21L.016 / 21M.616 Learning from the Past: Drama, Science, Performance
Spring 2009

ASTRONOMY 9: HISTORY OF COSMOLOGY
Handout #10
J. E. Baker
UC Berkeley, Spring 2000

Cosmology in Ancient Greece: Aristotle and Greek Astronomy

I. Aristotle (384 322 BC)

- Student of Plato's Academy
- Founded Lyceum
- Worked in almost every field of known science and philosophy!
- Profound influence on development of Western science
- Every effect must have a *cause*
- Important innovation: universe can be described by **natural laws** inferred by rational thought
- Aristotle's physics: mostly quite wrong, but strong common-sense appeal
    - Founded science of **mechanics** (physics of motion)
    - Developed the idea of "force", **impetus** theory of motion (wrong, but widely held even today!)
    - Thought force was *required* to keep Earthly objects in motion (didn't fully understand *inertia*)
- Aristotle applies his physics to the cosmos
    - Basic Earthly elements: air, earth, fire, water
    - Terrestrial and celestial physics are very different!
    - Two types of "natural" motion
      A) Earth: linear, straight-line, finite motion (air and fire go up, water and earth go down)
      B) Heavens: perfect, eternal, circular motion
    - Bodies are impelled to move to their "natural" location
    - Can only have one center ⇒ only one world
    - Circular motion must have a corresponding basic element ⇒ 5th element (quintessence): **ether** (heavenly, unchanging)
    - Cosmic division:
      A) Sub-lunary sphere (inside moon's orbit): earthly, changing, becoming, imperfect, made of 4 elements (Ionian)
      B) Celestial realm (moon and beyond): immutable, perfect, made of ether (Eleatic)
    - Objects don't get "left behind" ⇒ Earth is **fixed at the cosmic center**
    - Earth known to be spherical on *observational* grounds:
      A) Circular shadow during lunar eclipse
      B) Different stars become visible when travel north/south
    - Heavens are rotating ⇒ Universe must be **finite!**
    - Space has an unapproachable "edge"
    - Universe is **eternal**, uncreated
    - God rules from outside (primary cause of all motion)
    - Appropriates Eudoxus' sphere model to explain planetary motion
    - Better observations require more spheres ⇒ 55 total! (Still no explanation for varying brightnesses)
    - Aristotle thinks spheres are *physically real*
    - No "Void" (vacuum), unlike the Atomists

II. Heraclides of Pontus (c. 388 310 BC)

- Proposed **rotating** Earth to explain daily rotation of heavens
- Proposed Mercury and Venus orbit Sun, not Earth
- Ideas rejected by Aristotelians

III. Aristarchus of Samos (approx. 310 230 BC) "The Ancient Copernicus"

1

- Measuring the size of the cosmos...
- Estimated size of Moon to be $\approx 1/3$ size of Earth (from lunar eclipse shadow)
- Measured angle between Sun and Moon when Moon is half-full (called "first quarter")
- Concluded Sun is 18–20× further away than Moon
- But apparent (angular) sizes of Sun and Moon are the same $\Rightarrow$ Sun is at least 18 times as big as Moon, or 6 times as big as Earth!
- Used inaccurate data (Moon diameter $2°$, actually $0.5°$), and method doesn't work well in practice: Sun is actually much bigger still!
- **Heliocentric** model: Sun is at the center!
- Correct but rejected by Aristotelians, forgotten for 1500 years... Science is not a linear progression of ideas!

IV. Eratosthenes of Cyrene (276–194 BC)

- Clever measurement of the circumference of the earth
- Distance between Alexandria and Syene (now Aswan, Egypt) measured to be 5000 "stadia" (Greek unit of length)
- Compare noon shadows at summer solstice, find $7.2°$ difference
- Assume Sun is far away so that rays are parallel
- Circumference is then

$$C = \left(\frac{360°}{7.2°}\right) \times 5000 \text{ stadia} = 50 \times 5000 \text{ stadia} = 250{,}000 \text{ stadia}.$$

- Length of stadium is uncertain; result was very accurate if 1 stadium $= 157.2$ meters:

$$C = (250{,}000 \text{ stadia}) \times 1 = (250{,}000 \text{ stadia}) \times \left(\frac{157.2 \text{ m}}{1 \text{ stadia}}\right) \times \left(\frac{1 \text{ km}}{1000 \text{ m}}\right) \approx 40{,}000 \text{ km}$$

V. Appollonius of Perga (approx. 262–190 BC)

- Back to the geocentric cosmos
- A new answer to Plato's challenge to "save the phenomena"
- Different from Eudoxus' "onion" cosmos of spheres, more like a Ferris wheel
- Not totally geocentric: introduced **"eccentric** circle"
    - Earth remains motionless at cosmic center
    - Planets still move in circles at uniform speed
    - But center of circles is now displaced from Earth!
    - Apparent motion as viewed from Earth is of variable speed
- Also invented **epicycle**
    - Wheels upon wheels
    - Allows (complicated) explanation of retrograde motion
- "Theorist": did not try to apply ideas to observational data

