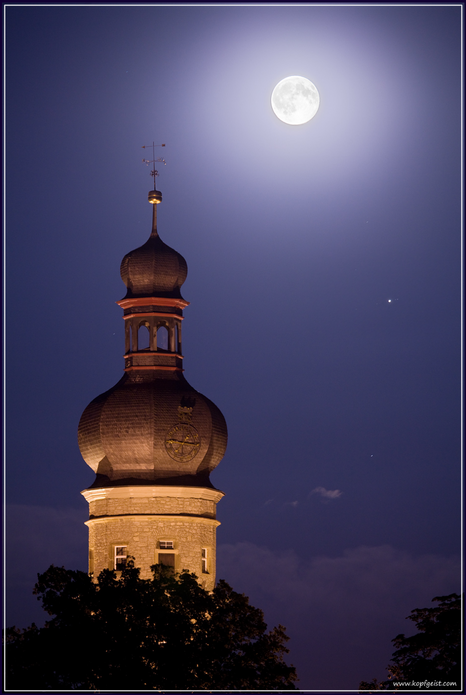
Kepler's laws

Astronomy 101
Syracuse University, Fall 2016
Walter Freeman

October 4, 2016



"And yet it moves."

–Galileo (attributed), on the Earth

Announcements

- Check your exam scores on Blackboard; if they're not right, tell me
- There are some entry errors, and a bug affecting people whose names start with Y/Z
- (This won't happen again!)
- Writing assignment due October 10 (next Monday)
- Take-home lab posted; due early December

Exam grading – philosophy

There are two ways you can demonstrate that you're an A student:

- Complete 90% of easy things correctly on an exam
- Complete 75% of hard things correctly on an exam

I would much rather ask you to do difficult things on an exam than easy things (which I did), and I am grading you accordingly.

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The exam grades will be rescaled approximately as follows before being factored into your final grade:

- 80+: A
- 70+: B
- 60+: C
- 50+: D

A new element of the course

Every time we meet, I can tell you what I'm thinking and planning.

But I only get your feedback through ABCD cards and by talking to a few of you.

I want to give you all more chances to give me feedback and to tell me what you think.

Starting Thursday, we're going to have *warmup problems*. How does this work?

Warmup problems

Here's how this works:

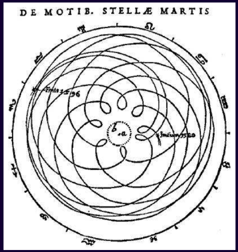
- I'll pose a question to you several days prior, sent out by email
- There will be a link to a Google Forms document for you to answer
- Think about the question and give your answer (should take no more than 10 minutes)
- If your answer is thought-provoking, I may read it in class
- Give your name or a pseudonym ("Alice", "Bob the Magnificent", "Galileo")

We're doing this so you can give me more feedback and more information about what and how you think!

Last time

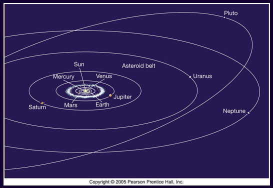
We left our story with two plausible models for the heavens:

The geocentric Ptolemaic model



- The planets (and everything else) revolve around Earth
- Inelegant system of "epicycles" needed to get planets right
- Everything moved in circles (elegant per Greeks)
- Earth and humanity at center (theologically not challenging)
- Very accurate predictions

The heliocentric Copernican model



- Earth is one of many planets, all orbiting the Sun
- Apparent motion = motion of Earth + motion of planets
- No (or very small) epicycles
- Less accurate than Ptolemaic model
- Matched Galileo's observations:
    - Moons of Jupiter
    - Phases of Venus

The Copernican model had a lot of attractive features, but was still less accurate – less good at actually telling you where the things in the sky would be!

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- What do we do?

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Maybe our data are wrong...

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Enter Tycho Brahe.

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- Was probably fun at parties (less so after his moose died)

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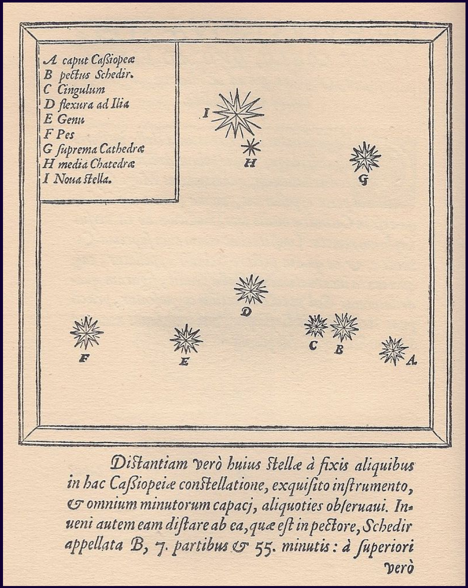

- Danish nobleman and astronomer, 1546-1601
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- Old worldview: world beyond the Moon is eternal
- ... nope: no observed parallax in the supernova → it's very far away!

