Astro 110-01 Lecture 7
The Copernican Revolution

or the revolutionaries:

Nicolas Copernicus (1473-1543)
Tycho Brahe (1546-1601)
Johannes Kepler (1571-1630)
Galileo Galilei (1564-1642)
Isaac Newton (1642-1727)

who toppled Aristotle’s cosmos
Recall: The Greek Geocentric Model of the heavenly spheres (around 400 BC)

- Earth is a sphere that rests in the center
- The Moon, Sun, and the planets each have their own spheres
- The outermost sphere holds the stars
- Most famous players: Aristotle and Plato
But this made it difficult to explain the apparent retrograde motion of planets...

Over a period of 10 weeks, Mars appears to stop, back up, then go forward again.
A way around the problem

• Plato had decreed that in the heavens only circular motion was possible.
• So, astronomers concocted the scheme of having the planets move in circles, called epicycles, that were themselves centered on other circles, called deferents.
• If an observation of a planet did not quite fit the existing system of deferents and epicycles, another epicycle could be added to improve the accuracy.
• This ancient system of astronomy was codified by the Alexandrian Greek astronomer Ptolemy (A.D. 100–170), in a book translated into Arabic and called *Almagest*.
• *Almagest* remained the principal textbook of astronomy for 1400 years until Copernicus.
So how does the Ptolemaic model explain retrograde motion? Planets *really do* go backward in this model.
Clicker Question: Retrograde motion

In the Greek geocentric model, the retrograde motion of a planet occurs when:
(a) Earth is about to pass the planet in its orbit around the Sun.
(b) The planet actually goes backward in its orbit around Earth.
(c) The planet is aligned with the Moon in our sky.
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Retrograde motion

The planet moves around the smaller circle while the small circle moves around the larger circle, with the resulting path indicated by the dashed curve.

Notice that the planet moves backward (apparent retrograde motion) whenever it is moving on the side of the small circle closer to Earth.
Clicker question: Retrograde motion (2)

This figure shows the circle upon circle motion of a planet in the Ptolemaic model.

At which point(s) is the planet in the middle of its period of retrograde motion in our sky?

(a) 2 only
(b) 3 only
(c) 1 only
(d) 1 and 3
Clicker question: Retrograde motion (2)

This figure shows the circle upon circle motion of a planet in the Ptolemaic model. At which point(s) is the planet in the middle of its period of retrograde motion in our sky?

(a) 2 only
Point 2 is in the middle of this part of the small circle and hence represents the middle of the period of apparent retrograde motion.

(b) 3 only
(c) 1 only
(d) 1 and 3
Stellar Parallax

• Greeks rejected the Sun-centered solar system because they could not detect stellar parallax
• But parallax depends on the distance of the object:
  – Nearer objects exhibit greater parallax than more distant objects
Stellar parallax (cont’d)

- Stellar parallax is the difference in direction of a celestial object as seen by an observer from two widely separated points.
- The measurement of parallax is used directly to find the distance of the body from the Earth (geocentric parallax) and from the Sun (heliocentric parallax).
- The two positions of the observer and the position of the object form a triangle; if the base line between the two observing points is known and the direction of the object as seen from each has been measured, the apex angle (the parallax) and the distance of the object from the observer can be found simply.
- In the determination of a celestial distance by parallax measurement, the base line is taken as long as possible in order to obtain the greatest precision of measurement. For the Sun and Moon, the base line used is the distance between two widely separated points on the Earth; for all bodies outside the solar system, the base line is the axis of the Earth’s orbit.
- The largest measured stellar parallax is 0.76", for the nearest star, Alpha Centauri; the smallest that can be directly measured is about 25 times smaller, but indirect methods permit calculation of the parallax, inversely proportional to the distance, for more and more distant objects but also with more and more uncertainty.

