away
C: The Moon is lit by the Sun, not from within
D: The Earth orbits the Sun


@neiltyson
A Lunar Eclipse flat-Earther's have never seen.

Greek natural philosophy

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Greek thinkers:

- saw the behavior of nature as *something we can understand*
- proposed models for things in nature
- used mathematics in these models
- Believed in the transcendent Truth and Beauty of mathematical perfection
- "Circles are the most perfect shape, thus things in the sky must go in circles"
- **Increasingly saw astronomy as a separate discipline from natural philosophy (argh!)**

Astronomy as separate from philosophy

Natural philosophy

- Concerned with the fundamental Truth of things
- Very concerned with logic, for instance
- Saw the heavens as mostly outside their purview
- Figuring out where the planets are is grunt work!

Greek astronomy

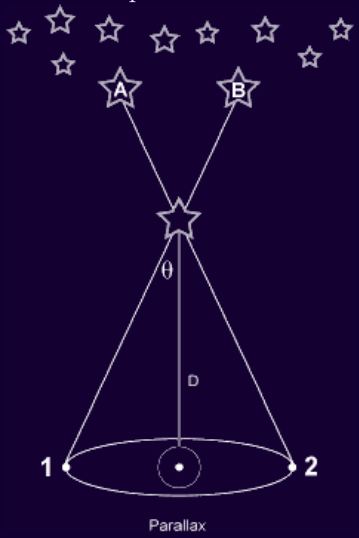
- Concerned with *predicting* the motions of stars and planets
- Not all that concerned with the *transcendent Truth* of their models
- "... but do we get the right answer?"
- Known mostly from Ptolemy's *Almagest*

Observational facts at the time

Everything we already learned:

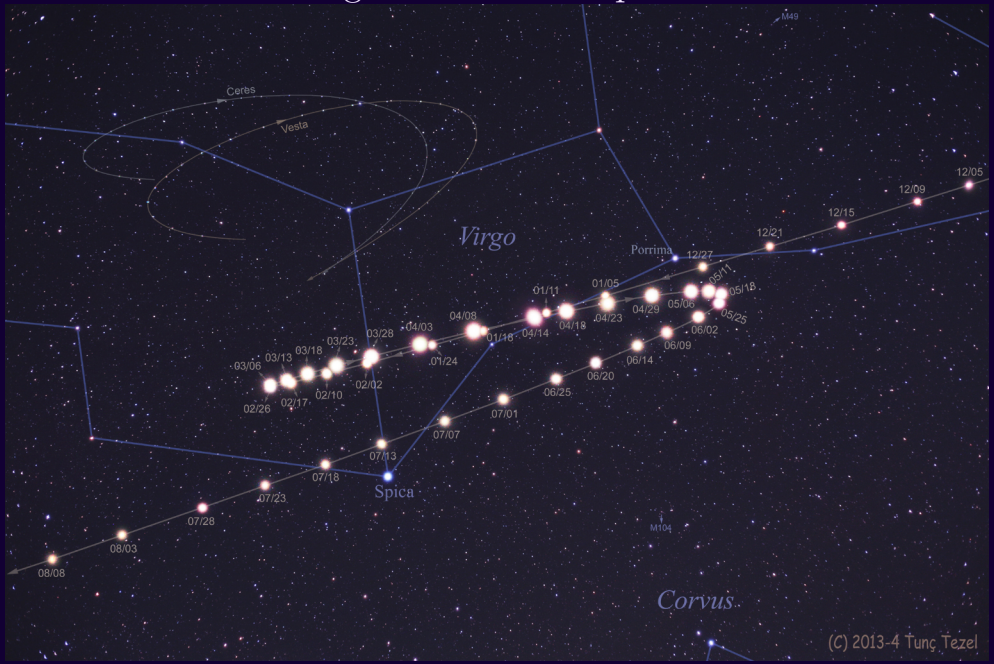
- Motion of the stars
- Phases of the Moon
- Seasons
- Eclipses, etc.

No stellar parallax:



Observational facts at the time – the hard one

Retrograde motion of planets:



Ptolemy and his model

Claudius Ptolemy lived in Alexandria, Egypt in the 2nd century CE.

This was a place and time where cultures met: Ancient Egypt, the Greek tradition and culture, and the Roman Empire.

He was a nuts-and-bolts guy – on the "astronomy" side of the philosophy/astronomy divide.

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That doesn't sound Greek – it's not. This name comes from Arabic, as do many others!