VI. Hipparchus of Rhodes (190–120 BC)

- Great Greek astronomer
- Synthesized Babylonian and Greek data with new Greek geometrical models from Appollonius
    - Model for Sun's motion (eccentric circle)
    - Model for Moon's motion (eccentric + epicycle)
- Also made accurate catalog of 850 star positions
- Discovered precession of equinoxes

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Lecture Notes by I. R. King: Greek Astronomy and the Ptolemaic System

1 Heraclides

We're going to go through today the developments that led to the Ptolemaic system of the motion of planets around the Earth, but the development of Greek thought, and in particular Greek science, was far from monolithic and undeviating. Two "aberrations" even appeared that are part of our modern view of the world: Heraclides suggested that the daily rising and setting of the sun, moon, and stars could be explained by a rotation of the earth on its axis, and Aristarchus (and probably Heraclides too) thought that the Earth went around the Sun. But these ideas attracted little attention or following. (I don't think Ptolemy even mentions Aristarchus or bothers to refute him.) Now it's very easy today to say, "Oh, those stupid Greeks! They had people who knew the right answer, but they ignored them." But this of course is a ridiculously naive view. They lived in a different world, with views that in many ways are just as intelligent as ours, but different fundamental ideas were dominant. In particular, philosophy dominated over scientific inquiry, and Aristotle's ideas about the nature of the earth and the heavens ruled out both of these motions of the earth. And let's not forget the role of common sense: everybody knows that whenever you accelerate you can feel it, and we certainly don't feel the earth spinning or rushing around the sun.

But I don't want to get off on this side track; let's get back to the development of Greek astronomy. But that brings us right back to Aristarchus.

2 Aristarchus

His heliocentric picture hasn't survived in writing; we know of it only through mention by others. But one thing he did was definitely mainstream: measuring the relative distances of the moon and sun. Magnificent in principle, but flawed in practice, for two reasons. First, it is hard to measure the time of quarter moon precisely. (This is usually excited to explain the poor accuracy of his result.) Second, and rarely noted, is the fact that the **eccentricity** (ellipticity) of the moon's orbit makes it move with varying speed, which vitiates the whole idea, unless you take an average over many moon orbits. The monthly variations are 5–10× larger than the effect Aristarchus was trying to measure.

3 Eratosthenes

One other quantity that was measured in ancient times is the size of the earth. Around 200 BC, Eratosthenes, who lived in Alexandria, had heard that in the town of Syene, some distance to the south of him, the sun was exactly overhead on the summer solstice (when the sun is farthest north). From the length of a shadow in Alexandria, he measured that the sun was 7.2° from his zenith at solstice. This angle is 1/50 of a full circle, so the circumference of the earth is 50× the distance from Syene to Alexandria. The accuracy of his result is not known with certainty, because the size of the unit he used is not known. A confusion of units also seems to have affected Columbus, who thought that the earth's circumference was smaller than it really is (and used the erroneous figures to justify his voyage across the ocean).

4 The Problem of Planetary Motions

The greatest achievement of ancient science was the working out of an accurate description of the complicated motions of the planets (for example, retrograde motion). How do we get around this? Appollonius (c. 200 BC) came up with the idea of the **epicycle.**

Another problem was non-uniform speed, which in the Aristotelian universe was unacceptable. It was well known that the sun doesn't move uniformly throughout the year; the lengths of the four seasons differ by several days. Appollonius had a solution for this one too: the **eccentric** circle. Motion was not around the cosmic center (earth) but rather around a displaced point. (Ironic that the greatest ancient authority on ellipses seems never to have thought of using them for orbits!)

5 Hipparchus

Hipparchus (c. 140 BC) was the greatest observer of ancient times. He cataloged about 850 stars, and observed the positions of the planets (Hipparchus was to Ptolemy as Tycho later was to Kepler). **Magnitudes** (a logarithmic measure of brightness) in his catalog established the system of magnitudes that we use today. Hipparchus also applied the ideas of Appollonius (the eccentric and epicycle) to real planetary data.

6 Ptolemy

Ptolemy (c. 150 AD) was the last great natural philosopher of classical times. He was responsible for putting together a picture of planetary motion that stood until the beginning of modern times. (He also drew the best world atlas of ancient times, which later influenced Columbus toward thinking that China was a reasonably short distance west of Europe!) He wrote a great compendium of math and astronomy: $\mu\epsilon\gamma\iota\sigma\tau o\varsigma$, or *Almagest* in its Arabic version.

Ptolemy used observations made by Hipparchus to measure the **parallax** of the moon. He seems to have gotten the right answer, but made two big mistakes which remarkably canceled out! Parallax exists for the stars too (since the earth moves round the sun) but is very small (since the stars are very far away).