[Excerpt from the Encyclopedia Britannica]
Stellar Parallax (cont’d)

- stellar parallax

http://sci2.esa.int/interactive/media/flashes/2_1_1.htm
Nicolaus Copernicus (1473–1543)

• In a book called *On the Revolutions of the Heavenly Bodies* (that was published as Copernicus lay on his deathbed), polish astronomer Copernicus proposed that the Sun, not the Earth, was the center of the Solar System.
• Such a model is called a *heliocentric system*.
Copernicus used the model to determine the layout of the solar system (planetary distances in AU).
Copernicus’ model

- Earth is just another planet (the third outward from the Sun)
- The Moon is in orbit around the Earth, not the Sun
- The stars are distant objects that do not revolve around the Sun.
- The Earth is assumed to rotate once in 24 hours, causing the stars to appear to revolve around the Earth in the opposite direction.
Retrograde Motion and Varying Brightness of the Planets

By banishing the idea that the Earth was the center of the Solar System, the Copernican system led to a simple explanation of both the varying brightness of the planets and retrograde motion:

- The planets in such a system naturally vary in brightness because they are not always at the same distance from Earth.
- The retrograde motion could be explained in terms of geometry and a faster motion for planets with smaller orbits.
Copernicus and the Need for Epicycles

• The model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.
• The Copernican model did not do away with the need for epicycles. Copernicus did not question the assumption of uniform circular motion.
• In the Copernican model the Sun was at the center, but the planets still executed uniform circular motion about it.
• Hence the Copernican model could not explain all the details of planetary motion on the celestial sphere without epicycles.
• But the Copernican system required many fewer epicycles than the Ptolemaic system because it moved the Sun to the center.
The Copernican Revolution

Three incorrect ideas held back the development of modern astronomy from the time of Aristotle
(1) the assumption that the Earth was the center of the Universe,
(2) the assumption of uniform circular motion in the heavens, and
(3) the assumption that objects in the heavens were made from a perfect, unchanging substance not found on the Earth.

Copernicus challenged assumption 1, but not assumption 2.

The Copernican model implicitly questions assumption 3 that the objects in the sky were made of special unchanging stuff:
◊ Since the Earth is just another planet, there will eventually be a natural progression to the idea that the planets are made from the same stuff that we find on the Earth.
• Copernicus was an unlikely revolutionary.
• It is believed by many that his book was only published at the end of his life because he feared ridicule and disfavor: by his peers and by the Church, which had elevated the ideas of Aristotle to the level of religious dogma.
• However, this reluctant revolutionary set in motion a chain of events that would eventually (long after his lifetime) produce the greatest revolution in thinking that Western civilization has seen.
• His ideas remained rather obscure for about 100 years after his death.
• But, in the 17th century the work of Kepler, Galileo, and Newton would build on the heliocentric Universe of Copernicus and produce the revolution that would sweep away completely the ideas of Aristotle and replace them with the modern view of astronomy and natural science.
• This sequence is commonly called the Copernican Revolution.
Been There, Done That: Aristarchus of Samos

Aristarchus 310 BC to 230 BC lived on the Greek island of Samos.

Aristarchus postulated that the planets orbited the Sun— not the Earth— over a thousand years before Copernicus and Galileo made similar arguments.

Aristarchus used clear logic to estimate the size of the Earth, the size and distance to our Moon, the size and distance to our Sun.

He even deduced that the points of light we see at night are not dots painted on some celestial sphere but stars like our Sun at enormous distances.

Aristarchus' discoveries remained truly unbelievable to the people of his time but stand today as pillars of deductive reasoning.
Tycho Brahe (1546-1601):

Danish astronomer best known for the astronomical observations which led Kepler to his theories of the Solar system.

He is also known for his metal nose (he lost his nose in a sword fight with another student over who was a better mathematician).

Brahe made his observations from Uraniborg, on an island in the sound between Denmark and Sweden called Hveen.

Most meticulous astronomical observer of his time.
1. Brahe’s Most Accurate Naked Eye Measurements

Brahe set out to solve the day's most pressing astronomical problem:

◊ to determine whether the Earth or the Sun was at the center of the Solar System.

To do this, he and his assistants created the first major astronomical observatory where they devised and used the most accurate pre-telescopic astronomical instruments.

The instruments of Brahe allowed him to perform the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
Most importantly, Brahe compiled extensive data on the planet Mars, which would later prove crucial to Kepler in his formulation of the laws of planetary motion because it would be sufficiently precise to demonstrate that the orbit of Mars was not a circle but an ellipse.

He still could not detect stellar parallax, and thus still thought Earth must be at the center of the solar system (but recognized that other planets go around Sun). Brahe never solved the Solar System problem himself - but left data so impressively accurate his assistant Johannes Kepler was able to develop definitive laws.
2. Brahe’s observations of a supernova

- Brahe made observations of a supernova (literally: nova= "new star") in 1572
  - This was a "star" that appeared suddenly where none had been seen before, and was visible for about 18 months before fading from view.