Ptolemaic model

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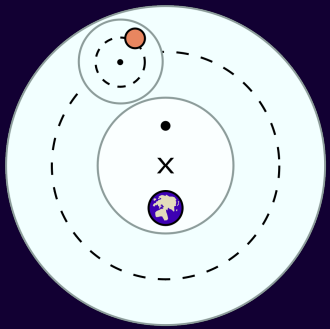
- Everything is attached to crystal spheres which spin in a uniform, perfect way around the Earth...
- ... well, sort of: the Earth isn't *quite* at the center of the planet-spheres
- ... well, sort of: they don't turn *quite* uniformly, but with a fudge that keeps the perfection of "circles"

Epicycles

This still fails to reproduce retrograde motion. What's the solution? More circles!



These circles-on-circles are called "epicycles". The center of the epicycle rotates not-quite-uniformly about a point not-quite-at-Earth, and then the planet rotates in a circle along the epicycle.

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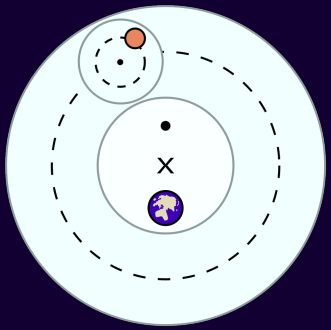

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Confused? Let's watch this in action: `https://youtu.be/utH-GHH1FT8?t=64`

The model in the Almagest

This model had a huge number of moving pieces: cycles on top of cycles, different centers and motion-fudges for each planet...

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This model had a huge number of moving pieces: cycles on top of cycles, different centers and motion-fudges for each planet...

... but it WORKED. Ptolemy published tables in the *Almagest* that could be used to predict, with astonishing precision, where the planets would be – even if he needed dozens of epicycles in total to do it.

What do you think about this?

A: This is far too complicated to be Truth; the Universe shouldn't be this hard

B: Some things are complicated; if this gets the right answer, then it is True

C: Truth is overrated; what matters is whether a model is useful for what it was designed to do

D: There is an abstract truth about nature, and a true model might predict other things we didn't expect

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E: Epicycles are just alternative facts!

From Egypt to Europe by way of the Islamic world

Alexandria in Egypt was the center of learning in the Western world ... until it wasn't.

The great Library at Alexandria was burned (everyone blames everyone else for this), and Alexandria declined as a center of scholarship.

The Muslims studied the Greek writing, and accumulated a great deal of knowledge about the motions of the sky; they named many of the stars, refined Ptolemy's model, and made enormous strides in *mathematics* (Arabic numerals, *al-jabr* (algebra), etc.)

The state of Europe, pre-Renaissance

Europe didn't really have much of a natural-philosophic or scientific tradition from the fall of the Roman Empire to c. 1400.

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"How many angels can dance on the head of a pin?" (not quite)

Copernicus (Polish/German, 1473-1543)

Ptolemy's model still worked – *brilliantly*. It was only off by a few degrees in a thousand years.

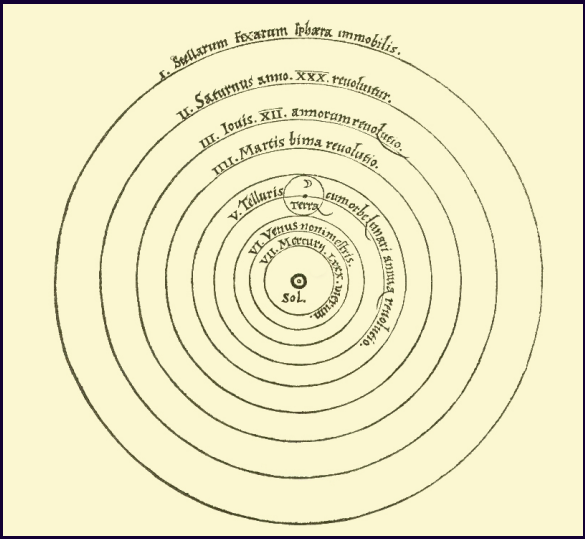
People had started to be dissatisfied with the complexity of it. It just *felt* inelegant!

Enter Copernicus. He proposed that, instead, everything orbits the Sun in perfect circles.

- Ptolemy's model was *geocentric* – the Earth is at the center
- Copernicus' model was *heliocentric* – the Sun is at the center

This allowed him to explain retrograde motion – *without* epicycles! (This is next week's lab.)

The philosophy of Copernicanism



The publisher added a preface to his book, saying, essentially:

"This is unusual. But it is just mathematics; it should be judged on whether or not it makes accurate predictions; this is separate from whether it contains actual philosophical truth!"

How should we judge Copernicus' model?