Whereas earlier scientists had been assembling ideas and observations (e.g., epicycle and eccentric of Appollonius; observations of Hipparchus, whose importance Ptolemy acknowledges), it was Ptolemy who finally put it all together to make a system that *worked* that is, it would fit observed positions in the past and could be used to predict them in the future. (Ironically, the greatest practical importance for this system was considered to be its use for astrology, which of all ignorant superstitions is the one that modern astronomers most abominate.)

The epicycle is the central device of the Ptolemaic system it can explain retrograde motion (which is much easier to explain in a heliocentric system!), but it's not enough. Ptolemy had to make things really fit well. He used the eccentric, which can account for varying speed. Today, we know that each planetary orbit has a different eccentricity (that is, degree of ellipticity or non-circularity) of its orbit. So in the Ptolemaic system, each planet has its circular orbit centered at a different place. But even on an eccentric circle, he still couldn't get the speeds right with uniform motion (a philosophical necessity), so he devised a new trick, the **equant**. This is another point, distinct from both earth and the center of the eccentric circle, from which the planet appears to sweep out equal angles in equal times. When you come to study Copernicus, you'll find that he was quite complacent about epicycles and even used some small ones himself, but he despised the equant.

In summary, a Ptolemaic orbit is defined by the **deferent**, epicycle, eccentric, and equant. Ptolemy found numerical values for each of the seven "planets" (including Sun and Moon), that would fit the observations of his day as well as those of Hipparchus, nearly 300 years earlier. His model provided a good fit (within a fraction of a degree) to all planetary motions for several centuries!

Some medieval Arabic astronomers added subsidiary epicycles, greatly complicating the system and leading to the idea that Ptolemy piled epicycles on top of epicycles. In fact, he didn't, and it was the (relatively) simple system just described that came into western Europe in the thirteenth century and was used there.

Ptolemy had succeeded brilliantly at solving Plato's old challenge to "save the phenomena". But his model had some shortcomings. First, it didn't contain any physics no explanation of *why* things move the way they do. (But note Copernicus also lacked physics, which was only supplied a century and a half later by Newton.) Secondly, there were some suspicious coincidences unexplained by Ptolemy's model. One was that the centers of the epicycles of Mercury and Venus were fixed on a line between the earth and sun.

A second coincidence was that retrograde motion always takes place when the planet is in the opposite direction from the sun (at **opposition**). But it worked, and it fit many Aristotelian principles, so it was just fine in its day.

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Cosmology in the Middle Ages

I. Early Middle Ages (approx. 200 1200 AD)

- Background
  - Rise in power of Christianity as state religion
  - Instituted by Emperor Constantine (324 AD)
  - Roman Empire divided into West (Latin) and East (Greek, Byzantine)
  - Time of great turmoil (invasion, social decay, corruption ...)
  - Attempts to repulse Germanic and Persian invaders fail; Rome falls in 400s, start of European "Dark Ages"
  - Catastrophic, fatalistic world-views mirrored in salvational themes of Christianity
- Greek curiosity about nature and love for reason are lost
- Natural philosophy no longer of interest, concern only with abstract theological questions
- Very few Greek writings survive
- Plato's *Timaeus* still widely read, also encyclopedic works of Latin compilers (Pliny, Macrobius, Capella, Chalcidius)
- Literal interpretation of scripture generally the final authority on cosmology
- Scholarly works all in Latin, knowledge of Greek fades
- Loss of Greek knowledge near total; from about 300 1000 AD, most "educated" western Europeans believe in **flat Earth!**
- Neo-Platonism generally dominates during this period
- St. Augustine (354 430)
  - Leads a wild, pleasure-seeking life until age 31, then adopts Christianity after trying many other philosophies
  - Philosophy seen as mere handmaiden to theology, not a distinct path to truth
  - Strongly influenced by Platonic ideas
  - Division of world into Forms vs. imperfect, shadowy reality, parallels the Christian "Fall" from grace
  - Plato's ideas wedded to Christian dogma
  - *The Confessions*: amplifies Plato's distrust of knowledge gained through the senses
  - Curiosity about the world, knowledge for its own sake, seen as an inherently sinful pleasure
  - Ideas further amplified by Augustine's followers
- St. Lactantius
  - Demolishes "pagan" idea of spherical Earth in *Divine Institutions* (written 302 323)
  - Earth believed flat for first time in almost 1000 years!
  - Argues against possibility of the antipodes
- Cosmas
  - First detailed description of early medieval cosmological system, in *Christian Topography* (written 535 547)
  - Cosmos as a giant Tabernacle
    * Much like earlier Babylonian/Hebrew views
    * Earth as flat rectangle or disc at the bottom of the universe
    * Cosmas was widely traveled, should have known better!
    * Earth surrounded by waters, also celestial waters above
    * Heavens are not spherical because Isaiah says God "laid them out like a tent"
    * Earth is tilted so the sun can go literally "down"
    * Tabernacle divided into two Aristotelian zones by firmament
    * Angels carry stars daily below the firmament

