THE NEWTONIAN REVOLUTION – Part One

Philosophy 167: Science Before Newton's *Principia*

Class 1

Overview of the Course; Ptolemaic Astronomy

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Class 1: Overview of the Course; Ptolemaic Astronomy

I. Overview of the Course

A. 1510-1810: The "Scientific Revolution"

1. General agreement that before, say, 1510 there was no high quality empirical science in the sense we use the term today, while by, say, 1810 Newtonian mechanics and gravitation were in place and thermodynamics, modern chemistry, optics, and electromagnetism were in the process of emerging

a. 1510: ***the*** exemplar of science at its best was Ptolemaic astronomy, though Copernicus was about to produce his initial proposal for replacing it

b. 1810: ***the*** exemplar of science at its best was Newtonian mechanics and celestial mechanics, and seminal experiments were being done following Volta's invention of the battery in 1800 in electrolysis and electricity, as well as in pneumatics and polarization of light

2. The "scientific revolution": a revolution in which we learned how to achieve extraordinarily high quality knowledge of the empirical world -- or at least appear on the surface to have achieved this

a. By 1810, a body of extraordinarily high quality empirical knowledge already established, and new knowledge in other areas being produced at an accelerating rate

b. By 1810, a method of conducting inquiry and marshaling evidence that was beginning to be directed at other areas (including human behavior)

c. By 1810, a standard by virtue of which empirical science came in the 19th century to have the highest intellectual authority, if it didn't have it before

3. To a predominant extent, this revolution took place during the 17th century, which opens with Gilbert's *De Magnete* and closes with the initial dissemination of Newton's *Principia*

4. This course and its second semester continuation amount to an examination of the scientific revolution over these 300 years, focusing on the 17th century

a. First 2 classes: pre-1600 developments

b. Next 12 classes: 17th century developments leading up to Newton's *Principia*

c. First 11 classes of next semester: Newton's *Principia*

d. Last 3 classes: its reception and impact during the 18th century

B. The "Newtonian Revolution": the *Principia*

1. Emphasis on Newton's *Principia* because, most agree, it was the pivotal event leading to modern advanced science

a. Published in 1687, with new editions in 1713 and 1726

b. Answered questions that had dominated empirical inquiry in the 17th century

c. Opened the way to new lines of inquiry that dominated the 18th century

2. Prefer to call this two semester course the "Newtonian revolution" because the phrase, "the scientific revolution" has come to cover a good deal of less successful empirical research

a. The real revolution: science as typified by the *Principia*

b. The real revolution: acknowledging science as exemplified by it

3. But from the day the book was published there was wide disagreement about what exactly the *Principia* achieves and how it achieves it – an exemplar, but of what?
   a. Three hundred years of controversy over the *Principia*, starting with Newton and Leibniz, continuing throughout the 18th century, leading to the emergence of philosophy of science as a discipline in the disputes between Whewell and Mill in the mid-19th century
   b. Disagreement continues unabated to the present day
   c. Agree that it represents science at its best, but disagree about what science at its best is
4. Ironic since Newton consciously wrote the *Principia* to show the world how to do truly successful empirical science, on his view in a way that it had never been done before
   a. Thought he had discovered how to achieve high quality knowledge of the empirical world
   b. Excitement with this discovery part of what drove him to complete the book (with the exception of a couple of papers a decade earlier, his first publication, at age 44)
5. To see why he might have thought this, need to understand just what science amounted to at the time he began writing the *Principia* in late 1684 or early 1685
   a. The main goal of this semester is to do this, putting the *Principia* into context
   b. After next week, focus on 1600-1684, ending with the insights that prompted Newton to write the book

C. A Course in the Philosophy of Science

1. Philosophy of science concerned with the nature and the limits of the "knowledge" achieved in the empirical sciences and with how the methods followed yield this "knowledge"
   a. Especially concerned with the status of generalizations and theories
   b. And with the process of adducing evidence in support of them
2. Philosophy 167 and 168 form a course in the philosophy of science
   a. Looks at one episode in the history of science, but always from the point of view of asking exactly how Newtonian science is epistemically different from what preceded it
   b. ***How did we first come to have high quality evidence in any science?*** -- an historical question, but also a philosophic question (what is it for evidence to be high versus low quality?)
3. The usual approach to studying the philosophy of science is to read various 20th century works by philosophers writing about science -- e.g. Philosophy 116
   a. Different views about the nature and limits of scientific "knowledge"
   b. Laying out unresolved issues and indicating why they remain unresolved
4. My preferred approach is to trace through an episode in the history of science in some detail to see how those issues become important and why there is room for disagreement over them
   a. Lends concrete substance to the fundamental questions in the philosophy of science, at the possible expense of a loss of generality

b. Makes science itself the ultimate arbiter of issues in philosophy of science

5. Only real shortcoming of this approach: regardless of which episode is chosen, virtually impossible to do justice to the material in less than two semesters

a. E.g. first semester laying out background and context in order to make the achievement studied in the next semester clear

b. The structure of this course

D. Reasons for Focusing on Newton's *Principia*

1. Various episodes can serve my purpose, but none so well as the revolution wrought by the *Principia*, for it brings out the key issues in the philosophy of science most clearly

2. The *Principia* really is the pivotal event in the history of science

a. It really did transform the way in which science -- i.e. empirical inquiry -- is done

b. It has served as the exemplar of how to develop a theory and adduce evidence for it throughout the subsequent history of physical science

c. To understand what it did is to be in a position to understand what science has done generally

3. Another virtue: material covered in this course accessible at the relevant level of detail within two semesters

a. Virtually no calculus in the *Principia*, and needless to say presupposes no subsequent developments in the history of science

b. Material it does presuppose -- various developments in 17th century science -- is what we will be covering this semester

4. Another virtue: can serve to illustrate the discipline of history of science at its best

a. A discipline that has developed largely in the 20th century, with many of its key figures specializing on Newton

b. Extraordinarily high quality historical research on Newton since World War II

5. Though a course in the philosophy of science, and not the history of science, taught by a philosopher of science who is not trained as a historian of science, it should nevertheless put you in a position to read in history of science critically and intelligently

E. Pedagogical Objectives

1. Immediate objective of this semester is to answer various questions about science as it evolved in the 17th century

a. What questions drove "scientific research" in the century, and where did they stand when Newton was drafting the *Principia*?

b. What different conceptions were there of how to go about marshalling empirical evidence for theoretical claims?

c. What were the most important methodological advances of the century, and how widely appreciated were they?

