The Copernican Revolution - Separating Science and Superstition

J. Pinkney
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Outline

• Our universe viewed by the ancients
• Greek cosmological models
• Copernican Revolution
  – Nicolaus Copernicus
  – Tycho Brahe
  – Johannes Kepler
  – Galileo Galilei
  – Isaac Newton
What the Ancients Knew

The Naked-Eye Universe

The Sun (daily motion and annual motion)
The Moon (phases, eclipses)
5 Planets (not including the Earth)
   Mercury, Venus, Mars, Jupiter, Saturn
6500 Stars
3 galaxies
Occasional novae and supernovae
Comets
Aurora, meteors, and other atmospheric phenomena
What the Ancients Knew

- Mysterious cultures
  - People of stonehenge, Plains Indians, Anasazi, Mayans
  - left behind calendar-like constructions.

- Well documented cultures
  - Greek, but also Chinese, Babylonian, Egyptian, Arab
  - left records of lunar cycles, eclipses, comets, novae, star maps, models

Unknown nature → superstition → astrology.
The Ancients: Stonehenge

- Building Phases:
- 2950 BC – 1600 BC (3 phases)
  - 30 Y-holes, 28 Z-holes, 56 Aubrey holes = 3 Saros cycles
  - Heel stone marks sunrise on Summer Solstice
The Plains Indians – Big Horn
The Mayans – Caracol in Chichen Itza
The Chacoan culture – Fajada Butte Sun Daggers, Chaco Canyon
What the Ancients Knew

- Well documented cultures
  - Chinese: comet records, zodiac, “year of the _____”
  - Sumerians/Babylonians: 1st alphabet, ziggurats, origin of western astrology, planetary rise times, math (60 subdivisions)
  - Egyptians: gods like Ra and Osiris, pyramids, Nile flooding
  - Arabs: upheld astronomy during dark ages, algebra, star names. Semantic distinction between astronomy and astrology – 1000 AD!

- All made astronomical measurements
- All had forms of astrology

Unknown nature → superstition → astrology.
Knowledge of the Ancient Greeks I.

- Ideas and philosophies were rich and varied, some correct and some incorrect.
  - Thales of Miletus (624-547 BC):
    - universe is rational
    - predicted eclipse ~585 BC
  - Pythagoras (570-497 BC):
    - math in nature, music of spheres
    - Earth and planets are spherical
  - Plato (428-347 BC):
    - Truth through pure thought over observations
    - Circle is most perfect form
Knowledge of the Ancient Greeks II.

• Eudoxus of Cnidus (390-337 BC):
  Nested (crystalline) sphere model
  27 spheres total, lunar node cycle.

• Aristotle (384-322 BC):
  – Earth is unmoving, heavens are perfect
  – Everything made of 4 elements: earth, water, wind, fire
  – If Earth rotated, we'd feel a wind
  – Phases of the Moon
  – If Earth revolved, the stars should exhibit parallax
Knowledge of the Ancient Greeks (cont.)

Parallax = the apparent motion or shifting of an object caused by the motion or shifting of the observer.

Stellar parallax – apparent motion of foreground stars due to Earth's orbital motion. (Typically <~ 0.1", biggest ~1.0" Proxima Cen.)
Knowledge of the Ancient Greeks III

- **Philolaus (480-385 BC)**
  - Earth in motion around invisible “fire”

- **Aristarchus (310-230 BC)**
  - The Earth orbits around the Sun (!)

- **Eratosthenes (276-195 BC)**
  - Measured circumference of the Earth.
  - Invents armillary sphere

- **Hipparchus (190-120 BC)**
  - Discovered precession of Earth's spin axis
  - Uses epicycles, deferents and eccentrics in modelling motion of Sun and Moon.
Eratosthenes' method

(Syene = Aswan, Egypt)
Knowledge of the Ancient Greeks (cont.)

Earth's spin axis precesses with 26,000 yr period (Hipparchus 160-127 BC)

Retrograde motion of planets can be modelled with epicycles and deferents (Hipparchus)
Knowledge of the Ancient Greeks (cont.)

Cause of precession:
Knowledge of the Ancient Greeks IV

- Claudius Ptolemy (AD c.90-168)
  - Geocentric universe model
  - Adopts Hipparchus' epicycles to reproduce retrograde motion of planets
  - Added equants to better match speeds of planets
  - Writings on Optics, Geography, Music
  - Astronomy: "Mathematike Syntaxis" = "The Almagest"
  - Astrology: "Tetrabiblos" relates horoscopes to Aristotelian philosophy
The Appearance of the Planets

- Daily motion
- Change brightness, position and angular speed across sky.
- All orbit CCW as seen from "North".
- Usually eastward motion, occasional westward motion we call ... Retrograde Motion!
Planetary Configurations

- **Inferior planets**
  - Two conjunctions

- **Superior planets**
  - One conjunction
  - Opposition
Synodic and Sidereal Periods

- **Synodic period:** time interval between successive conjunctions or oppositions, $1\rightarrow 3$
- **Sidereal period:** time interval for one complete orbit relative to background stars, $1\rightarrow 2$
Epicycles on Deferents

• Ptolemy et al. desired uniform circular motions
Ptolemy’s Model - complex!

