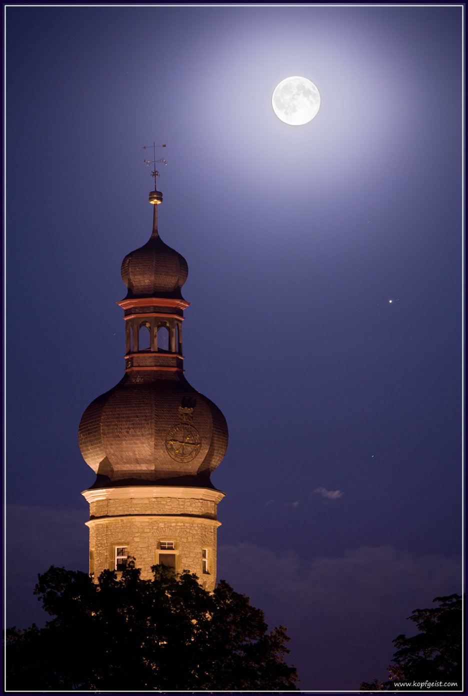
Kepler's laws

Astronomy 101
Syracuse University, Fall 2017
Walter Freeman

September 28, 2017



"And yet it moves."

–Galileo (attributed), on the Earth

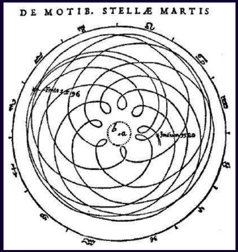
Announcements

- Exam grades posted on Blackboard sometime before Tuesday

Last time

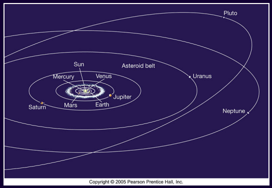
We left our story with two plausible models for the heavens:

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

- Different circular orbits?

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

- Different circular orbits?
- Epicycles again?

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

- Different circular orbits?
- Epicycles again?
- Different shapes?

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

- Different circular orbits?
- Epicycles again?
- Different shapes?
- This is hard because now we have to think about both the Earth and the planets (see simulation)

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!

Science doesn't attempt to explain the world "only a little bit" – if Nature is based on underlying physical laws, they should predict *everything!*

Is there a refinement of the Copernican model we can make?

- Different circular orbits?
- Epicycles again?
- Different shapes?
- This is hard because now we have to think about both the Earth and the planets (see simulation)
- What do we do?

What do we do when we don't know what to do?

Maybe our data are wrong...

The measurements of the sky that people had been using were "good enough" for navigation, but they weren't ever intended for precision natural philosophy: determining the truth of things...

What do we do when we don't know what to do?

Maybe our data are wrong...

The measurements of the sky that people had been using were "good enough" for navigation, but they weren't ever intended for precision natural philosophy: determining the truth of things...

Enter Tycho Brahe.

Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Built a fancy castle called Uraniborg to do research
- Levied huge taxes on peasants to pay for it

Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Built a fancy castle called Uraniborg to do research
- Levied huge taxes on peasants to pay for it
- Lost a big chunk of his nose in a duel and got a brass replacement made

Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Built a fancy castle called Uraniborg to do research
- Levied huge taxes on peasants to pay for it
- Lost a big chunk of his nose in a duel and got a brass replacement made
- Had better facial hair than any of us

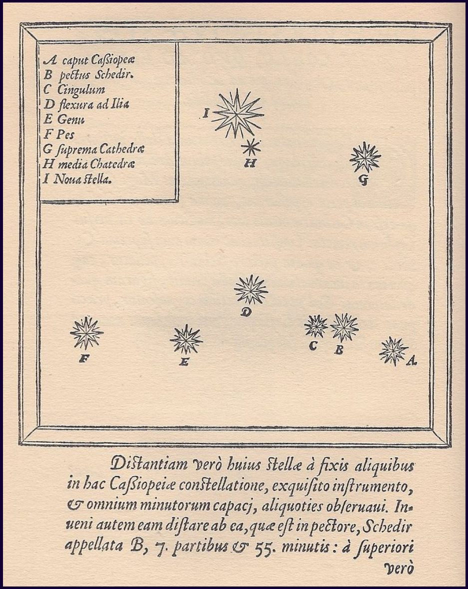
Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Built a fancy castle called Uraniborg to do research
- Levied huge taxes on peasants to pay for it
- Lost a big chunk of his nose in a duel and got a brass replacement made
- Had better facial hair than any of us
- Had a pet moose that drank too much beer and died