2. But, at least on my view, the main pedagogical objective of virtually every liberal arts course ought to be to put you in an effective position to continue your education
   a. Courses are necessarily limited in scope; you need to be in a position to go beyond them
   b. Question, then, is what I intend this course to prepare you to do
3. First, you should be in a position to read original scientific works effectively on your own, not just from the 17th century and earlier, but extending into recent times
   a. Learn how to read works in the historical context in which they were written, but at the same time recognizing the potential impact they can and did have
   b. Especially learn how to identify the questions works are responding to and why these questions were important at the time
4. Second, you should be in a position to read material in the philosophy of science critically, especially works that offer general accounts of scientific methodology
   a. Science in fact is extremely complicated, in ways that make any description of how science works adventurous
   b. You should have sufficiently detailed appreciation of one episode in science to be able to challenge overly simplistic philosophy of science
5. Third, you should be in a position to read secondary material in the history of science with a sharp critical eye, taking advantage of it, but maintaining healthy doubts about what it says
   a. Develop a nose for first rate history of science, in contrast to efforts dominated by prior conceptions of science and of its history
   b. Learn how to distinguish problematic conjectures from solidly established findings
   c. In the process you are likely to develop a healthy knee-jerk distrust of much of the secondary literature, for the simple reason that few, if any, of us have a deep enough understanding of how science works to make sweeping statements about it

F. Organization of the First Semester Course
1. Syllabus self-explanatory as far as it goes
   a. Basic structure: focus consecutively on Kepler, Galileo, Descartes, Huygens, and early Newton -- the giants of the century
   b. As you will see, this not because they alone were important, but because everything pivots around their work
2. Specific readings -- some long, some shorter, but generally requiring around 5 hours -- assigned each week along with "study questions"
   a. Should purchase Kuhn's *Copernican Revolution*, Kepler's *Epitome of Copernican Astronomy*, the 3 Galileo books -- all books appropriate to own for good
   b. All other readings, including excerpts from Descartes' *Principia*, will be available on Trunk to save you money

c. Suggest purchase of Westfall's *Construction of Modern Science* to provide you a reference book for background

3. Course requirements: a short, ungraded initial paper, three 6 to 8 page papers

a. Drafts of the three main papers on indicated dates, with final versions of the papers at the end of exam period

b. Papers play a critical role in learning in the course, and hence will insist within reason that drafts come in on time -- e.g. lose rewrite privilege otherwise, and receive little comments

c. Short initial paper to help you sort out the three different world systems

4. Also included with syllabus: a list of key events in science, the figures responsible, and their dates to give you a panoramic overview of the 3 centuries

a. At the end of each set of notes is a list of "select sources," the sources I have used in preparing the notes over the last 28 years; do not mistake this for an exhaustive bibliography

b. A valuable general reference: *Dictionary of Scientific Biography*

5. Three final comments about the course

a. Science distribution credit automatic for second semester, but not for first

b. A lecture course, but not in sense that you sit passively taking notes on what I say

(1) Lectures serve role of putting you in position to read and to write papers more effectively

(2) This by putting certain things hopefully in better focus and by providing you additional background

(3) Strongly encourage interruption and questions

(4) Notes will be available on Trunk from each class, plus optional further readings

c. A personal comment: there is no course I teach or have thought of teaching that I think has greater intellectual value for you

(1) Regardless of orientation -- science, engineering, humanities -- material of this course can provide a picture of science that will be of value the rest of your lives

(2) I intend the course to be one of the most memorable intellectual experiences of your life -- as it has proved to be for many people in it over the last 25 years

II. Astronomy, as Inherited by Ptolemy

A. The Celestial Sphere

1. The sphere of the stars: diurnal motion

a. Picture all the stars as if on a sphere surrounding the earth -- the celestial sphere (spherical astronomy)

b. Diurnal rotation about diameter through north and south celestial poles

c. Each star traces a circle, in part visible with time lapse photography

d. (The question of the distance of the stars, or any other celestial object, from the earth is the first fundamental evidence problem to note in this course!)

2. Celestial equator: the great circle midway between the two poles and perpendicular to the diameter through them
    a. Instead of longitude and latitude, the corresponding "coordinate" system for the celestial sphere has right ascension and declination
    b. Right ascension in units of hours, with 24 hours around the equator: corresponding to times when stars etc. ascend; declination in degrees, corresponding to geographical latitude
3. In addition to the diurnal motion which it shares with the stars, the sun moves about 1 deg eastward each day with respect to the stars
    a. Taking roughly 365 and 1/4 days to complete its way around the sphere
    b. North of the celestial equator for roughly half of this time, south the other half
4. The path the sun follows among the stars is called the ecliptic -- the line along which solar and lunar eclipses occur
    a. Inclined at a little more than 23 deg from equator, with intersection points called the vernal and autumnal equinoxes, and the extreme points the two solstices
    b. Celestial latitude and longitude measured with respect to the ecliptic, with a north and south ecliptic pole, and not with respect to the equator
    c. From time immemorial, ecliptic divided into 12 constellations, each 30 deg wide: the signs of the zodiac
5. The vernal equinox slowly moves among the stars, taking 26,000 years to complete its circuit
    a. Precession of the equinoxes, actually from the wobble of the spheroidally shaped earth
    b. From Aries to Pisces, soon to be entering the age of Aquarius
    c. That precession occurs was known for a long time before the pattern and rate were determined; the precise cause was first announced in Newton's *Principia*

B. Planets: "Wandering Stars"

1. The Sun is accordingly a wandering celestial body, in contrast to the "fixed stars", which stay in the same position with respect to one another
    a. Wanders at a certain average rate per day
    b. But in fact this rate not uniform: e.g. takes 94 and 1/2 days from the vernal equinox to the summer solstice, and 92 and 1/2 days from the summer solstice to the autumnal equinox
2. The Moon is another example of a celestial body that "wanders" among the stars, at a much faster rate than the sun (around 27 and 1/3 days to complete the circuit), moving north and south of the ecliptic
    a. Latitude of the moon quite complex: line of nodes itself moving with time
    b. Eclipses as the classic prediction problem in astronomy, made difficult by the non-uniform longitudinal and latitudinal motion of the moon: the 18 year Saros cycle, a repeating cycle of sequences of eclipses, discovered by the Babylonians

3. The (other) wandering stars or planets known before 1781: Mercury, Venus, Mars, Jupiter, and Saturn
    a. Mercury and Venus always near the Sun, reaching "maximum elongations"
    b. Mars, Jupiter, and Saturn not so constrained: conjunctions and oppositions
    c. Mars in opposition every 780 or so days, Jupiter every 400 or so days, and Saturn every 380 or so days
4. Primary motion of each of the planets is again eastward, with some variability, along the zodiac, but each wanders north and south of the ecliptic
    a. Division of the motion into two components: longitudinal motion along the ecliptic, and latitudinal motion perpendicular to it
    b. Each planet's latitudes are separate from all the others, but no planet visible to the naked eye ever wanders very far from the ecliptic: no more than roughly 9 deg
5. Each of the planets has its own distinctive period for completing one circuit with respect to the fixed stars, which the Babylonians had determined to high precision several centuries B.C.
    a. Mean motion -- average number of eastward degrees per day -- varies from planet to planet
    b. Mercury fastest, then Venus, Mars, Jupiter, and Saturn, with the Moon faster than Mercury, and the Sun between Venus and Mars

C. The Problem of the Planets

1. In addition to their normal eastward motion, the five planets also on regular occasions exhibit "retrograde motion" -- a daily westward motion
    a. Appear to come to a stop, reverse direction for a few days, then again stop and resume their normal motion, describing “loops” as shown in the NASA photographs for Mars in Appendix
    b. E.g. time between two consecutive beginnings of retrograde motion for Mars is roughly 780 days, for Jupiter roughly 400, and for Saturn around 380
    c. Graphical display in the Appendix exhibits the pattern for Jupiter over one ancient period
2. Points at which planets appear to come to a stop are called "stationary points", with planets speeding up and slowing down in between
    a. Points at which motion reverses, with a certain number of days between consecutive points
    b. Another prediction -- i.e. calculational -- problem of ancient astronomy: not just when retrograde motion begins on the average, but also the variations from one case to another
    c. Mean time of return to e.g. stationary point at beginning of retrograde motion called the “synodic period” because it involves longitudinal relationship of planet to earth and sun
    d. Babylonians had also worked out the synodic periods of all of the visible planets several centuries B.C.
3. A basic regularity to the pattern -- e.g. 780 days between periods of retrograde motion for Mars, with roughly the same number of days of retrograde motion in each loop

a. But marked variations within this pattern, and hence different loops from one occasion to another: e.g. 760 days one time, 775 another, etc.
b. Planetary speeds vary too: e.g. roughly 40 percent variation in apparent longitudinal motion per day of Mars from one extreme to another while away from retrograde