- **Eccentric** - displaces Earth from center
- **Equant** – center of epicycle has uniform angular speed when viewed from this point
- 80+ epicycles
- It works pretty well!
- Occam’s Razor (1348)
  - Accept the simplest explanation
Ptolemy’s Model

• Venus and Mercury on invisible “bar”
• Speed is still a problem
THE COPERNICAN REVOLUTION

NICOLAUS COPERNICUS

1473

1512 1st Comment

1543 De Revolutionibus

TYCHO BRAHE

1546

JOHANNES KEPLER

1571

New Astronomy

1609

The Harmony of the Worlds

1619

GALILEO GALILEI

1564

1632 Dialogue of the Two Chief World Systems

1633 Trial at Rome by the Inquisition

1642

1642
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<td>1512</td>
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<td>1686</td>
<td>Sir Isaac Newton</td>
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<td>1727</td>
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Copernicus (1473-1543)

- Polish Son of merchant
- a mathematician, astronomer, physician, classical scholar, translator, Catholic cleric, jurist, governor, military leader, diplomat and economist
- Astronomy is avocation
- Publications
  - On the Revolutions of the Heavenly Spheres (1543)
  - Little Commentary (1514)
  - Trigonometry, Narratio Prima (Rheticus)
  - Prutenic tables (1551)
- Reluctant to publish because of fear of criticism, or fear of persecution by church
- In 2005, skull recovered in Cathedral of Frauenberg
• Is there something simpler? How about the Sun in the Center!!!?
• Keep some Aristotelian ideas
  – spheres (circles)
  – uniform motion
• Major Changes
  – Sun centered (heliocentric)
  – Earth rotates
  – Earth is no different from the other planets and stars!
• Established order of the planets
• Less complicated explanation for retrograde motion
Copernicus

• Predictions of existing observations are not better than Ptolemy’s!!
• Slightly simpler
  – No equants
  – Fewer epicycles (still a lot)
    • If you remove epicycles?
      – Copernicus does okay
      – Ptolemy’s is a disaster
• Discriminating experiments not available
Tycho Brahe (1546-1601)

- Danish nobleman
- Wore metal nose
- Death (bladder or mercury)
- Built “Uraniborg” in Hven
- Meticulous measurements
- Observed supernovae of 1572
- Could not detect parallax
- Develops Tychonic System
- Hired Kepler in 1600
Tycho Brahe

• Left Kepler with 20 years of meticulous planet measurements.
  – 5x better precision
    • 2-4 arc-minutes (1/30 of a degree) compared to 10 arc-minutes (1/6 of a degree)
    • 20 years of data
  – Neither Ptolemy nor Copernicus’s models are able to reproduce the observations!
Johannes Kepler (1571-1630)

- Mathematician, astronomer, astrologer
- Had religious convictions - God had created the world according to an intelligible plan that is accessible through the natural light of reason.
- Geometry in nature – tries concentric regular solids for 4 years.
- Astrology, numerology
- “mother sold drugs”
Johannes Kepler

- Supported Copernicus (heliocentric) and Galileo
- Copernicus's Model
  - Struggles to make it work
  - Throws out circles and uniform motion
- Tries Sun-focused ellipse idea
  - A mistake causes him to put it aside
  - It works!!
  - Predicts all existing data including Tycho's
- Kepler's 3 laws

**Figure 1.26**
The arrangement of the solar system as it is now known. Uranus, Neptune, and Pluto are visible only with a telescope. The orbits are elliptical, although their ellipticity is too small to be visible in this diagram.
Kepler's 1st law

The planets follow elliptical paths with the Sun at one focus.
Kepler's 2\textsuperscript{nd} Law

The planets vary their orbital speed such that they sweep out equal areas in equal time intervals, as seen from the Sun.
Kepler's 3\textsuperscript{rd} law

\[ P^2 = a^3 \]

Period increases with distance from the Sun.
Galileo (1564-1642)

- He supports Copernicus, Kepler
- 1609 - uses telescope for astronomical observations
- Experiments & observations refuted Aristotelian physics
  - Free-fall, inclined plane, speed of light experiments
  - Moons of Jupiter orbit Jupiter!
  - Phases of Venus include the gibbous phase!
  - Spots on Sun
  - Milky Way resolves into stars
  - Saturn has ears?
  - Moon has mountains, craters
- “Father of Modern Physics”
Galileo and Jupiter

The “Galilean Moons”: Io, Europa, Ganymede, and Callisto.

Not everything orbits the Earth!

Note: These moons could be used to measure the speed of light!