- Philoponus (6th c.)
  - Argues *against* the common abuse of scriptures to prove non-spherical heavens
  - Ideas have little influence on dominant Church
- Isidore (570 636)
  - Bishop in western Church
  - Also mentions spherical heavens and earth, going against the orthodoxy
- Bede (approx. 673 735, English monk)
  - Another unorthodox teacher of spherical Earth
  - Moves Earth from cosmic bottom back to center
  - Influenced by Pliny
- Virgil or Fergil (8th c., Irish ecclesiastic)
  - Threatened with expulsion from Church for teaching of spherical Earth
  - But not much happens; condemnation of cosmological heresy not at all strict
- Gerbert
  - Noted scholar and astronomer, becomes Pope Sylvester II in 999 AD
  - Spherical Earth now firmly reinstated
- Immutability of the Heavens
  - Like Aristotle, believed in perfect, unchanging celestial realm for Moon and above
  - Appearance of supernovae in 1006 and 1054 barely even noted, though 1006 as bright as quarter Moon!
  - As evidence of celestial change, clashed with medieval world-view
  - Chinese astronomy reached high-point, left records of many celestial events including the SNe
- By 1000, European knowledge roughly same as 500 BC Greece!

II. Cosmic Innovation in Arabia (approx. 700 1250 AD)

- Preservation and translation of many important Greek works (Ptolemy, Aristotle, Euclid, ...)
- Significant contributions to mathematics (algebra, numerals, sin function, ...)
- Re-introduction of Greek texts to Europe via Islamic Spain starting in 1200s
- Sparked rebirth of scientific curiosity in Europe at end of Middle Ages
- Built large, organized observatories for new tables of planetary motion

A) Adalusian school (Iberian peninsula)
  - Followers of Aristotle's physics: uniform, geocentric, circular motion is only natural possibility
  - Rejected Ptolemaic equant (non-uniform), epicycles and eccentric (not geocentric) as against physical principles
  - Reverted to Aristotelian model with concentric spheres
  - Predictions for planets off by up to 21°!

B) Maragha school (Persia)
  - Desired to improve accuracy of Ptolemaic model with new data and mathematical tricks
  - al-Tusi (d. 1274) invented Tusi couple
    - Combination of two circles, one smaller inside the other
    - Can produce variety of motion, even linear!
  - Ptolemy's eccentric and equant replaced with Tusi couples
  - Back to uniform circular motion, with little loss of accuracy

III. Late Middle Ages and Early Renaissance (approx. 1200 1500)

- By mid 1200s, translations of Aristotle and Ptolemy come to Europe via Arabia and Spain
- Philosophers comment on ancient Greeks, add few new ideas
- Aristotle's influence eclipses Plato's
- St. Thomas Aquinias (1227 1274)
  - Marriage of Aristotelian ideas and Christian dogma

- Revelation still most important source of knowledge, but natural philosophy recognized as a distinct path to truth, followed when not directly contradicting scripture
- Aristotelian physics instituted as dogma, not challenged
- Believed Aristotle already contained all that could be known about the world, nothing left to discover!
- Problems uniting Aristotle with Christianity:
  A) Eternal vs. created cosmos
  B) Only one world a limit on God's power?

- Roger Bacon (1214 1294)
  - Unlike most, did not follow Aristotle as dogma
  - Stressed use of *experiment* as path to truth
  - Establishment of scientific method
  - Imprisoned for two years for promoting "dangerous novelties"

- Dante (approx. 1300)
  - *Divine Comedy* presents dominant medieval view of cosmos
  - Hierarchical chain of being, walled-in, finite cosmos
  - Aristotelian lunary/sub-lunary division subdivided into many concentric shells
  - Outer shell is most perfect, angelic; Lucifer at center of Earth

- Nicolas of Oresme (1323 1382, France)
  - Wrote *Book of the Heavens and the World*
  - Familiar with Heraclides' idea of rotating Earth
  - Notes *relative* nature of motion
  - Argues rotation of Earth more natural than rotation of heavens!
  - Refutes his own ideas at the end of the work

- Nicolas of Cusa (1401 1464, France)
  - Argues for unbounded, eternal universe in *On Learned Ignorance*
  - Earth moves!
  - Forced to write apology, quotes ancient philosophers

- Regiomontanus (1436 1476)
  - Completes Peuerbach's translation of Ptolemy's *Almagest* from original Greek
  - Discovers errors up to 2° in planetary motions, eclipse ends one hour early

- Columbus (1492 trans-Atlantic voyage)
  - Did not have to convince anyone of spherical Earth (fiction invented by American writer Washington Irving)
  - Knew of accurate 9th c. Arabic computation of circumference
  - Got value 25% too small by assuming Arabic mi = Roman mi
  - Wrong Ptolemaic geography, thought Asia extended far east
  - Used to justify voyage
  - Europe not at cosmic center