4. Each of the five planets has its own distinct basic pattern of periods of retrograde motion, and its own distinct pattern of variations on this basic pattern
   a. Can be seen in examples of Mars and Jupiter, where loops vary
   b. An anomaly on top of the anomaly of retrograde motion
   c. Well before 300 B.C. the Babylonians had discovered "great cycles" in which the patterns of retrograde loops and timings of stationary points repeat: e.g. 71 years for Jupiter (see Appendix for others)
5. The problem of the planets: give an account ('***logos***') of retrograde motion, including basic pattern, size of loops, and variations for each of the five planets
   a. Not to predict longitude and latitude every day
   b. Focus instead on salient events – i.e. ***phenomena***: conjunctions, oppositions, stationary points, longitudinal distance between them
   c. For the Babylonians, just predict; for the Greeks, to give a geometric representation of the constituent motions giving rise to the patterns
6. Classical designations: "***the first inequality***": variation in mean daily angular speed, as in 40 percent variation for Mars and smaller variation for Sun; "***the second inequality***": retrograde motion, as exhibited by the planets, but not the sun and moon

D. Classical Greek Solutions

1. Various classical solutions to the problem, but with epicylic theory coming to dominate for the second inequality in the 3rd century B.C.
   a. No evidence of motion of earth, hence reasonable to conclude that retrograde motion arising from motion on a second circle -- i.e. an epicycle, the center of which moves along a circle called the "deferent"
   b. Epicycle consistent with planets being brightest during retrograde motion
   c. Aristarchus in 3rd century B.C. the one notable exception, who had the earth and the five planets going around the sun
2. In 4th century B.C. Eudoxus had devised a system of nested homocentric spheres in response to the problem -- see Aristotle, *On the Heavens* and quote from *Metaphysics* (Lambda) in the Appendix
   a. Basic idea of solid spheres retained in epicycle theory
   b. But with spheres rotating on rotating spheres instead of nested homocentric spheres
3. Most of what we know about Eudoxus's solution comes either from Aristotle (or from modern efforts to recreate it on the basis of what Aristotle says

a. Aristotle himself modifies Eudoxus's system for the planets slightly, seemingly to make it more physically tractable
b. While not altering his homocentric sphere models for the sun and moon

4. In his *On the Heavens* Aristotle provides philosophical and quasi-empirical arguments to support key features of Eudoxus's system
   a. The natural motion of the four elements is toward the center of the earth, while the natural motion of the celestial ether is circular
   b. All motions in the heavens have to be (eternal) uniform circular motions insofar as any speeding up and slowing down would require an external cause
   c. The earth is a sphere at the exact center, because of the natural motions toward its center
   d. The earth does not move, so that the apparent diurnal motion of the stars has to arise from motion of the sphere of the fixed stars
   e. The earth is small compared to the stars
5. These doctrines of Aristotle remained influential over the next fourteen centuries, leading to a number of conflicts with Ptolemaic astronomy
   a. Ptolemy did not have the earth at the exact center of the motions of either the sun or any of the planets, but instead at different distances from the center of their motion along the zodiac
   b. In the case of the moon and the planets, Ptolemy openly violated the requirement of uniform circular motion, replacing it with equiangular motion about a point off-center

E. Classical Greek Solutions After Aristotle

1. The two centuries after Aristotle died (322 B.C.) produced four great figures in classical Greek mathematics who continued to have a dominant influence over the next millennium and a half
   a. Euclid, who thrived in Alexandria around 320-280 B.C.: *Elements*, writings on optics
   b. Archimedes of Syracuse: (287-212 B.C.) writings on science that Galileo took as his model
   c. Apollonius of Perga (ca. 262-190 B.C.): *Conics*, but also writings in astronomy no longer extant
   d. Hipparchus of Nicea (ca. 190-120 B.C.): a fully developed, but inadequate epicyclic system that was the starting point for Ptolemy 300 years later; writings no longer extant, so that what we know of his work is from the *Almagest*
2. Greeks early looked for ways to account for anomalies in the motion of the moon and sun -- i.e. deviations from mean motion, for that reason called ***inequalities***
   a. From proof by Apollonius, recognized epicycle and eccenter as equivalent alternatives, allowing sun and moon to be either merely appearing to be moving at different angular speeds at different times or to be engaged in a compound of two uniform circular motions
   b. Willingness to use the two physically distinct but mathematically equivalent devices interchangeably a sign that their primary interest was calculational -- i.e. calculate locations and timing of salient events among the stars

c. (An instance of the second fundamental evidence problem in astronomy recognized as early as mid third century B.C.: which observed motions with respect to the fixed stars are real, as represented by the epicycle, and which merely apparent, as represented by the eccenter?

3. The two fundamental evidence problems of astronomy are distinct:
    a. The problem of distances from the earth: if the distance of every celestial object from the earth were known (on some common measure) at all times, then their observed angular positions would suffice to determine their locations with respect to one another at all times, and hence too trajectories relative to one another -- e.g. is the sun or the earth near the center of Mars's orbit?
    b. But still would not be able to say which apparent motions and changes of motion are real; only what the motions and changes of motion are relative to some point taken as at rest; i.e. the problem of the proper point to which all apparent motions should be referred would remain
    c. Fully appreciated early in ancient Greek astronomy: stars vs. earth's rotation; sun vs. earth)
5. Apollonius's cinematic models around 225 B.C. used (major) planetary epicycles and (minor) epicycles and eccentricity for sun and moon: the forerunner to Hipparchus
    a. Epicycles for retrograde, yielding uniform patterns, with similarly uniform patterns of speeding up and slowing down for sun and moon
    b. Thus a first-order approximation to the anomalous motion
6. Hipparchus, unlike Apollonius, had access to Babylonian records stretching back centuries, which, coupled with his own careful observations and refinements (ca. 150 B.C.), showed that this first-order Apollonian approximation is definitely inadequate
    a. Need more complexity in models, such as combining eccentricity and epicyclic motion
    b. At this juncture, reached beyond mathematical methods available at the time
    c. Hipparchus's refined cinematic models essentially the point from which Ptolemaic astronomy takes off, including his models for the Sun and Moon

