THE NEWTONIAN REVOLUTION – Part One

Philosophy 167: Science Before Newton's *Principia*

Class 2

16th Century Astronomy: Copernicus and Tycho Brahe

September 9, 2014

TABLE OF CONTENTS

Philosophy 167: Science Before Newton's Principia

Assignment for September 9

16th Century Astronomy: Copernicus and Tycho Brahe

Reading:

Kuhn, Thomas. The Copernican Revolution. pp. 1-77, 134-209.

Evans, James, "On the function and probable origin of Ptolemy's equant," American Journal of Physics, v. 52, 1984, pp. 1080-1089.

Gingerich, Owen. "Ptolemy, Copernicus, and Kepler," from The Eye of Heaven, pp. 3-38.

Questions to Focus On:

1. In what, if any, respects was the Copernican system simpler than the Ptolemaic? In answering, consider not just planetary motion, but also diurnal motion and the precession of the equinox.

2. What empirical evidence was there as of 1600 in support of the claim that the Copernican system is basically true and the Ptolemaic system is not?

3. Were there any other considerations as of 1600 that provided grounds, solid or otherwise, for preferring the Copernican system to the Ptolemaic?

4. Were there any reasons as of 1600 for taking the Tychonic system seriously as an alternative to the Copernican and Ptolemaic systems?

5. Why was the Tychonic system incompatible with the classical doctrine of the crystalline spheres? How strongly should this have counted against it?

6. What empirical evidence was there as of 1600 favoring the Copernican system over the Tychonic? Was there any empirical evidence favoring the Tychonic?

7. What suggestions might be given to a practicing astronomer in 1600 looking for some way to adduce empirical evidence that would once and for all resolve the dispute over the three chief systems?

Class 2: 16th Century Astronomy: Copernicus and Tycho Brahe

I. The Copernican Revolution

A. Ptolemaic Astronomy: e.g. Longitudes of Mars

1. The part of Ptolemaic astronomy of chief concern to us is his account of planetary longitudes, using compound circles

   a. Such phenomena as retrograde motion, variations in lengths of retrograde loops and in their timing, and variations in rates of movement (e.g. Mars 40 percent faster in Capricorn than in Cancer)

   b. Two classic inequalities: “first” or zodiacal inequality, the variation in speed around the ecliptic; “second” or solar inequality, retrograde motion (when in opposition to the sun)

   c. Long standing efforts to predict such phenomena, akin to efforts to predict eclipses, which exhibit a similar underlying regularity and a complex pattern of regular variations from it

   d. Contrast Ptolemy's problem with that of being presented with a body of longitude data and finding a "curve" that will fit it

   e. Ptolemy giving a comparatively simple rule that captures to reasonably high approximation a complex pattern exhibited by nature

2. Overall basic system inherited from Apollonius and Hipparchus: geocentric, with major epicycles to account for retrograde motion

   a. Sun and moon without major epicycles, for no retrograde motion

   b. Center of epicycles of inner planets always aligned with mean sun, and angular position of outer planets on their epicycles always aligned with earth-mean sun vector

   c. Distances from the Earth -- radii -- indeterminable save that of moon (and Ptolemy thought sun as well, from eclipses), though ratio of deferent to epicycle radii known

3. Ptolemy takes up device of eccenter from Apollonius and Hipparchus, but then adds bisected eccentricity, and consequently equant, in order to account for variations in basic longitudinal patterns

   a. Same configuration in every case but Mercury: captures a generality

   b. Mercury with center of deferent on inner epicycle, largely because being misled by erroneous observations

   c. Seven parameters or "elements" (six independent), the last two of which simply "starts the clock": ratio of radii, eccentricity, period on deferent, period on epicycle (to return at opposition to same stars), direction of line of apsides, and locations (planet on epicycle and epicyle on deferent) at some (epochal) time

   d. First five elements suffice to represent, to a good approximation, the complexities of the retro-grade phenomena, which exhibit a large number of degrees of freedom: captures a generality

   e. Mars: r/R = 39;30; e = 6;0 (i.e. 0.1); mean motion of anomaly = 0;27,42 per day; mean motion of longitude = 0;31, 26 per day; apogee at Cancer 25;30 (A.D. 139)