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Copernicus: A Reluctant Revolutionary

I. Nicolas Copernicus (1473 1543, Poland)

- Moves Sun back to (well, near) center
- Revolutionary implications:
    - Earth is just another planet going round the sun
    - Demolishes Aristotelian spheres and walled-in medieval Christian universe
    - Universe becomes vast (lack of parallax)
    - Erases division of earthly vs. celestial realms
    - Aristotelian physics unsatisfactory: where is the center?
    - Breaks the close link between man, god, and universe
    - Loss of stability, rest, order
    - The Greeks did not discover all scientific knowledge
- Idea that our place in universe is not special: still called the **Copernican Principle**
- But these revolutionary ideas were not trumpeted (or even consciously recognized) by Copernicus! Merely *implied* by his work
- Heliocentric idea at first *welcomed* by relatively open-minded Church! Big trouble only decades after death of Copernicus, around 1600
- Copernicus was conservative, backward-looking, unwitting instigator of his revolution
- Last Aristotelian of the great scientists, at home in the medieval cosmos
- By standards of his day, Copernicus was a relic of an earlier world view!
    - Aristotelian physics long called into question by Bacon, Oresme, Cusa, ...
    - Aristarchus' heliocentric ideas never really forgotten, and were discussed openly prior to Copernicus
    - Winds of humanist Renaissance blowing from Italy, little effect on Copernicus despite his studies at Bologna
    - Still answering Plato's challenge to "save the phenomena", not trying to revolutionize cosmology
- Blind faith in ancient authority
    - Data mostly from Ptolemy
    - Only 27 recorded observations of his own, didn't bother to get modern instruments
    - Spent a lot of energy accounting for variation (not really there) in precession of equinoxes
- Other important revolutions going on
    - Luther's *95 Theses* and Reformation
    - Invention of printing press   rise of vernacular
    - Journey of Columbus   Europe is not the center of the world?
- Caged in almost Pythagorean secrecy, little courage of conviction, plagued by doubts and fears of ridicule (but little threat of religious persecution)
- The Copernican system
    - Introduces even *more* epicylces than Ptolemy! (About 48 vs. 40)
    - No real observational improvement over Ptolemy
    - Only circular motions
    - Sun is displaced from center of orbits   as bad as the despised equants!
- Born of wealthy merchant parents, influenced by overbearing uncle Lucas and scandalous brother Andreas
- Studies some astronomy at Univ of Cracow (1490s)
- Studies Canon law at Bologna (1496)

- Studies medicine at Padua (1501)
- Cushy job as Canon of Frauenburg cathedral, few responsibilities
- Unsocial life largely spent locked away in lonely tower at Frauenburg
- Few human relationships: lived with housekeeper Anna Schillings until ordered by Church to get rid of her (Counter Reformation), one close friend (Giese), one disciple (Rheticus)
- Motivation for heliocentric idea: Ptolemy's equants not in accord with Aristotelian physics!
- *Commentariolus* (Little Commentary): preliminary announcement of heliocentric idea, manuscript only, 1510 1514
- Seven axioms:
  - A) Heavenly bodies do not all move round same center
  - B) Earth is center of moon's orbit and terrestrial gravity, but not universe
  - C) Sun is the center of the universe
  - D) Earth's distance from Sun much smaller than to stars
  - E) Earth's rotation causes daily rising and setting
  - F) Annual motion of Sun against fixed stars due to Earth's orbit
  - G) Retrograde motion also due to heliocentric orbits
- *First Account*: written by Rheticus, no mention of Copernicus by name, 1539
- *On the Revolutions of the Heavenly Spheres*, 1543, one of the worst-selling books in history!
- Not placed on Index of forbidden books for 73 years
- Copernicus delays publication for decades, finally gives in to pressure from Rheticus and Giese
- In dedication to Pope, Copernicus mentions Giese and others who influenced him, but not Rheticus!
- Rheticus demoted from Dean at Wittenburg to mere cushy Prof at Leipzig due to his homosexuality
- Leaves publication of *Revolutions* to pal Osiander
- Osiander views heliocentric idea as mere calculating hypothesis, does not believe in its *truth*
- Anonymously adds preface which goes too far in appeasing theologians: Copernicus merely "saving the phenomena"
- Died of cerebral hemorrhage 1543, may have just seen published copy of *Revolutions* with Osiander's preface
- Hit on idea of **ellipse** for planetary motions, but for the wrong reasons and by faulty logic! Crossed out in manuscript
- Given Copernicus' trepidation and lack of originality and courage, why wasn't heliocentric model hit on earlier?
  - Physics wasn't there yet   deficiencies in Aristotle recognized, but no replacement yet
  - Copernicus was really interpreting Ptolemy, *not nature*; waste of time to humanist scientists
- Why does Copernicus get all the attention?
  - He *systematized* the heliocentric idea into a cosmological model (though one rooted in the past)
  - Writings attract notoriety (mostly heresay) at the right time