F. The Problem Inherited by Ptolemy

1. Requisite mathematics developed over the next roughly 300 years
    a. Menelaus and spherical trigonometry the most important development, but also classical trigonometry
    b. Most of the developments lost because the *Almagest* covered them so well that interest in work leading up to it disappeared, just as in the case of Euclid's *Elements*
2. Problem: give an account (***logos***) of non-uniform patterns of retrograde motion of Mercury, Venus, Mars, Jupiter, and Saturn and non-uniform motion of sun and moon that handles main observable "inequalities" -- systematic departures from uniform (apparent) motion
3. Ptolemy's formulation (inherited from Hipparchus etc.): to develop an account of planets on the basis of the philosophic postulate that the observed irregularities of planetary motion are the result of the combination of uniform circular – or at least equiangular -- motions

a. Perfection of circular motion vs. calculational tractability of uniform circular motion

b. Unclear which was more important to Ptolemy, or to anyone else at the time

4. Ptolemy's *Almagest* vs. his *Planetary Hypotheses*, some decades later

a. Former gave a mathematical account of motion of sun, moon, and planets

b. Latter offers hypotheses about the physical basis of this motion -- essentially a rotating solid sphere account, with epicycles from smaller spheres centered on the surface of the larger ones

c. Determined the minimum size (in units of Earth-Sun distance) required to fit everything in, with the sphere of the stars on the outside and no spheres overlapping any others

5. Ptolemy (around 150 A.D.) prolific: The *Handy Tables*, the *Geography*, the *Tetrabiblos*, the *Optics*, the *Harmonics*, treatises on logic, on sundials, on stereographic projection

a. A university professor, in a less anachronistic sense than you might think

b. In the world center of learning, Alexandria

III. Ptolemy's *Almagest*

A. Overview of the Book

1. *Mathematical syntaxis* (systematic treatise): "a complete exposition of mathematical astronomy as the Greeks understood the term" (Toomer), in 13 Books

a. '*Almagest*': the great one, a Latinization of an Arabic adaptation of Greek; the work preserved in Arabic speaking world during Middle Ages and brought from there into Europe in 12th century

b. Very much a textbook, instructing how to calculate a wide range of quantities and solve various problems in spherical astronomy

2. Books I and II: Preliminaries (e.g. earth at center of universe, motionless, etc.); followed by spherical trigonometry and its application to a range of calculational problems of interest, with tables

a. Using chord function, rather than sine and cosine: chord $\theta = 2 \sin(\theta/2)$

b. Calculate such things as terrestrial latitudes from length of longest day, transformations between equatorial and ecliptic coordinates etc., including many calculations of astrological interest

c. Approach: formulate problems in terms of spherical triangles, then employ Menelaus's theorem to determine the unknown quantity, given five other quantities

3. Books III - VI: Sun, basic lunar, advanced lunar, and eclipses

a. Mean sun provides basic unit of time, employing tropical rather than sidereal year, including a slightly erroneous value for the length of the mean tropical year inherited from Hipparchus

b. Everything else built off of solar theory

c. Note, however, the privileged position of eclipses: emphasis on predicting special events

4. Books VII & VIII: a catalog of the principal fixed stars

a. Stars come after moon because moon used as a marker for the sun, and time connected to the sun

b. (Note the calculational orientation of the work)

c. A catalog of visible stars that remained a primary reference until modern times

5. Books IX - XIII: on the planets
    a. IX-XI on longitudinal motion
    b. XII on stationary points, retrogradations, and maximum elongations: the phenomena of primary classical interest, comparable to eclipses
    c. XIII on latitudes
6. Throughout the work the mathematics needed to calculate quantities of interest, including calculating parameters of celestial orbits from observations
    a. In principle, able to determine values of parameters from preferred observations (specified by Ptolemy) -- if need be, correcting those given by him
    b. Then can calculate position (geocentric longitude and latitude) of Sun, Moon, any planet, or any star at any time whatever
    c. I.e. a complete calculational system
    d. With supplementary easy to use tables to aid in the calculations
7. Time and again the Almagest reminds the reader of Apollonius's theorem and hence of the possibility of representing various non-uniform motions either by an epicycle or an eccenter
    a. No one who has read the book should ever have thought that the representations Ptolemy in fact adopted were uniquely determined
    b. Still, the parameters of the orbits remained essentially the same either way, again by virtue of the equivalence Apollonius had established

B. General Remarks on the System

1. Basic system, ignoring irregularities of sun and moon and variations in patterns of retrograde motion
    a. Mercury and Venus tied to (mean) Sun; moon and outer planets not
    b. Location of outer planets on their epicycles tied to (mean) Sun
2. No planetary distances, save for distance to moon (via parallax) and (inaccurate) estimate of distance to sun via lunar eclipses
    a. In each case, set radius of each primary circle R=60 (using Babylonian sexagesimal number system with units or degrees, firsts, seconds, thirds etc. not fractions or modern decimals)
    b. Nothing in the system that allows radii to be determined from observations on any uniform basis, for planetary parallaxes not observable
    c. Sequence from Moon to Saturn conjectured on basis of time required for each to return to the same place along the zodiac, and not on any more direct basis, using observations
3. Primary circle for planetary orbits called the deferent, and secondary circle the epicycle
    a. Ratio of radii of epicycle to deferent, r/R, determinable for each outer planet, in effect from (average) angular size of retrograde loops (see Swerdlow in Appendix)
    b. Even more directly for Mercury and Venus, from (average) maximum elongations (via another theorem of Apollonius)

4. Ptolemy separates problem of longitudes from that of latitudes, the latter of which he tries to handle through deferents and epicycles inclined to ecliptic
    a. Not a fixed inclination through center of earth or any other center
    b. Because observations (mostly made during retrograde loops) defy such a fixed inclination
    c. Instead deferents and epicycles tilting over time in an effort to capture shapes of loops
5. Here going to ignore account of latitudes, which was much less successful, except at oppositions
    a. No so salient a pattern in latitudes like the ones for longitudes
    b. I.e. basic pattern of stationary points in case of longitude and pattern of systematic variations in them; the shape of the retrograde loops the sole counterpart for latitudes
    c. Nothing comparable in case of latitude, and hence nothing to help build theory around
6. Theory of latitudes turned out not to be the worst glitch in Ptolemy's astronomy
    a. Adopted too slow a value for the precession of the equinox -- Hipparchus's lower bound estimate
    b. As a consequence, his origin, the vernal equinox, fell progressively behind over the centuries, introducing a systematic, though easily corrected, error in all longitudes (though not in relative positions of celestial objects)
    c. A lesser small, but accumulating error (again easily corrected) from using Hipparchus's difference between the tropical year and the sidereal year, which was about 5 min off

C. The Account of the Sun

1. Essentially Hipparchus's account, including the decision to use the tropical year, and not the sidereal year, as the basic unit of time
    a. Ptolemy gives credit; indeed the main source for our knowledge of Apollonius and Hipparchus
    b. May well have adopted without extensive critical review, for appears not to have thought that he had to do everything
    c. But did emphasize Apollonius’s theorem and did feel free to go back and forth between eccentric and epicyclic models of the first inequality of the sun
    d. That in turn raises a question about just what the status of epicycles and eccentrics were, merely alternative computational devices to describe the apparent motion, or something more
2. Mean motion, with principal anomaly via eccenter (1/24 R) corresponding to 94 1/2 days from vernal equinox to summer solstice, and 92 1/2 days from summer solstice to autumnal equinox
    a. Thus Sun not really speeding up and slowing down on this model, but only appears to do so because observer located off center -- (second evidence problem again!)
    b. Contrast with all of the other orbiting bodies, for which the variations in longitudinal motion are part apparent and part real
3. "Equation of center": relation between true sun and mean sun; “equation of time”: relation between variable length of time from one noon to the next and mean solar day
    a. "Mean Sun": where Sun would appear to be if its apparent angular motion were uniform

b. "Mean solar day": length of day were it uniform; tied to sidereal day, which (as far as they could tell) is uniform (23 hours 56 minutes and 4 seconds: 365¼/366¼ × 24 hours)
c. Both provide basic references throughout the system
d. Equation of center gives angular correction to locate where Sun actually appears
e. Equation of time gives correction versus mean solar day; it involves both apparent variation of sun in speed and angle between the ecliptic and the celestial equator