- This clearly represented a change in the sky. [Prevailing opinion held that the supernova was not really a star but some local phenomenon in the atmosphere (remember: the heavens were supposed to be unchanging in the Aristotelian view)].

- Brahe's meticulous observations showed that the supernova did not change position with respect to the other stars (no parallax). \(\backslash\) it was a real star, not a local object.

- This was early evidence against the immutable nature of the heavens

- He also showed that it was much further away than the Moon
3. Brahe’s Observations of a comet

- Brahe made careful observations of a comet in 1577.
- By measuring the parallax for the comet, he was able to show that the comet was further away than the Moon. [This contradicted the teachings of Aristotle, who had held that comets were atmospheric phenomena ("gases burning in the atmosphere" was a common explanation among Aristotelians)].
- Comets represented an obvious change in a celestial sphere that was supposed to be unchanging; furthermore, it was very difficult to ascribe uniform circular motion to a comet.
A wrong conclusion: the case of the missing stellar parallax

- Brahe made the best measurements that had yet been made in the search for stellar parallax. Upon finding no parallax for the stars, he (correctly) concluded that either
  - the earth was motionless at the center of the Universe, or
  - the stars were so far away that their parallax was too small to measure.

- It was not the first time in human history that a great thinker formulated a pivotal question correctly, but then made the wrong choice of possible answers:
  - Brahe did not believe that the stars could possibly be so far away and so concluded that the Earth was the center of the Universe and that Copernicus was wrong.
Brahe: Summary

• Brahe proposed a model of the Solar System that was intermediate between the Ptolemaic and Copernican models (it had the Earth at the center).
• It proved to be incorrect, but was the most widely accepted model of the Solar System for a time.

Brahe's ideas about his data were not always correct, but the quality of the observations themselves was central to the development of modern astronomy.
• In the interplay between quantitative observation and theoretical construction that characterizes the development of modern science, Brahe was the master of the first but was deficient in the second.

• The next great development in the history of astronomy was the theoretical intuition of Johannes Kepler (1571-1630), a German who went to Prague to become Brahe's assistant.
Brahe's Data and Kepler

• Kepler and Brahe did not get along well.
• Brahe apparently mistrusted Kepler, fearing that his bright young assistant might eclipse his reputation.
• He therefore let Kepler see only part of his voluminous data.
• He set Kepler the task of understanding the orbit of the planet Mars, which was particularly troublesome. It is believed that part of the motivation for giving the Mars problem to Kepler was that it was difficult, and Brahe hoped it would occupy Kepler while Brahe worked on his theory of the Solar System.
• It was precisely the Martian data that allowed Kepler to formulate the correct laws of planetary motion, thus eventually achieving a place in the development of astronomy far surpassing that of Brahe.
Kepler and the Elliptical Orbits

- Unlike Brahe, Kepler believed firmly in the Copernican system.
- The reason that the orbit of Mars was particularly difficult was that Copernicus had correctly placed the Sun at the center of the Solar System, but had erred in assuming the orbits of the planets to be circles.
- Thus, in the Copernican theory epicycles were still required to explain the details of planetary motion.
- Kepler was forced finally to the realization that the orbits of the planets were not the circles demanded by Aristotle and assumed implicitly by Copernicus,
  - but were instead the "flattened circles" called ellipses

The difficulties with the Martian orbit derive precisely from the fact that the orbit of Mars was the most elliptical of the planets for which Brahe had extensive data.
• Kepler first tried to match Tycho’s observations with circular orbits.

• But an 8-arcminute discrepancy led him eventually to ellipses.

“If I had believed that we could ignore these eight minutes [of arc], 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.”
What is an ellipse?

An ellipse looks like an elongated circle.
Eccentricity of an Ellipse

Eccentricity and Semimajor Axis of an Ellipse
Kepler’s three laws of planetary motions
**Kepler’s First Law:**
The orbit of each planet around the Sun is an **ellipse** with the Sun at one focus.
Kepler’s Second Law:
As a planet moves around its orbit, it sweeps out equal areas in equal times.

\[ \text{A planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.} \]
Kepler's 2nd Law
Kepler’s Third Law

- The ratio of the squares of the revolutionary periods for two planets is equal to the ratio of the cubes of their semimajor axes:

\[
\frac{P_1^2}{P_2^2} = \frac{R_1^3}{R_2^3}
\]

- Choosing subscript 1 for the Earth, the relation can be rewritten as:

\[p^2 = a^3\]

with \(p\) = orbital period in years

and \(a\) = average distance from Sun in AU