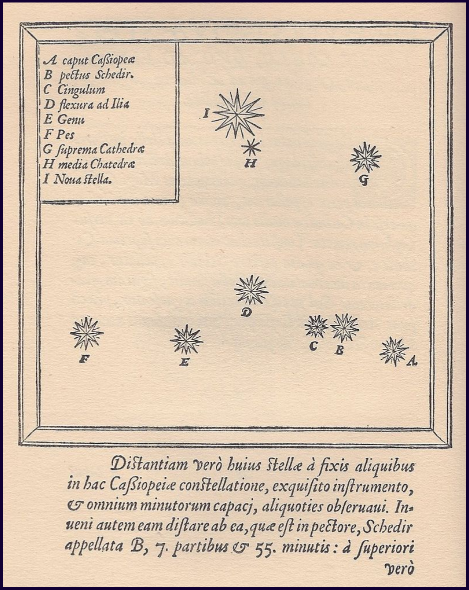
Tycho Brahe

- Danish nobleman and astronomer, 1546-1601
- Built a fancy castle called Uraniborg to do research
- Levied huge taxes on peasants to pay for it
- Lost a big chunk of his nose in a duel and got a brass replacement made
- Had better facial hair than any of us
- Had a pet moose that drank too much beer and died
- Was probably fun at parties (less so after his moose died)

Tycho Brahe



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



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

You've probably been wondering when we're going to stop this history of false starts and learn how things actually *do* work...

Johannes Kepler

You've probably been wondering when we're going to stop this history of false starts and learn how things actually *do* work...

... 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

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

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

"If I had believed that we could ignore that 8/60 of a degree, I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy." –Kepler

“*If I had believed that we could ignore that 8/60 of a degree, I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.*” –Kepler

“*There is a force in the Earth which causes the Moon to move.*” –Kepler, to Archduke Ferdinand

"If I had believed that we could ignore that 8/60 of a degree, I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy." –Kepler

"There is a force in the Earth which causes the Moon to move." –Kepler, to Archduke Ferdinand

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.

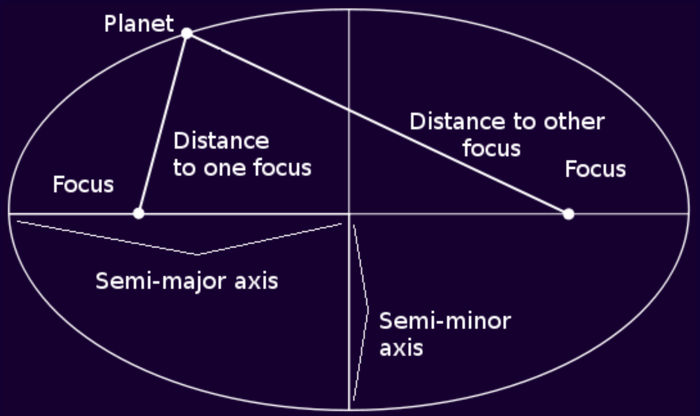
Kepler's laws of planetary motion

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

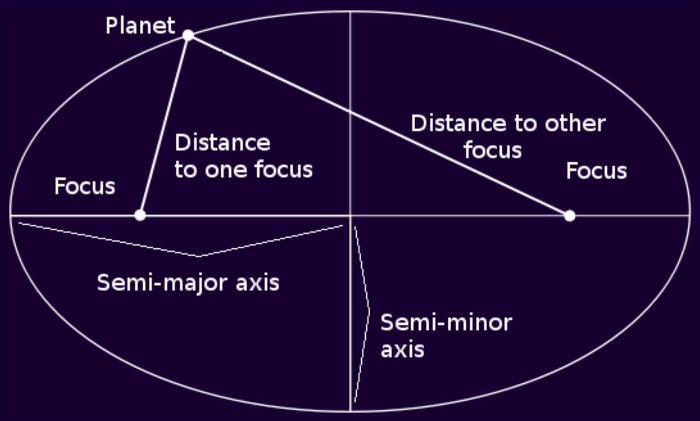
An ellipse is just a stretched circle. Mathematically: it's the curve around two points such that the *sum* of the distances to those points is a constant. A circle is just an ellipse with both foci at the same point.