4. In representing the phenomena of planetary longitudinal "anomalies", Ptolemy provided a system that predicted planetary longitudes at all times, past and future
    a. Longitudinal discrepancies of the order of 1 to 2 deg not uncommon, though little attention given them (and same for latitudes, though they capture general shape of retrograde loops)
    b. Main emphasis on patterns of anomalies, which Ptolemy was able to represent far more accurately than anyone before him, and how they relate to the values of the orbital elements
5. Ptolemy provides a complete, tractable computational system, and not just a qualitative scheme
    a. Calculational procedures to infer elements from observations, with theory indicating (1) which observations serve that purpose best and (2) how to conceptualize the elements geometrically
    b. Calculational procedures, with Tables, for determining planet location at any time: usually as a series of corrections to a first pass, "idealized" value
    c. Restriction to circles reflects not just "perfection of circular motion", but also calculational tractability of circles
    d. Actual orbits are very nearly circular, so assumption of circularity not a large source of error
6. Moreover, given three working hypotheses proposed at the beginning of the *Almagest* -- (1) the Earth is motionless, (2) all zodiacal motion is centered around it, and (3) all real celestial motion involves compounds of equiangular motion -- Ptolemaic orbital theory was “data-driven”
    a. For under these working hypotheses, retrograde motion is real, not merely apparent
    b. Then, as shown last time, each of the features of a Ptolemaic orbit derive from something specific in the observed motions, and it in turn determines the value of the related parameter
    c. The fact that the same values, to high precision, for those parameters keep being obtained from new observations – i.e. the values are stable -- then provides a continuing test of the models

B. A Problem Raised for Philosophy of Science

1. Its achievement notwithstanding, Ptolemaic astronomy has to be regarded at least to some extent as a failure in the history of science, an impediment to progress that had to be overcome, at least to get at the physics governing orbital motion
    a. A case can be made that it was a garden-path that had to be abandoned before modern science could get started
    b. Yet a garden-path that had impressive empirical evidence behind it, and hence was more difficult to abandon than if it had been a mere philosophical conjecture
2. Our current science has various mathematical theories -- calculational systems -- akin to Ptolemaic astronomy that are accurate, at least to a reasonable approximation, and offer accounts of prominent regularities -- i.e. phenomena
    a. E.g. classical electromagnetic theory, Newtonian mechanics, and thermodynamics
    b. Were it not for computational intractabilities, quantum mechanics too, which at least in principle covers every question in chemistry

3. This gives us more than just passing reason to want to identify something methodologically unsound in Ptolemaic astronomy, something that differentiates it methodologically from our science
   a. For, if it was methodologically sound in all respects, then perhaps our current science too may turn out to be a garden-path that we will have to abandon at some point in the future, reconstituting science from the ground up in the way that mathematical astronomy was reconstituted following Copernicus and Kepler
   b. Ptolemaic science stood for 1400 years, while the our science has stood for less than 350 years
   c. If we are going to insist that modern science is superior as science, we best identify some features in Ptolemaic science that we can now see were objectionable at the time
4. When one looks in detail at Ptolemaic astronomy, the question of what was wrong with it turns out to be more difficult than one might have first thought
   a. As noted at the end of the last section, it was empirically driven to a remarkable extent -- indeed, more so than Copernicus's astronomy
   b. In many other respects it had a remarkable amount in common with our science -- again, more so than Copernicus's work in many respects
   c. Evidence from (1) success in predicting salient events, (2) while models require only five principal constants (3) whose values come from model-mediated stable measurements
   d. It was at least as good as contemporary economics -- Swerdlow has said that it was much better
5. In particular, the objections to Ptolemaic astronomy that we have inherited from Galileo and others of the 17th century do not stand up so well under scrutiny
   a. Its complexity was empirically driven, and it did succeed in reducing far more complicated phenomena to a comparatively simple theoretical basis
   b. When construed as describing planetary motion relative to the Earth as a reference point, it can arguably be viewed as true to a first approximation
   c. Whatever fudging Ptolemy did was open to correction via subsequent observations; he even showed how to go about using observations to improve the values of his elements
   d. Cumulative or growing inaccuracies were subject to fairly straightforward correction
   e. Inaccuracies in longitude and latitude were not cumulative, and there was no immediately transparent pattern to them
6. My suggestion last time was that the worst feature of Ptolemaic astronomy was that the theory was not used as a tool in ongoing research -- e.g. by defining deviations from the theory and attempting to find patterns in them that would lead to refinements
   a. Ptolemy not so much at fault in this regard, for he had shown how to do this in the case of his lunar theory
   b. But after him, a hiatus in ***empirically driven*** efforts to extend the theory or to gain insights from deviations from it