4. Precession of equinox: 1 deg per century, Hipparchus's lower limit
   a. Correct value near 1.4 deg per century (36,000 years versus 26,000 years)
   b. As remarked above, a systematic error in all absolute longitudes (as measured from the vernal equinox) growing over time, though not in relative longitudes
   c. Error less from blind acceptance of Hipparchus's value than it may at first seem, for Ptolemy obtained supporting evidence from the apparent motion of the apsides of Mercury, which he (wrongly) concluded was 1 deg per century, and then attributed it to precession of the equinox
5. Nothing particularly original in Ptolemy's solar theory, though you should appreciate that it is by no means crude or simple
   a. Does predict variation in angular movement of Sun to reasonably high accuracy -- i.e. the equation of center -- and also the variation in the length of the apparent solar day
   b. As such, predicting patterned deviations from basic regularity
   c. In other words, a "second-order" theory, providing refinements of the first-order uniform circular motion theory

D. The Account of the Moon

1. The principal inequality taken from Hipparchus: a small epicycle, computationally equivalent to eccenter, to account for basic pattern of speeding up and slowing down
   a. Again, perfectly comfortable starting from earlier work
   b. Other considerations favor (minor) epicycle over eccenter
2. Simple theory includes (1) forward motion of apsidal line; (2) common plane of deferent and epicycle tilted with respect to ecliptic; and (3) regression of the line of nodes (at the ends of which the Moon is in the plane of the ecliptic)
   a. First amounts to around 3 deg per revolution on average (9 year cycle)
   b. Second and third needed for account of latitudes, with third amounting to around 1½ deg per revolution on average (18 year cycle)
3. Ptolemy discovered that, while adequate to predict motion in syzygies and hence eclipses, not adequate for motion in quadrants: a further anomaly
   a. A major discovery of Ptolemy, now called the "evection": a significant deviation in longitude when Moon at the quadrants, not apparent from eclipses

b. He ends up handling it via a (circularly) moving eccenter

4. Ptolemy then discovered a still further anomaly -- i.e. discrepancy between theory and observation -- when Moon in octants that is not handled by this moving eccenter
   a. Just as with first anomaly he discovered, found that irregularity correlated with relative earth-moon-sun positions
   b. Handles it by requiring motion on epicycle to be measured from the "mean," not the true apogee
5. One feature of his lunar theory stood out as a shortcoming right down to the time of Copernicus
   a. Theory predicts that the distance between the earth and the moon varies much more widely than parallax and apparent diameter measurements indicate
   b. Specifically, model calls for variation from 64 to 34 earth-radii, which would produce almost a factor of 2 variation in the apparent diameter of the Moon, while the actual variation in apparent diameter is closer to 10 percent
6. In spite of this and other lesser shortcomings, the account of lunar motion the other major advance of *Almagest* over all prior Greek astronomy
   a. Major advances: two newly discovered anomalies, and realization that they correlate with earth-moon-sun positions
   b. Each discovered via deviations from less refined model, leading to further refinement in described motion
   c. Notice that Ptolemy here refining his theory on the basis of systematic deviations from simpler versions of it -- a sequence of successive approximations
7. (An aside: the motion of the moon turns out to be the most difficult of that of any of the naked-eye observable bodies in our planetary system
   a. For this reason we will give little emphasis to it until we get to the *Principia*
   b. And even there, as you will see, it proved more complicated than Newton could handle)

E. The Problem of Planetary Motion for Ptolemy

1. The *Almagest* presents only Ptolemy's finished account, not the way in which he reached it
   a. This gives the impression that Ptolemy simply came up with a hypothetical model and then accepted it because it gave good results
   b. Noel Swerdlow and Jim Evans have each made a compelling case to the contrary, reconstructing steps by which Ptolemy reached his model for Mars from passing remarks in the *Almagest*
   c. Swerdlow's reconstruction presented here (paper in Supplementary Readings); paper by Jim Edwards assigned for next class offers a parallel account
2. From what Ptolemy says, Hipparchus had made the same move in trying to account for the variations in the retrograde loops as he had for the sun
   a. Put the center of the epicycle on a circle eccentric with respect to earth -- an eccenter – to account for the first or zodiacal inequality

b. The "equation of center" – d_1 in Swerdlow's diagram in the Appendix -- gives an optical correction for the center of the epicycle

c. Oppositions of the planet provide direct observation of this center, and hence establish the magnitude and direction of the eccentricity

d. But oppositions do not give any information about the distance of the center of the epicycle from the Earth

3. Hipparchus found that this model, while giving a good equation of center, gives totally inaccurate lengths of different retrograde loops, at least for Mars

   a. Where model predicts longest retrograde arcs, actual arcs are shortest, and vice versa

   b. This was the 300 year old problem that Ptolemy faced and solved

4. Ptolemy's solution: since model gives the direction, but not the distance of the center of the epicycle from the earth, let empirical data determine the distance

   a. Since the radius of that circle, the deferent, is in effect given (i.e. R=60), this amounts to letting data determine where its center is located

   b. In other words, do not presuppose that the center of the deferent is at the point of equiangular motion

   c. Instead, taking directions dictated by the point of equiangular motion as given, use the lengths of the retrograde loops to locate the center of the deferent

   d. Different combinations of data on retrograde loops for Mars consistently implied that the center of the deferent is very near the midpoint between the Earth and the point of equiangular motion

   e. Venus provided an independent way of locating the center of the deferent, from the variations in maximum elongations, and it too gave the midpoint

   f. Only the model-mediated determination for Venus is presented in the *Almagest*, with the text appearing simply to adopt the conclusion drawn from Venus for the three outer planets

5. The "***bisection of eccentricity***": use oppositions to determine total eccentricity and then locate the center of the deferent at the midpoint between O and E -- i.e. the observer and the "equant"

   a. An empirically driven refinement to Hipparchus's model, solving the 300 year problem of giving an account of the retrograde loops

   b. Ptolemy had mathematics not available to Hipparchus

   c. Given the insight that distance from O to the center of the epicycle is not empirically fixed by fixing the location of E, used that mathematics to infer the distance from (redundant) observations

   d. Observations consistently implied, to within reasonable approximation, a bisection of eccentricity (see Evans on qualifications to this claim)

   e. Conclude exactly a bisection: a conclusion that amounts to shifting the circular trajectory of the center of the epicycle by moving its center nearer the earth along the line of apsides