II. Thomas Digges (1546 1595, England)

- Translated part of Copernicus' *Revolutions*
- Leader of English Copernicans
- Precise observations of Tycho's (1572) SN
- Lack of parallax implied very large distance
- Added a new idea to Copernican model: **infinite space**, with stars at varying distances

Handout #14
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Tycho Brahe and Johannes Kepler

I. Tycho Brahe (1546 1601, Denmark)

- The "Astronomer Prince", a very eccentric character, pompous and arrogant nobleman
- 1557: Studies law in Copenhagen (age 13)
- 1558: Witnesses partial solar eclipse, amazed that astronomical events are *predictable*, devotes self to astronomy
- Dispute with relative over who was best at math ⇒ duel, nose sliced off and replaced with silver!
- Important recognition: astronomy needs continuing observations of greater *precision* and *accuracy*
- Builds improved instruments, becomes greatest pre-telescopic observational astronomer
- Positional data accurate to 2′ (1/30th of a degree)!
- Important astronomical events in Tycho's life
  - A) 1558: Partial solar eclipse
  - B) 1572: Supernova in Cassiopeia
    - No measured parallax ⇒ well beyond the moon in Aristotle's celestial realm
    - Heavenly change, contradicts Aristotelian cosmos
  - C) 1577: Comet
    - Limits on parallax ⇒ at least 6× farther than Moon
    - No mere "atmospheric phenomenon"!
- King Frederick II gives Tycho the entire island of Hveen!
- Tycho builds grandiose observatory Uraniborg, "Castle of the Heavens"
- Rules the island in grand dictatorial style
- Tycho's cosmology
  - Compromise between geocentric and Copernican ideas
  - Earth remains motionless at cosmic center (plausible, since fixed stars did not have measurable parallax)
  - Sun goes round earth as in geocentric model
  - But other planets go round Sun, as in Copernican model!
  - Note: Tycho's model breaks the "celestial spheres"
- Becomes "Imperial Mathematicus" to Rudolph II in Prague (1596)
- 1601: Dies of uremia after dinner with the Rosenbergs, "let me not seem to have lived in vain"

II. Johannes Kepler (1571 1630, b. Germany)

- Founded "astrophysics"
- Search for mathematical laws to describe natural phenomena (planetary motion)
- Nightmarish childhood
- Attended Lutheran seminary from age 13 17
- Prof of math and astronomy at Gratz by age 23!
- Kepler deeply influenced by Pythagorean thought
  - Beauty of geometry and mathematics
  - Harmony of the spheres
  - Convinced that cosmos must be geometrically beautiful
  - Mystical inspiration for work
- Kepler's "day job": astrology!
  - 1601: writes treatise that breaks with principles of Ptolemaic astrology
  - Tries to make astrology more "certain", based on harmonies
  - Importance at imperial court of Holy Roman Emp. Rudolph II

- Thought souls interacted with planets, "the hidden cause"
- Kepler's main obsession: significance of the fact that there were *six* known planets
  - Today we know that planets formed out of gravitational instability in a disk-shaped nebula 5 billion years ago
  - Fact that there are 9 is an "accident" of the initial conditions of the nebula (rarity of such a configuration is unknown so far other solar systems look very different, but we can't detect similar ones to our own for another decade or two)
  - For Kepler, six planets must be related to the five regular polyhedra (*Platonic solids*)
  - Solids with regular polygons as faces and all vertices look the same
  - Can prove that *only five exist*:
    A) Tetrahedron: 4 triangular faces, 3 edges at each vertex
    B) Octahedron: 8 triangular faces, 4 edges at each vertex
    C) Icosahedron: 20 triangular faces, 5 edges at each vertex
    D) Cube: 4 square faces, 3 edges at each vertex
    E) Dodecahedron: 12 pentagonal faces, 3 edges at each vertex
  - Kepler thought that planets moved on six spheres circumscribed and inscribed around the five solids
  - Finally failed to reconcile with observations, though fit to within about 5% error
  - Very modern scientific innovation: if theory doesn't fit the observations, must discard it!
- "Under a calamitous sky", Kepler marries a rich widow, "simple of mind and fat of body" with a "stupid, sulking, lonely, melancholy complexion"
- Very personal and amusing (though obscure) writings, unusual record of the blind alleys and frustrations in scientific thought
- 1597: *Mysterium Cosmographicum (Secret of the Universe)*
  - Presents Kepler's cosmology involving Platonic solids
  - First outspoken defense of Copernicus (50 yrs after death!)
  - Search for the physical causes of planetary motion
- Kepler recognizes that he needs good data $\Rightarrow$ Tycho
- 1600: Tycho invites Kepler to join him; rocky relationship, constant arguing
- Tycho knows Kepler has theoretical brilliance to interpret his data, but jealously guards his data
- After Tycho's death, Kepler gets Tycho's title and data
- Struggles long and hard trying to understand the motion of Mars
- Heliocentric model of orbit of Mars using circles leads to a stubborn error of 8', even with use of equant
- "Because these 8' could not be ignored, they alone have led to a total reformation of astronomy."
- 1609: *Astronomia Nova (New Astronomy)*
  - Problem of orbit shape; spends years trying all kinds of ovals and epicycles, finally stumbles across answer
  - First 2 of **Kepler's three laws:**
    1. Planetary orbits are *ellipses* with Sun at one focus
    2. Orbits sweep out equal areas in equal times
  - Finally smashes the dogma of uniform circular motion!
  - No more epicycles
  - First precise, verifiable *natural laws*
  - Work on magnetism at this time by William Gilbert (1544 1603, physician to Elizabeth I)
  - Kepler thinks the planets are held in their orbits by "magnetic" force from Sun which "diminishes in ratio to distance as does the force of light"
  - Connection of Earthly with celestial
  - Tantalizingly close to idea of universal gravity, but doesn't quite get it
  - Kepler's cosmos and the Holy Trinity: Father Sun at center, Son Sphere of stars at circumference, Holy Ghost force from Sun in intervening space
- 1619: *Harmonice Mundi (Harmony of the Worlds)*
  - Importance of Pythagorean harmony and geometry