c. (Not inconceivable that efforts to do so might have led to using the actual sun rather than the mean sun as a reference, and with them to reduced discrepancies in predicted longitudes -- which might have made the theory even more entrenched

d. Not clear whether comparable progress on latitudes would have been possible, though shift from mean to actual sun might have been enough)

7. Perhaps a better formulation of my complaint is that, for all of Ptolemy's emphasis on empirical evidence, insufficient emphasis was placed on questions that remained open or had been only tentatively closed on the basis of very limited evidence; e.g.

a. Are the Earth and the mean sun the appropriate points to which to refer all the motions?

b. What are the distances of the planets from one another (and is the ordering of them correct)?

c. Would any other object added to the system have to describe basically the same motion?

d. (Note the subjunctive in this last question; this will become important in a couple of weeks)

C. Background: 13 Centuries of Ptolemaic Astronomy

1. Ptolemaic mathematical astronomy remained essentially intact over the next 14 centuries, forming the basis of the academic discipline of astronomy

a. In Alexandria, then Arabs (and Iranians), and finally into Europe in the 12th century via the Moor migration into Spain

b. A discipline within the great universities of Europe that started to be formed in the 13th century: Paris, Oxford, Bologna, etc.

c. Textbooks explicating the basic system found in the *Almagest*, most notably *Sphaera* of John of Sacrobosco (ca. 1250) the main source until end of 15th century

2. Criticisms directed not at small inaccuracies in daily longitudes, which go virtually unmentioned, but at violations of uniform circular motion and non-centrality of the earth, on "philosophical" grounds

a. Found how to use a minor epicycle on top of the major one to get same effect as the equant

b. Worries not just about abandonment of uniform circular motion, but also about underlying physical mechanisms: how to realize equant with nested rotating (solid) spheres

c. Also some attention to clearly wrong implication about how near the moon comes to the earth

3. Improvements in some aspects of Ptolemaic astronomy, but not in planetary orbits (nor in latitudes)

a. Some improvement in sun and moon via further observations

b. Correction to 1 deg per century precession of equinox, which was becoming glaringly wrong, throwing everything else off, after a few centuries

c. Trepidation, a superposed, cyclic variation in the precession rate, keeping the average between Hipparchus and Ptolemy at 1 deg per century

d. Alfonsine Tables (around 1270) an updated version of Ptolemy, incorporating trepidation and other small modifications (thought to be improvements), but with same basic treatment of planetary longitudes

4. From 11th century on, increasingly outspoken "doubts" (*Shukūk*) among Islamic astronomers of Ptolemy's violations of such "accepted principles"-- his phrase -- as strictly uniform circular motion and earth in exact center without offering any justifications (see Saliba quotation in Appendix)
   a. Some alternative mathematical approaches, most notably by al-Urdī (d. 1266), al-Ţūsī (d. 1274), al-Shīrāzī (d. 1311)
   b. Ultimately, a complete alternative system of longitudes by Ibn al-Shāţīr (d. 1375), obtained through a mathematical transformation of Ptolemaic theories that preserved uniform circular motion throughout with the earth at a center (thereby achieving consistency with Aristotle) while also eliminating empirical shortcoming of his theory of the moon
   c. None of this work was translated into a European language, and hence it remained unheralded in the west until the second half of the 20th century
   d. Nevertheless, as we shall see below, it somehow diffused into European Renaissance astronomy apparently through word of mouth, especially in northern Italy
5. By the late 15th century, when Copernicus was growing up, Alfonsine Tables becoming clearly inadequate -- e.g. several day slippage in vernal equinox, indicating need for calendar reform
   a. In part from failures of trepidation to correct Ptolemy's mistaken precession rate
   b. But also from Ptolemy's use of tropical year as his basic time unit, with Hipparchus's slightly incorrect value (365+1/4-1/300) resulted in a cumulative error distributed throughout his system that had become quite obvious three centuries after the tables were formed
6. Perhaps as part of the spirit of the age, there was a good deal of critical discussion of Ptolemaic astronomy in the European universities at the end of the 15th century, especially in northern Italy, where the Renaissance was flourishing
   a. Attempts to form physical models, with consequent interest in alternatives to equant
   b. Criticisms of implied claim about the moon, and about failures underlying calendar problems
   c. But no radically new systems -- Ptolemaic still taught, though most students of astronomy learned it from watered-down abridgements and commentaries, not from the *Almagest* itself
   d. *Almagest* in Greek published in 1515, ending need to rely on old, inadequate Latin translation