F. Ptolemy's Model of Planetary Motion

1. Turn now from Swerdlow's reconstruction to the finished model Ptolemy gives in the *Almagest*
   a. Deferent and epicycle just as with Hipparchus
   b. Angular location of planet on epicycle corresponds to direction from earth O to mean sun for outer planets
   c. Angular location of center of epicycle always tied to mean sun for inner planets
2. The distinctive feature of the model: the center of the epicycle is not moving with uniform angular velocity on its circle, the deferent, but is instead doing so with respect to a point E located symmetrically with respect to O on the opposite side of the center M of the deferent
   a. Others after Ptolemy called this point "the equant" -- the center of equal angular motion of the center of the epicycle
   b. The introduction of the equant was regarded as Ptolemy's great contribution
   c. Note the abandonment of uniform circular motion: the center of the epicycle is speeding up and slowing down on the deferent, with half of the total change in apparent motion a real change in motion, and half only apparent!
   d. This deviation from uniform circular motion was a major source of objection to Ptolemy over the next 13 centuries, including Copernicus
3. Given the tie to the mean Sun, Ptolemy's model had five basic parameters -- called "elements" -- per planet: ratio of radii of deferent and epicycle, eccentricity, direction of line of apsides with respect to the stars, period of one complete revolution on deferent (tropical or sidereal period), and period of one complete revolution on epicycle (synodic period)
   a. Two other elements needed to fix a starting point in time: location of planet on epicycle and epicycle on deferent at some (epochal) time -- e.g. a time of some specific vernal equinox (or accession to a throne)
   b. But (given tie to mean sun) five basic elements plus start time needed to "represent" complex motion displaying many more (apparent) degrees of freedom, or at least degrees of irregularity, in the patterns of retrograde motion
   c. An extraordinary discovery, which he surely took to be a "secret of the universe" type of discovery
4. The empirical basis for the standard Ptolemaic planetary model
   a. The mean speeds on the deferent and epicycle from the tropical and synodic periods, i.e. the mean times of return to the same location along the zodiac and with respect to Earth and Sun
   b. The orientation of the line of apsides (relative to the stars of along the zodiac) from the locations of the maximum and minimum apparent angular speeds: apogee where apparently slowest
   c. The total eccentricity from the ratio of the maximum and minimum apparent angular speeds -- i.e. the distance from the earth to the point of presumed equiangular motion

   d. The pattern of variation in timing and width of retrograde motions then requires the center of the deferent to be located midway between the earth and that point: bisection of eccentricity
   e. Specifically, given Ptolemy's method of deriving the ratio of the deferent and epicycle radii, do not given consistent values of ratio from one retrograde loop to the next unless the center is located (very nearly) midway between the two points
   f. This implies that, of the total change in the apparent angular speed from minimum to maximum, half is only merely apparent and half is real
5. Not only a "model", but complete computational procedure for taking preferred observations to determine the elements and for then calculating geocentric longitudes
   a. Calculationally tractable; even more so with tables
   b. Model helps indicate which observations to use to determine elements
6. Mercury the only planet that posed a special problem for Ptolemy, requiring a feature beyond the basic epicycle-eccenter-equant model
   a. Not clear what data led Ptolemy to augment the model for Mercury
   b. One thing that makes Mercury different is that its (elliptical) orbit has a large eccentricity (0.2 versus 0.09 for Mars, 0.007 for Venus, and all others less than 0.06) -- i.e. Mercury orbit most elliptical (though even then its minor axis is only 2 percent shorter than its major axis)
   c. Another thing: Mercury difficult to observe, because of short time during which it can be observed and atmospheric refraction
   d. Ptolemy could easily have been misled by data; note, though, that he let data dictate the model, and his ultimate model has a trajectory approximating an ellipse
7. Ptolemy's solution for Mercury: a moving center for deferent, somewhat akin to way his first newly discovered anomaly of moon handled
   a. Motion on the two smaller circles constrained so as to counterbalance one another
   b. The only oddity in an otherwise uniform account of the longitudes of the five planets
   c. But even this less glaring than it may at first seem, for Mercury nearest the moon and hence not so odd that its motion involves features of the moon's

G. The Achievement of Ptolemaic Astronomy

1. Achieved what he set out to: a complete, computationally tractable account of the motion of the sun, moon, and five planets, covering all principal irregularities to a high degree of approximation
   a. First successful account in history
   b. No real improvement on its accuracy until the first decade of the 17th century, with Kepler
2. Focused on oppositions, stationary points, patterns of retrograde loops, maximum elongations, principal anomalies etc., where it had extraordinary success
   a. Complete prediction of latitude and longitude for all time, past and future, including (incorrect) effects of precession of the equinoxes

b. But this primarily to the end of an account of the main regular irregularities in the motion, including the regular anomalies or inequalities, marked by various salient locations like stationary points, oppositions and conjunctions, and eclipses

3. Not 100 percent successful, for account of moon yields clearly wrong claim about how close it comes to the earth

a. Latitudes of planets also not especially successful: errors of 2 deg or more common (four times the width of the moon)

b. Errors well above the naked eye observation level in longitudes too: as much as 8 widths of the moon, and often more than two widths

c. Also, Mercury did require a somewhat different treatment from the other four planets

4. Still, level of accuracy impressively high, as shown in the figure for some retrograde loops of Mars

a. Not a great deal of interest in individual observations, and hence in discrepancies of sort shown in figure, so long as basic patterns of retrograde loops correct (as they visibly are)

b. Ptolemy himself calls attention to the possibility of improving orbital elements with better future observations, but no one appears to have done much to that end in the next 14 centuries

c. I.e. no one seems to have gathered the body of data needed to refine Ptolemy's orbital parameters

d. This step would have had to be taken before anyone could realize that his overall model of planetary motion could not achieve accuracy beyond a certain level

e. I.e. the sort of realization he himself achieved in the case of the basic theory of the Moon

5. Achievement maybe best captured by Neugebauer, who divides the entire history of astronomy into three parts, separated by Ptolemy's *Almagest* and Newton's *Principia*

a. Of comparable importance in history of science to Newton's *Principia*, for mathematical tractability and quantitative accuracy the standard ever afterwards in astronomy

b. Though stretching, not absurd to change Neugebauer's view about the history of astronomy to one about the history of science

c. Really did reduce a set of very complicated motions down to a quite simple theoretical model -- at least quite simple compared to the level of complications in the apparent motions themselves

d. This is one of the fundamental things we have demanded of mathematical "theories" of empirical phenomena ever since

e. But then, even beyond that, have the values of the parameters of the model determined from observations by measurements mediated by the model, with the demand that these measurements be robust

H. Shortcomings of Ptolemaic Astronomy

1. Concern here is with shortcomings that were detectable at the time, not ones that became evident after Newton and the advent of modern celestial mechanics, or even after 1600

a. Will examine Ptolemaic science from a modern perspective in Part IV below

b. Concern here is to identify shortcomings that in fact led to further research over the next centuries, or that might well have done so