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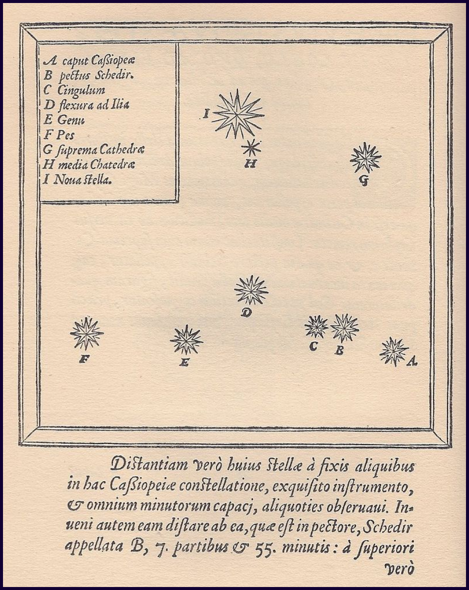

A caput Caßiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G suprema Cathedræ
H media Chatedræ
I Noua stella.

I H G D F E C B A

Distantiam verò huius stellæ à fixis aliquibus
in hac Caßiopeiæ constellatione, exquisito instrumento,
& omnium minutorum capacj, aliquoties obseruaui. In-
ueni autem eam distare ab ea, quæ est in pectore, Schedir
appellata B, 7. partibus & 55. minutis: à superiori
verò

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- Didn't observe parallax in the distant stars
- Two options:
  - The Earth doesn't move
  - The stars are very far away
- He believed the former
- Proposed another model for the Solar System

Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Best known for his precision measurements of the sky from Uraniborg
- Made high precision observations of the motions of the planets and stars
- Even had a crude correction for atmosphere bending light
- Measurements accurate to a few minutes of arc (1/60'ths of a degree!)
- Made these measurements with his assistant Sophie...
- ... and his later assistant Johannes Kepler, who didn't murder him

Johannes Kepler

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... here we go. Kepler, Tycho's assistant, finally got it right.

Kepler was a Copernican, and disagreed with his boss.

He tried to improve Copernicus' model, which used circular orbits, and mostly succeeded. But...

- Tycho's data were incredibly precise
- No matter how he rearranged the circles, there was an error of at least 8/60 of a degree for Mars
- Kepler worked at Uraniborg – he knew how precise the data could be

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Do we:

- A: Reject the belief that Nature must be elegant
- B: Reject the need for our model to match the data precisely
- C: Reject Tycho's data?
- D: Reexamine our ideas about what elegance looks like

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Kepler didn't only want to discover *how the planets moved*; he wanted to know *why*. He didn't figure it out, but he was on the path that led to modern science.

Even if the *answer* doesn't have the perfect elegance of circles, modern science looks for its elegance in *laws*, not in all of their consequences! Kepler discovered the consequences; the laws weren't uncovered yet.

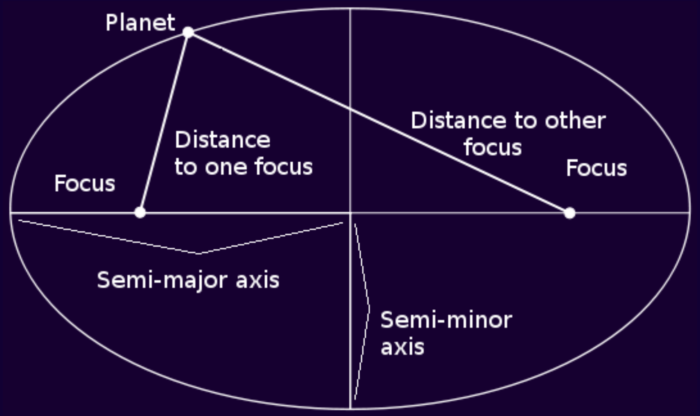
Kepler's laws of planetary motion

1. The planets move in *ellipses*, with the Sun at one focus
2. The line joining the planet and the Sun sweeps out equal areas in equal times
   Alternate formulation: Within its orbit, a planet's speed is inversely proportional to its distance from the Sun
3. The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of the ellipse.

Let's talk about each of these in turn.

Kepler's first law

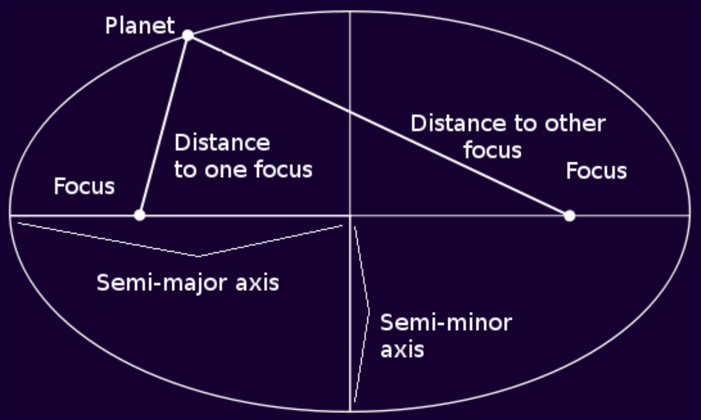
An ellipse is just a stretched circle. Mathematically: it's the curve around two points such that the *sum* of the distances to those points is a constant. A circle is just an ellipse with both foci at the same point.