D. 15th Century Planetary Astronomy: Regiomantanus

1. A community of university astronomers in Europe in the 15th century, extending from Poland and Germany into Italy
   a. Spearheaded by Johannes Müller (1436-1476), better known by his Latin name, Regiomantanus
   b. Born in Königsberg, taught briefly in Padua, ending in Nuremberg
   c. Knew the *Almagest* in great detail, as well as at least some Arabic astronomy
2. Based on observations he concluded around 1460 that the Alfonsine tables were seriously inadequate, attributing the cause to a corruption of Ptolemaic astronomy
   a. Called for reform in astronomy based on systematic observations, which he initiated himself

b. His picture of reform was to remove misunderstandings and errors that had made their way into Ptolemaic astronomy, returning to the original but with the sort of superior observational basis Ptolemy had originally called for

c. In early 1460s finished *Epitome of the Almagest*, an abridged Latin translation with comments, begun by his senior colleague Peurbach [1423-1461]); published in print, 1496

d. This became the basic source for Copernicus and subsequent generations

3. Regiomantanus's approach typical of the era: classic learning had become corrupted by the Scholastics; the solution was to return to the original works

a. Regiomantanus initiated a huge publishing program, including the *Almagest*, *Geography*, and two other works of Ptolemy; Euclid's *Elements*; the surviving works of Archimedes; and the *Conics* of Appolonius (all of which he knew)

b. His death at age 40 curtailed this project, though they were all published during the next century, in some cases continuing his effort

c. Before he died he published two works of his own that contributed significantly to astronomy during the next decades: a 7-place trigonometric table to the minute of arc and a nearly 900 page Ephemerides for 1475-1506, giving calculated daily positions of the sun, moon, and planets

4. (One must not underestimate the importance of the invention of the printing press (ca. 1440s) to the emergence of active research in astronomy in Europe at this time

a. Just as Luther's German translation of the Bible (1536) made it accessible to a large range of people, so too the printed versions of classic and current works in astronomy and mathematics made them widely available

b. It also opened the way to intellectual careers for the first time to people who lacked voluminous memories, for memory ceased being a prerequisite)

5. Regiomantanus was the most talented of the astronomers of the era, but there were many others too

a. His associate, Bernhard Walther (1430-1506) continued his program of observations over the period from 1475 to 1504, providing a good deal of useful data, especially of the sun

b. These observations, together with those of Peurbach and Regiomantanus, were published (by Schöner) in 1544, and republished in 1618 by Snel

E. Nicolaus Copernicus: A Brief Biography

1. Born in 1473 in Torun, son of a well-to-do merchant who died when he was 10, after which he grew up under his uncle, the Bishop of Ermland

a. Associated with Church all his life: canon, though never a priest

b. Apparently lived in Ermland, which borders on Prussia, from roughly 1503 on, after completing his education -- i.e. from age 30 on

c. Performed duties as canon, acted as a medical doctor, and carried on his research in astronomy