- Compares ratio of min/max distances of each planet from Sun with musical harmonies; music of the heavens!
- After much trial and error, stumbles onto **Third law:** $P^2 \propto a^3$
    * P = period of planet (how long to go around Sun)
    * a = semi-major axis of ellipse (for special case of circle, radius)
    * If P in years, a in A.U., then constant is 1:

$$\left(\frac{P}{1 \text{ year}}\right)^2 = \left(\frac{a}{1 \text{ AU}}\right)^3$$

    * A.U. = astronomical unit = Earth-Sun distance = 1.5×10^8 km
- 1621: *Epitome of Copernican Astronomy*
    - Generalization of 3 laws to all planets
    - First textbook of Copernican astronomy
    - Placed on Index of forbidden books
- 1627: *Rudolphine Tables*
    - Use of 3 laws to predict planetary motions
- Kepler still does not understand physical reasons *why* his laws exist...
- *Somnium*: last published work
    - First real modern science fiction story
    - Dream of a journey to the moon
- Dies sickly and poor, unable to collect monies owed to him

Handout #15
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UC Berkeley, Spring 2000

Galileo

I. Giordano Bruno (1548 1600, Italy)

- Philosopher, victim of religious persecution (one of about two reputed scholars in 1500 1700)
- 1572: Ordained as priest
- Belief in infinite universe, multitude of worlds (Cusa, Digges)
- Other solar systems with worlds inhabited by beings similar to humans
- Pantheist, held that Jesus was merely a sorcerer
- Defended views as philosophical, not theological; refused to make a formal retraction
- Sentenced by Roman Inquistion, burned at stake for religious heresy in 1600
- Inspired later liberal humanist thought, anticipated ideas in modern cosmology (though his arguments were philosophical, not scientific)

II. Galileo Galilei (1564 1642, Italy)

- Major contributions to cosmological science:
  - Introduced telescope as essential tool for astronomy
  - Advocated heliocentric Copernican model
  - Stressed experimental methods in science
  - Mechanics: formulated principle of inertia
  - Also contributed to other scientific disciplines
- "Second-generation" Renaissance man, fully modern in outlook
- Wrote in Italian vernacular
  - Easily read, terse, scientific writing style (very different from others!)
  - Alternates between brilliant defenses of freedom of thought and sophistry, deception
  - Grand polemical style: builds up arguments for opponents' views, then demolishes them and makes them look foolish
  - Creates a lot of enemies! Contempt for opponents' intelligence
- 1609: Galileo makes a telescope
  - Theoretical ideas discussed around 1600 by Kepler and others
  - First telescopes made in Holland around 1608
  - Galileo constructed his based on reports of these
  - Set apart from others by improvements, made more powerful scopes
  - Gave 8× scope to Venetian senate for military defense, rewarded with tenure and doubled salary
  - Telescopic "discoveries"
    A) Mountains, craters, valleys (*"maria", seas*) on the Moon: celestial objects not perfect spheres!
    B) Four moons orbiting Jupiter, a "mini-Copernican" system, "Medicean" stars, dubbed "satellites" by Kepler: composite motion of Earth's Moon not an argument against Copernicus
    C) Found many stars invisible to naked eye, Milky Way made of stars!
  - Announced in *Siderius Nuncius (Starry Messenger)*, immediate sensation
  - Later "discoveries":
    A) Two lobes around Saturn (scope not powerful enough to tell they were rings)
    B) Spots on the Sun (Jesuit astronomer Scheiner argued were satellites, Galileo showed on or near Sun's surface)
    C) Venus goes through full set of phases
    D) Comets (2, inaugurated 30 Years War): like Aristotelians, G. argued they were illusions: (cometary orbits very elliptical, so did not fit with original Copernican circular model!)