A: Whether it is simpler than Ptolemy's, and still more or less predicts things well

B: Whether it is more aesthetically pleasing – more *elegant* – and still more or less makes accurate predictions

C: Forget simplicity and elegance – are its predictions more precise? (Remember, Ptolemy's model was wrong by a degree after a thousand years)

D: Whether it predicted anything *new* that hadn't been observed before

Whoops.

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Copernicus' model was actually *less precise* than Ptolemy's at predicting celestial motion. You could fix it up with epicycles, but not even all that well...

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There are things orbiting Jupiter! These are the four largest moons of Jupiter, called the "Galilean moons" after their discoverer.

- If things orbit Jupiter, then not everything orbits the Earth! We are not the center of everything!
- This was a huge shakeup – to philosophy, and to *religion!*

Liverpool, NY (just north of Syracuse); 10:22 PM, June 18, 2019

500mm f/5.6 lens with 1.4x teleconverter; ISO 500, 1/250, f/8 (moons brightened in post)

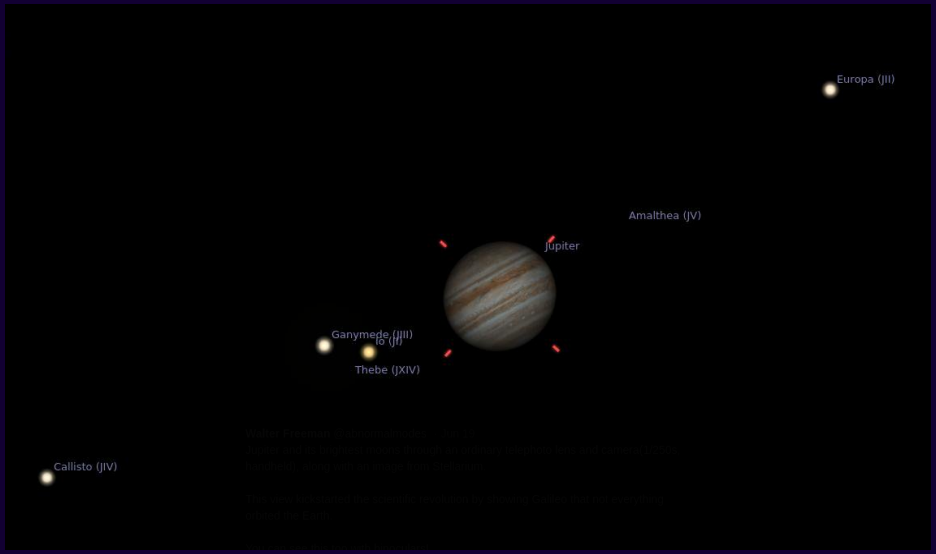

Image capture from Stellarium

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The “Galileo Affair”

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- He argued that the moons of Jupiter, along with the phases of Venus, proved the Earth moved.
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- The Church un-banned his books and heliocentrism in 1835.

Where we've come from, and where we're going

Galileo's work began a shift from *astronomy* to *astrophysics*.

(Ancient) Astronomy

- Predicts the motion of things
- Not that concerned with their nature
- An exercise in calculation

Astrophysics

- Concerned with understanding the *nature* of things in the sky
- "What are they and by what rules do they operate?"
- Predict their motion by understanding their nature

There's a reason you are taking this class in the physics building!

... but it doesn't quite work!

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What would be the best next step?

A: Doublecheck Copernicus' math, to see if his circles could be realigned to get better results

B: Make the most precise measurements of the planets that you can

C: Find other heliocentric models besides the one Copernicus had

D: Stick the Galilean moons around Jupiter in the Ptolemaic model and accept it as true

Three of these happened!

- Someone made impressively precise measurements of the motions of the planets
- Someone doublechecked Copernicus' math:
  - ... they found that a different arrangement of circles *almost* matched the data
  - ... but it was off by one-eighth of a degree!
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- Next time: this story, and a full transition to modern science

Summary

- Ancient Greeks separated philosophy from astronomy:
  - Philosophy: what is Truth?
  - Astronomy: how can I calculate when Venus will rise?
- Ptolemy's geocentric model
  - Planets carried on "epicycles", circles revolving on circles, around the Earth at the center
  - The Sun, the Moon, and the stars are also all on spheres revolving around the Earth
  - Very complicated, but gave accurate predictions
- Copernican heliocentric model
  - Planets and the Earth orbit the Sun
  - Simpler – gets retrograde motion right without epicycles
  - ... not as precise!
- Galileo's contribution
  - Used the telescope for astronomy for the first time
  - Observed the moons of Jupiter and the phases of Venus
  - Argued for a sun-centric model
  - Was accused of being a heretic; he's stepped on powerful toes!