Some terms:

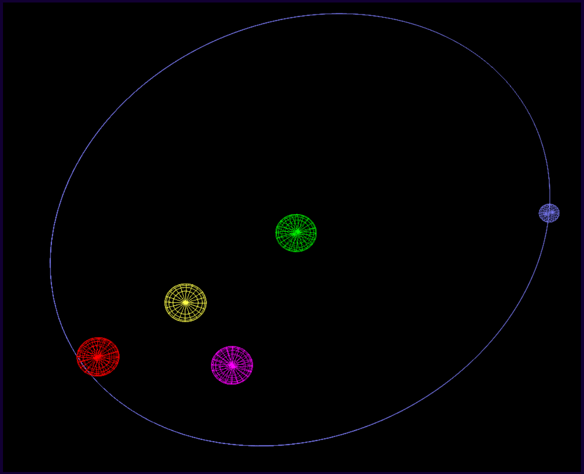
- Focus: One of the two points
- Semimajor axis: the largest distance from the center to the edge
- Eccentricity: how stretched out an ellipse is

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

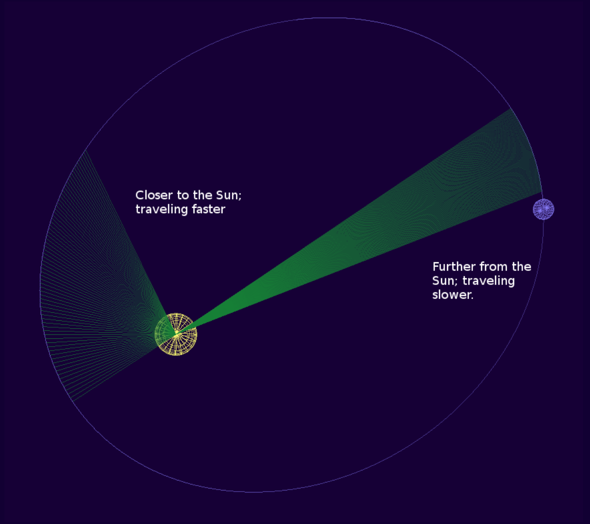
B: The green one

C: The yellow one

D: The purple one

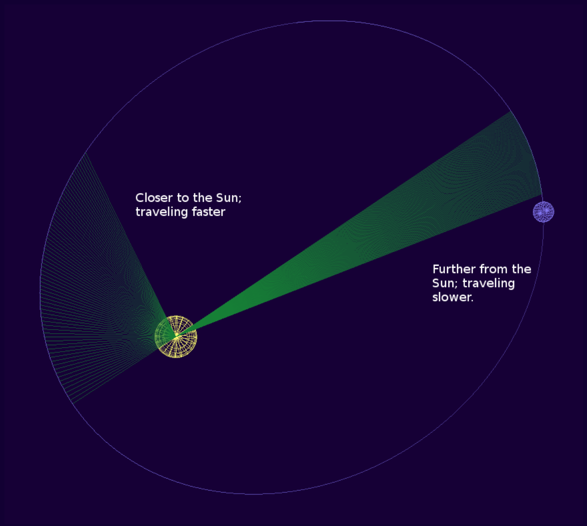
Kepler's second law

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



Kepler's second law

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



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 slowly at aphelion

D: Halley's Comet spends roughly equal amounts of time near the Sun, and far from it

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 slowly at aphelion

D: Halley's Comet spends roughly equal amounts of time near the Sun, and far from it

(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.