- Very jealous of priority, secretive: communicated discoveries in anagram form
- "You cannot help it ... that it was granted to me alone to discover all the new phenomena in the sky and nothing to anybody else. This is the truth which neither malice nor envy can suppress."
- Galileo and Copernicanism
  - Taught heliocentric ideas of Copernicus
  - In letters, claimed belief at an early age
  - No committal to Copernicansim *in published work* until age 50
  - Galileo's real fear (up to age 50 or so, no real threat of religious persecution): being laughed off the stage by mediocre Aristotelian professors!
  - Kepler encouraged him, apparently taken as reproach (G. very sensitive to criticism!)
  - Ignored Kepler's ideas and preached the *original Copernican model*, with all its ugly epicycles!
- Copernicanism and the Church
  - 1610: No official position on cosmological systems
  - Models are to be considered scientific hypotheses, not "Truth"
  - Galileo blows up after hearing rumors of dinner-party conversations(!) where Copernicanism said to conflict with scripture (e.g., Grand Duchess Christina, 1615)
  - *Letter to Christina* (originally to student Castelli)
    * Claims Copernican model is *factually true*
    * Calls for reinterpretation of scripture
    * Subtly shifts burden of proof to theologians: they must demonstrate Copernicanism is *false*, otherwise reinterpretation must happen by default!
    * Church's position: show us *proof* of theory, only then will we reinterpret
    * Inaccurate copies of letter sent to Inquisition by G.'s opponents
  - Copernicus' *Revolutions* placed on Index for 4 years until 9 sentences regarding "truth" of the model were changed
  - 1616: Cardinal Bellarmine to G.: do not "hold or defend" Copernican theory
- The Competing Cosmologies
  - Pope Urban VIII: admirer and supporter of G.
    * Copernicanism may work, but all-powerful God could produce same phenomena by different means
  - 1630: *Dialog Concerning Two Chief World Systems*
    * Characters: Salviati (G.'s spokesman), Sagredo (intelligent person), Simplicio ("simpleton", Aristotelian)
    * Simplicio gives the Pope's argument $\Rightarrow$ bad consequences for G.!
    * Remains on Index until 1835
  - G. forced decision between Ptolemy and Copernicus, ignored Tycho's model and Kepler's ellipses
  - Ptolemaic system ruled out by phases of Venus, question really between Copernicus (+ Kepler) and Tycho
  - Defects in Copernicus: epicycles (ignoring Kepler), lack of stellar parallax (argument for Tycho), Sun not at exact center
  - Galilean moons showed composite motion, so why not let planets move around Sun plus Sun around Earth (Tycho)?
  - Galileo thought he had the required *proof* of the Copernican model: **theory of the tides** (really a self-delusion!)
    * At midnight, orbital and rotational motions add: water "falls behind"
    * At noon, subtract: water "rushes ahead"
    * Contradicts G.'s own ideas about inertia!
    * Predicts only one high tide per day, at exactly noon! (Actually two, times constantly shifting)
    * Kepler had correctly guessed tides were due to Moon (G. dismissed as occult nonsense!)

- Galileo and the Inquisition
  - Questioned beginning in 1632, age 68
  - Proved that G. had "held, defended, and taught" Copernicanism as truth, called his opponents "mental pygmies" and "dumb idiots"
  - Afraid, defeated, and broken, renounces his beliefs
  - G. repeatedly denies what is in his own book, pretends he had not supported Copernicus since decree of 1616!
  - According to legend (probably untrue), mutters *eppur si muove*
  - Never went to prison, held in "house arrest" in a rather nice villa
  - Continues his most important work: the science of dynamics
- Contributions to mechanics (study of motion)
  - Culmination of work by earlier post-Aristotelians (e.g., Orseme)
  - 1609: Study of falling bodies: $d \propto t^2$, parabolic trajectories
  - **Inertia:** objects at rest stay at rest, objects in motion continue in motion (straight-line, constant speed), unless acted on by some external force
  - Force seen as necessary to *alter* motion, not sustain it as in Aristotle
  - Thought experiment of frictionless, inclined plane
  - Relativity of motion, simple addition of velocities
  - 1636: *Dialogues Concerning Two New Sciences*
- Died in 1642 (Newton born), bones of middle finger now displayed in Florence Museum for the History of Science
- Was the conflict between religion and science inevitable?
  - Probably not, more a result of individual personalities
  - Church had adapted before (spherical Earth, about 1000 AD)
  - Might have moved to Tycho's model as a prelude to true heliocentric model, had G. not forced the issue
  - Lasting repercussions: hostility of Church towards scientific cosmology
  - G. not "rehabilitated" by Rome until 1992!