Some terms:

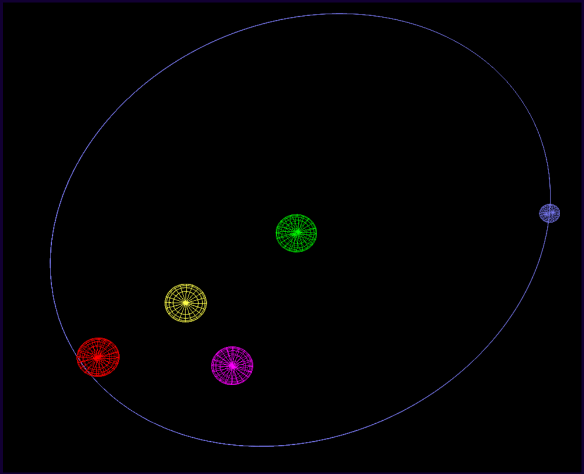
- Focus: One of the two points
- Semimajor axis: the largest distance from the center to the edge
- Eccentricity: how stretched out an ellipse is

Some properties of ellipses



- The two foci always lie along the major axis ("wide axis")
- The closer together the foci, the less eccentric
- If both foci are exactly at the middle, you get a circle
- Both foci lie inside the ellipse

Here's an orbit. Which is the correct position for the Sun?



A: The red one

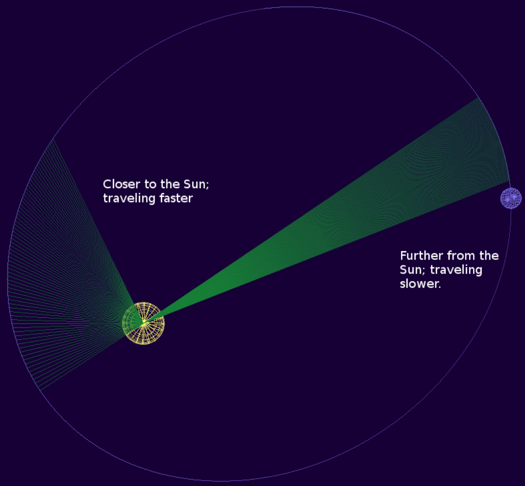
B: The green one

C: The yellow one

D: The purple one

Kepler's second law

In an eccentric orbit, a planet travels fastest when it's nearer the Sun.



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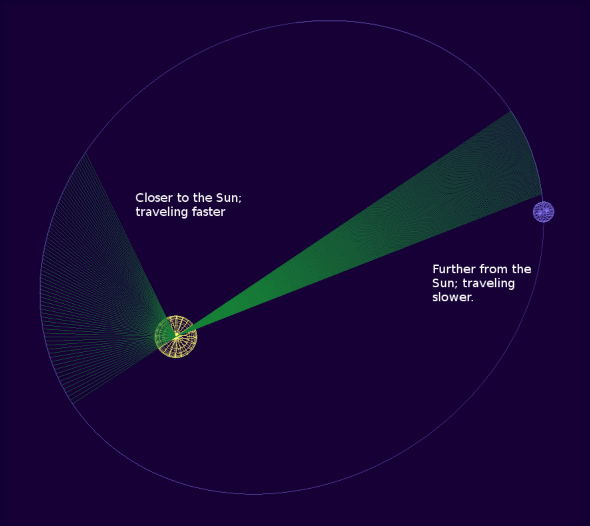

Let's watch this in an animation...

Comets

Comets have highly eccentric orbits. Halley's Comet's furthest point from the Sun – its *aphelion* – is 35 AU away. But its *perihelion* – the nearest point to the Sun – is 0.6 AU away.

Which statement is true?

A: Halley's Comet spends most of its time far from the Sun, and only a little time near the Sun

B: Halley's Comet moves slowly near perihelion, and quickly at aphelion

C: Halley's Comet moves quickly near perihelion, and quickly at aphelion

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(Get creative with your folding...)

Complete *Lecture Tutorials* pp. 21-24.

We will do something else after this.

Kepler's Third Law

Kepler's third law of orbital motion says that the square of a planet's *orbital period* is proportional to the cube of its *semimajor axis*.

Simply put: if a planet is further from the Sun, it takes longer to go around.

If the distance is doubled, the time required *more than doubles*.

Let's watch this...

Complete *Lecture Tutorials* pp. 25-28.