2. As good an education as could be had at the time

a. University of Cracow from 1491 to 1495, where studied astronomy, among other things

b. Canon law and astronomy in Bologna from 1496 to 1501, then medicine at Padua from 1501 to 1503, with degree in law from Ferrara in 1503

c. Astronomy a hot topic in both Bologna and Padua

3. We have comparatively little biographical information on Copernicus's efforts in astronomy -- indeed, not even on when and how he became so proficient

a. Noted enough that Pope invited him to Rome in 1514 to comment on calendar reform that eventuated in the Gregorian calendar in 1582

b. He refused, saying that motions of sun and moon had to be worked out correctly before appropriate to turn to calendar

4. Sometime around 1610 Copernicus formed the idea of the heliocentric system

a. *Commentariolu*s summarizes system -- a manuscript that he circulated (date of composition unknown, but almost certainly no later than 1514)

b. First section, included in the Appendix, lays out his motivation and axioms

c. Spent much of the next 20 to 30 years developing complete heliocentric system, at a level of detail comparable to Ptolemy's *Almagest*

d. Delay in publication not because of fears of Church, but because of fear of ridicule (see his prefatory remarks); probably also hoping to find some compelling evidence for his system

5. Rheticus came to work with him in 1539, published a summary in 1540, and arranged for full publication (in Lutheran Germany) of *De Revolutionibus* as Copernicus apparently preferred to call it

a. Publication carried through by Osiander, who anonymously added preface saying just a hypothesis (undoubtedly out of fear of Lutheran Church, for Luther himself had dismissed Copernicus's heliocentrism when he heard of it)

b. Legend has it that Copernicus saw printed book, or at least pages from it, on his death bed and was upset by the preface

c. Whether this is true or not, Copernicus was definitely opposed to the idea that astronomical models should be regarded just as hypotheses used for calculations -- indeed, he was opposed to Scholastic nominalism quite generally, not just this one manifestation of it

F. Copernicus and Ibn al-Shāţir (d. 1375)

1. A chance discovery in 1957 of an Arabic manuscript by Ibn al-Shāţir (*The Ultimate Quest regarding the Rectification of* [*Astronomical*] *Principles*) in an Oxford University library has transformed Copernican scholarship -- and increasingly the historiography of Islamic science as well, though this transformation is still in process

a. Before: Copernicus effected a mathematical transformation of Ptolemaic astronomy into a heliocentric system, in the process eliminating all violations of uniform circular motion as well as the error on the variation of the distance of the moon in that astronomy

b. But Ibn al-Shāţir in the manuscript had already eliminated all violations of uniform circular motion and the error on the moon in just the way Copernicus does
c. After: Copernicus effected a mathematical transformation of Ibn al-Shāţir's "rectified" version of Ptolemaic astronomy into a heliocentric system

2. Ibn al-Shāţir, though living in Damascus, was part of a school of astronomers centered at the observatory in Marāgha (Iran) founded in the thirteenth century and thriving until at least 1316
3. Ibn al-Shāţir's manuscript offers cinematic theories for the sun, moon, and five planets that amount observationally to Ptolemy's, but systematically eliminate all traces of non-uniform circular motion
   a. Replace the equant in the orbits of Venus, Mars, Jupiter, and Saturn with a small epicycle (along which the center of the major epicycle then moves) in a way (to be discussed later) that gives the same effect as the equant, but with a slightly different trajectory
   b. Offered an entirely new theory of the moon, using epicycles on epicycles to capture all three of Ptolemy's inequalities, in the process no longer having the variation in the distance of the moon from the Earth flagrantly violate the small variation in its apparent diameters
   c. Offered a new theory of Mercury in which the length of a radius vector varies during the course of its zodiacal motion, effecting the same approximation to an elliptical trajectory as Ptolemy had (but using the Islamic uniform circular motion device called al-Ţūsī's couple)
4. Copernicus adopts exactly same devices in the models of those orbits in his *Commentariolis* (even including a small epicycle instead of an eccentric) while eliminating the major epicycles in Ibn al-Shāţir's models by having them become the orbit of the Earth around the sun
   a. A mathematical transformation of Ibn al-Shāţir's models into ones in which the planets and the Earth are in orbit around the sun
   b. By the time of *de Revolutionibus* Copernicus switched to eccenters and modified his models a little for Venus and Mercury after realizing that a direct transformation doesn't quite work
   c. But save for some subtleties involving values of parameters (see Appendix), the models of Mars, Jupiter, and Saturn remained transformations, and the moon model remained Ibn al-Shāţir's
5. Swerdlow: the parallels are "too remarkable a series of coincidences to admit the possibility of independent discovery"
   a. Not just how (1) the equant was eliminated for Venus, Mars, Jupiter, and Saturn, but also (2) the new theory of the moon and (3) the new theory of Mercury recur in *Commentariolis*
   b. Evidence that Copernicus did not discover these independently from his giving an incorrect reason for one aspect of the new theory of Mercury
   c. We still do not know when and how Copernicus became aware of Ibn al-Shāţir's models, or even how well he understood them, given that he did not know Arabic
6. Has led now to viewing Copernicus not as the beginning of modern astronomy, but as the last figure in the ancient tradition, more specifically the last of the Marāgha school