2. Two empirical shortcomings were expressly noted over the course of the next 10 or so centuries:
   a. The observationally unacceptable excessive variation in the distance from the earth to the moon
   b. The too slow rate of the precession of the equinoxes, leading to the date of the vernal equinox gradually slipping earlier and earlier
3. Two further shortcomings that might be regarded as "philosophical" insofar as they involve violations of Aristotle were also expressly noted
   a. The non-uniformity of the motion on the deferent circle, losing the perfection of circular motion and violating the requirement that the motion be compounded out of uniform motion on circles
   b. The earth is at the center of the stars, but the centers of the deferents do not coincide either with one another or with the earth, nor with the center of the sun's orbit
   c. Both of these might also be regarded as obstacles to realizing the required motions physically, even in a mechanical model of the system (of which there were many attempts)
   d. (Also unclear how tilting account of latitudes could be physically or circularly realized)
4. Other shortcomings were not expressly noted over those centuries, but were likely recognized
   a. Discrepancies between calculated and observed longitudes and latitudes greater than 2 deg, that is, four apparent widths of the moon
   b. No solution for the distances, absolute or even relative, of planets and sun from earth; even in his later *Planetary Hypotheses* Ptolemy could only determine the minimum size required to fit everything inside of the sphere of the stars without having the spheres intersect
   c. Each planetary orbit independent of all other planetary orbits, so not really a planetary system: only tie is via relation of each to the mean sun
   d. The seemingly ad hoc character of having the motions of each of the five planets tied to that of the mean sun even though they were otherwise independent of one another
   e. The latter three, all of which were emphasized by Copernicus, can again be regarded as largely "philosophical," while the first is empirical
5. Given these shortcomings, one might well ask why more than a millennium passed before thoroughly worked out alternatives to the Ptolemaic system emerged
   a. Part of the reason was the difficulty of developing an alternative as good as Ptolemaic theory was in predicting salient phenomena
   b. In other words, the *Almagest* set a standard of excellence that any serious alternative had to match, and this proved far more demanding than we might now think
   c. Another part of the reason was a failure to appreciate that the discrepancies in planetary longitudes and latitudes might be telling them something important to the orbital theory
   d. But this may be a failure only from a far more modern standpoint

IV. Some Philosophic Issues

A. Introduction: Ptolemy as Bad Science?

1. In short, Ptolemaic astronomy is one of the greatest achievements in intellectual history -- so great that it rather overwhelmed everyone for over 1000 years
   a. Criticisms, revisions for sun and moon, various difficulties emerging over time such as with precession of equinox
   b. But no real alternative proposed until Copernicus, and no substantial revision to Ptolemaic orbital theory until Kepler
2. Yet Ptolemaic astronomy the standard example of "bad" science over the last 350 years
   a. Bad science, inferior science, pseudo-science, or non-science
   b. I.e. the example to contrast with modern science, the sort of thing the scientific revolution came to replace: science rejected as fundamentally wrong in certain key respects, something we want to claim is not true of any well-established modern science
3. The view of Ptolemaic science as bad science, which derives in no small part from Galileo's invective against it (as we shaill see later), is not so wide-spread today
   a. Historical research, most notably by Neugebauer and his protegé Swerdlow, as well as Toomer, has done much to reclaim the status of Ptolemy in the history of science
   b. But notice that that merely underscores the real question here: ***if Ptolemaic science was not such bad science by modern standards, then what is it about our current science that assures us that large parts of it are not going to be rejected as fundamentally wrong -- and even ridiculed -- in the future in just the manner that happened with Ptolemaic science?***
   c. Some sociologists of science, notably Bruno Latour, insist that nothing assures us of this
4. At least since mid-century (Koyré and Kuhn), historians of science have regarded it as inappropriate to judge the "science" of any other time by our current standards
   a. Let each period define 'science' and set methodological standards for itself, and then judge work in the period on the basis of this definition and these standards
   b. The alternative is to impose our definition and our standards without recognizing that they may turn out to have been just as parochial as theirs were
5. Nevertheless, in some sense modern science seems superior to Ptolemy, and much of this course -- in the philosophy of science -- is devoted to trying to spell out this sense
   a. So must ultimately face the issue, how, if at all, is Ptolemaic astronomy epistemically inferior, if only in an effort to better understand our conception of science today
   b. Begin to face the issue now by asking, what was the worst feature of Ptolemaic astronomy?
6. I will be violating Koyré's and Kuhn's dictum in this way throughout the course, judging the science we review not merely from the standards of the time, but also from contemporary standards -- always in an effort to understand the latter better, not to demean the former

B. Issue: What Claim is Ptolemaic Theory Making?

1. First, however, should pause to consider more carefully what sort of claim the Ptolemaic system should be interpreted as making
   a. Have used the word 'account' to avoid words like 'explain' and 'predict' -- words couching distinctions within contemporary philosophy of science that may have been irrelevant to Ptolemy
   b. Issue: given our more sophisticated views about the different ways in which his account might be interpreted, how is it best interpreted?
2. It is definitely not a mere recapitulation of existing data, or a curve-fit of some sort on old data
   a. Definitely meant to project beyond all existing data
   b. Takes the regularities it addresses themselves to be projectable -- as occurring repeatedly indefinitely into the past and into the future
3. Though it yields longitudes and latitudes versus time, seems primarily an account of -- a theory about -- various regularities noted in the past, and not about individually observed longitudes and latitudes
   a. Distinguish between data (or observations) and phenomena, where latter are the regularities exhibited within the data
   b. Ptolemy seems to have been aiming at giving an account of these phenomena, including some new ones he discovered as a consequence of his account
4. Not a mere recapitulation of the phenomena it accounts for either, for these phenomena exhibit far more "degrees of freedom" -- far more distinct, seemingly independent variations -- than Ptolemy's account has elements
   a. In particular, six independent elements, to account for a much larger number of variations in retrograde motion
   b. In some sense a reduction of a complicated range of phenomena to a comparatively simple base
   c. Furthermore, generalizations: same basic model, with exception of minor addition in case of Mercury, covers all planets
5. Thus at the very least making a strong claim: whatever the true motions are, they are reducible to a simple basic account at least to a sufficient approximation to "save the phenomena" of interest
   a. An account whose elements can be determined from a handful of observations
   b. And that is computationally tractable both in derivation and application, allowing a set of questions pertaining to observable locations over time to receive computed answers
   c. Thus a mathematical theory in the modern sense -- a complete question-answering system of the same general sort that we now learn in physics and other such fields
6. This in contrast to claiming that describing the precise motions of the planet or giving an account of the physical mechanisms underlying their motions
   a. Phenomena either result from a motion involving compounds of circles with eccenters and equants, or are as if they result from such a motion

b. Thus, at the very least, a starting point for pursuing the precise motions and the physical mechanisms underlying them

C. Issue: Is It Bad Because It Is Too Complicated?

1. Most common criticism of Ptolemaic astronomy today is that the system was inordinately complicated -- so complicated that no one in their right mind should have taken the system seriously
   a. "Epicycles on epicycles" -- a claim that in fact is basically false, though it does appear to have a historical source in a remark made in the 13th century by King Alphonso of Spain
   b. As you will see by the end of the course, orbital descriptions are not less complicated today, because in fact the orbital motion really is quite complicated
2. Still the classic complaint that Ptolemaic astronomy is too complicated can be put into a forceful form -- e.g. it is too complicated in the sense that his cinematic models involve too many ad hoc elements, making then too Rube Goldbergish
   a. Obvious reply: but captures an extraordinary range of phenomena -- primary regularities and secondary and tertiary anomalies -- within a model involving only a handful of parameters, with the same basic model generalizing across several planets
   b. What more can we legitimately ask for? (Indeed, has modern science done more than this?)
   c. This is not to deny the arbitrary features of the model, and differences from one planet to another
      (1) Sun and moon different from the others and from each other
      (2) Inner planets tied to (mean) sun and hence different
      (3) Outer planets tied to (mean) sun in a different, seemingly arbitrary way
      (4) Mercury requires exceptional feature, and Moon requires two
   d. But Ptolemaic astronomer can reply not just that the data force those features on us, but -- more importantly -- that his mathematical representation served to reveal these secondary regularities, which otherwise might have seemed to have no pattern to them!
3. There is a related classic complaint, perhaps better capturing the intent: Ptolemaic astronomy is too complicated in the sense that no physical mechanism seems to fit it, and on surface not very likely that one can be found
   a. The basic system of the crystalline spheres ceases to work -- i.e. can no longer build an actual running model -- once the complications are included
   b. Equant the major problem, for can't be handled by rotating spheres in any obvious way – a complaint raised in Islamic astronomy, as well as by Copernicus
   c. But inner epicycles for Mercury and Moon also a problem
4. A legitimate complaint, but as we shall see later in the course, less injurious than one might think, for a complaint that holds against many of the great successes in modern "good" science
   a. At the time Ptolemy had little empirical basis for making claims about the underlying physical mechanisms

b. Especially in the light of the empirical basis he had for the planetary theory, even with its many complications, claims about the underlying mechanisms had to be regarded as mere conjectures -- that is, as hypotheses in contrast to features dictated in significant part by observations

c. The most that can be said is that his planetary theory shed little light on the underlying physical processes; but this is true of lots of the greatest theories in science