Ole Roemer 1677
Galileo observed Venus in a gibbous phase. Which of these two models predict a gibbous phase?
Galileo's troubles

Galileo was more vociferous and brash than Copernicus and Kepler.

1610: Published *Sidereal Nuncius* (Starry Messenger)
1616: Galileo (and Copernicus) judged to be heretical
1632: Published *Dialogue Concerning the Two Chief World Systems*.
   - Simplicio speaks words of Pope Urban VIII.
   - Published in Italian
1633: Sentenced to house arrest.
1642: Dies in house arrest.
Isaac Newton (1643–1727)

English physicist, mathematician, theologian, alchemist

Invents calculus

Urged by Halley to publish “Principia”

Philosophiæ Naturalis Principia Mathematica

3 laws of motion

Universal law of gravitation

Can explain Kepler's laws!

Finally, we have a reason for the orbits!

“God governs all things and knows all that is or can be done.”

\[ F = G \frac{m_1 m_2}{r^2} \]
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Isaac Newton's “Fixes” to Kepler's Laws

Kepler I: The planets orbit in ellipses with the principle focus on the center of mass of the solar system, (not the Sun)

Kepler III: add the total mass of the system to the denominator ...

\[ P^2 = \frac{a^3}{M_{tot}} \]
The Copernican Revolution ...

matching!

Nicolaus Copernicus
Tycho Brahe
Johannes Kepler
Galileo
Newton

Observed gibbous phase of Venus
Made precision measurements of planets
Used ellipses to model solar system
Said gravity accelerates the planets
Revived the heliocentric model
Figuring out the remaining loose ends of the Solar System

Verification that Earth is in motion
Ole Roemer's, 1677 - Jupiter Moon delays
James Bradley, 1728 – aberration of starlight
Frederick Bessel 1838 – first parallax

What is 1 Astronomical Unit???
Use timings of Venus during transits across Sun
Bounce radar off of Venus when near inferior conjunction
Transits of Venus

2004 Transit of Venus

Ecliptic

Universal Time

Arc-Minutes

Courtesy of F. Espenak, NASA's GSFC
Transits of Venus

Previous transits: 1761, 1769, 1874, 1882, 2004, ...

Last transit: June 6, 2012

Next transits: 2117, 2125

How it works: 3.4° tilt, 8:13
243 yr cycle.

Inferior conjunction while both planets on line of nodes.
Science vs Superstition – it never ends

The Copernican Principle

Sun not at center of galaxy, or of Local Group, or of Local Supercluster, or of expansion of universe. Are humans the only intel. life?

“Crazies” coming out of the woodwork

There are people at both extremes; pure skepticism and belief.

Each of us has to reconcile facts with beliefs. Follow Kepler's Lead!

See “The Demon-Haunted World: Science As a Candle in the Dark” - C. Sagan
Ecliptic

- Seasonal variations due to orbital motion and the 23.5° tilt of Earth’s rotational axis
General philosophy of science

Karl Popper: Logic of falsification

Theories can never be verified by observation.
Theories can be falsified by observation, and so discarded.
The only acceptable theories are those which are falsifiable.

Thomas Kuhn: Paradigms and paradigm shifts

“Normal science” -- investigation within a paradigm
Revolutions -- paradigm shifts driven by anomalous data

Niels Bohr: Correspondence principle

New theories must reduce to good old theories in some limit.
# A Summary of the Early History of Astronomy

<table>
<thead>
<tr>
<th>Observations</th>
<th>Typical Dates</th>
<th>Theories</th>
</tr>
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<tbody>
<tr>
<td>Stars, sun, moon, and planets are moving overhead.</td>
<td>3000 B.C.</td>
<td>Pythagorean theory: Earth-centered transparent spheres.</td>
</tr>
<tr>
<td>Each planet moves at a varying rate; retrograde motion.</td>
<td>500</td>
<td>Theory of multiple Earth-centered transparent spheres.</td>
</tr>
<tr>
<td>Heaven and Earth seem different; Earth seems motionless, apparently contradicting Aristarchus's theory.</td>
<td>300</td>
<td>Aristarchus's theory: sun-centered circles.</td>
</tr>
<tr>
<td>Planets are brighter during retrograde motion.</td>
<td>200</td>
<td>Theory of Earth-centered epicycles.</td>
</tr>
<tr>
<td>Detailed quantitative measurements show need for small corrections.</td>
<td>100</td>
<td>Ptolemy's theory: Earth-centered epicycles, equants.</td>
</tr>
<tr>
<td>Brahe's accurate measurements disprove Ptolemy's and Copernicus's theories.</td>
<td>A.D. 100</td>
<td>Copernicus's theory: sun-centered circles.</td>
</tr>
<tr>
<td>Galileo's telescopic observations disprove Earth-centered theories.</td>
<td>1500</td>
<td>Kepler's theory: sun-focused ellipses.</td>
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<td>1600</td>
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