5. In sum, the complaint that the complexity of Ptolemaic astronomy was by itself enough to raise serious doubts about it does not stand up well under scrutiny

   a. This is not to say that complexity objections to scientific theories are never appropriate

   b. Rather, the point is that such objections are legitimate only in special circumstances that we have not yet identified, beyond arguing that they did not so clearly hold in the case of Ptolemy, at least in the context of all other information available to him at the time

   c. In particular, the bald fact of complexity is not even a serious prima facie objection to a scientific theory, for once you get past the classroom level you will find that many fields of contemporary physics are staggeringly complex -- e.g. contemporary wave-particle optics

D. Issue: Is It Bad Because It Is Simply False?

1. Of course, the preceding defense of Ptolemy begins to raise a worry, for we know that Ptolemaic astronomy is seriously false, and we don't want any false theories to count as good science

   a. For, if they do, we may have to make allowances for the possibility that current theories satisfying the strictures of good science may turn out to be false too

   b. Idea: false theories that are held for extended periods of time, as if the final word, must in some sense be bad science, for the whole point of methodological strictures is to preclude just that!

2. An obvious basis for saying that Ptolemaic science is inferior science is that it is false, for the planets do not in fact describe epicyclic motion, nor for that matter uniform angular motion with respect to some point in space

   a. Indeed, Ptolemaic science is even worse than false, for it was in certain respects a dead-end, a garden-path, that had to be surmounted before scientific progress could be made

   b. In particular, an impediment to gaining empirical access to the underlying physical processes

3. While there is surely some truth to this complaint, it does have the fault of presupposing that we must take Ptolemy as asserting without qualification that the planets really do describe epicyclic motion, with the Earth at the center

   a. The *Almagest* opens with a brief argument against the motion of the Earth that is best read as making a prima facie case that the Earth is an appropriate reference point for all other motion

   b. This at least opens the possibility of interpreting his theory as making a weaker claim: it is describing the motion of the celestial bodies relative to the Earth, taken as a reference point

4. If we adopt this slightly less extreme interpretation of Ptolemaic theory, then accusation of falsity has to be qualified too

a. For relative to Earth the planets do exhibit (as we shall see) at least something akin to the compound circular motion that he says

(1) In the case of the outer planets, the epicycle represents the orbit of the Earth, while the deferent does so in the case of the inner planets

(2) But in both cases a compound of two basically eccentric circular motions

b. Moreover, the other main claim -- that the variations in apparent motion are roughly half attributable to a real variation in motion, described by the equant, and half to an appearance arising from the observer being off-center -- also can be defended in retrospect

5. In other words, taken this way, Ptolemaic astronomy is, at least to a first approximation, true!

a. What is more, these elements of truth proved historically important, for they were the basis of subsequent developments

b. So, Ptolemaic astronomy was not even a dead-end or a garden-path in any simple way

E. Issue: Is It Bad Because It Is Too Inaccurate?

1. There is a more subtle version of the complaint that Ptolemaic astronomy is false

a. There was sufficient evidence available at the time, or at least over the next centuries, to establish that Ptolemaic astronomy is false

b. Namely discrepancies day in and day out between observed longitudes and those given by the theory, not to mention discrepancies in latitude as well

2. Ptolemaic astronomy is indeed not exact, for predicted longitudes, and latitudes too, wrong by much more than observational error (said by Ptolemy to be around 10 min of arc)

a. As remarked above, errors in latitude of 2 deg common, and as figure for the retrograde loops of Mars shows, longitudes off by this much and more, even 4 deg every once and a while

b. Diameter of the Moon is 30 min -- half a degree -- so that these discrepancies are clear to the naked eye

c. Though, unlike the discrepancy owing to the mistaken rate of precession of the equinox, these errors are not cumulative

3. Reply: fair enough, but the only claim is that the theory holds to a sufficient approximation to yield a good account of the primary phenomena

a. Furthermore, as Ptolemy himself illustrates in the case of the Moon, theory holds to a sufficient approximation to be a basis for continuing research in which future observations may yield better elements, or reveal further patterned anomalies

b. Every theory always has its discrepancies, so the mere presence of discrepancies here is not grounds for an indictment

c. The whole idea is to use theory to expose discrepancies so that they can in turn be learned from

d. Ptolemy himself not only illustrates this, but invites just such future attention in the way he instructs the reader in using observations to fix the orbital parameters

4. Historically, however, this is not what happened; no one appears to have pursued the observational data needed to be in a position to describe the discrepancies in longitudes and latitudes systematically, much less to expose telling patterns in them
   a. Perhaps some started, but failed to see any pattern right away, and lacking an adequate base of data, abandoned the effort
   b. Or perhaps the view was that the discrepancies were not to be taken all that seriously -- e.g. they may involve observational errors, or they may be the consequences of ill-behaved secondary mechanisms that are beyond the scope of scientific investigation
   c. Or perhaps nobody even became concerned about the discrepancies, because, Ptolemy's own efforts in this direction notwithstanding, they lacked the modern concept of exact science on which every systematic discrepancy with observation is taken as raising a worry
5. Regardless, so far as I can see, the most serious fault of Ptolemaic astronomy, though less so of Ptolemy himself, is a failure to use it as a basis for further research, attempting to identify residual imperfections and characterize these as new phenomena requiring refinements of the theory
   a. Ptolemy showed the value of doing just this with his discovery and treatment of the second and third lunar anomalies
   b. But subsequent astronomers did not exploit Ptolemaic astronomy in this way
   c. If they had, they would have made a number of startling and useful discoveries, though the effort in doing so would have had to extend across a community over a substantial period of time
6. Maybe this is the primary lesson to learn from the "failures" of Ptolemaic astronomy: a community of demanding scientists is needed to subject theories to constant criticism -- repeatedly revisiting the evidence for their fundamental principles and presuppositions underlying them
   a. Not just the "greats" of the history of science who have made science what it is, but also the many lesser figures whose primary role has been one of critical assimilation
   b. Such a community would have at least begun developing a record of the inaccuracies of Ptolemaic theory, in the process raising questions
   c. The history of science might have been substantially different if such a community had been at work in the 1000 years following publication of the *Almagest*

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Credits for Appendix

Slide 2: Seeds (1988)

Slides 3, 14, 15: Evans (1998)

Slides 5-8: NASA.gov/multimedia/imagegallery

Slides 9, 23, 30: Neugebauer (1975)

Slides 16, 22, 25: Evans (1984)

Slide 21: www.faculty.umb.edu

Slides 26-28: Swerdlow, unpub lished