G. The Many Different Copernican Revolutions

1. *De Revolutionibus* the source of the "Copernican Revolution", which is probably best viewed as several distinct revolutions
   a. As Kuhn emphasizes, book itself a technical work in mathematical astronomy that only those educated in the discipline had a prayer of reading
   b. And as a book in mathematical astronomy, we have just seen was far less revolutionary than one might think, save for the shift to heliocentrism, with the moving earth
2. Copernican revolution in who is the ultimate intellectual authority, the ultimate arbiter of what is true
   a. The Church and theologians in 1533, empirical scientists in 1833
   b. Copernicanism a key instrument in this essentially political revolution, though largely because Galileo made it so, and the Church responded in the way it did to his challenge
   c. Reformation alone probably enough to undercut religion as ultimate arbiter of truth
3. Copernican revolution in conceptual scheme and world view: shift from earth and hence humans being the center of the universe to earth being a mere incidental speck in vast universe
   a. Enormous intellectual impact, akin to Darwin's impact, with repercussions in all aspects of intellectual activity; akin to Darwin in other ways as well, including its being put forward as a new explanation not necessitated by any specific data
   b. Not an element in *De Revolutionibus*, and resulting impact almost entirely among people who not only never read the book, but could scarcely have understood the mathematical astronomy in it if they had
   c. What Kuhn primarily concerned with in his book
4. Copernican revolution in "science" -- i.e. in natural philosophy: increased emphasis on idea that appearances can be deceptive and therefore cannot be straightforwardly relied on as evidence
   a. Copernicus tied to rise of neo-Platonism, with its opposition to Aristotle's trust in appearances
   b. Leads to increasing emphasis on evidence beyond mere agreement with appearances, usually on mathematical elegance or way in which various aspects of theory interlock with one another
   c. Eddington's refrain: never trust any data until it is confirmed by theory -- theory gains an evidential role in its own right
5. These revolutions notwithstanding, the only one of real interest to us is the Copernican revolution in mathematical astronomy, which *De Revolutionibus* merely started
   a. A narrow, highly technical academic discipline, with a couple of hundred specialists and a comparable number of amateurs
   b. Like every such discipline, a life of its own, driven by desire to tinker with existing ideas and come up with improvements and new ideas
   c. Rest of today: impact *De Revolutionibus* had within the discipline of mathematical astronomy in the first half century after its publication

6. Copernicus's contribution to mathematical astronomy was to show that Ptolemaic astronomy could be mathematically transformed into a heliocentric astronomy, preserving all "positional" evidence!
    a. Fundamentally a mathematical discovery, creating a problem in evidence, namely how to choose between two very different accounts of the same observational facts
    b. Not to demean the extraordinary conceptual step Copernicus took, as indicated by the 1700 years between Aristarchus and him in which a heliocentric approach to retrograde motion was ignored
    c. Copernicus's contribution to the history of ideas is immense, but his contribution to the history of scientific evidence is more modest

H. Some Comments on Kuhn's View of Science
1. Pause here to contrast Kuhn's view of science with the view that will be at the center of this course
    a. Kuhn's view of science most prominent, if not most dominant from 1960s to at least 1990s; built around claim that empiricial evidence plays much less of a role in the development of science than one might think
    b. Challenge to those like myself who want to argue to the contrary is to show how empirical evidence ultimately dominates the history of science
    c. This course a response to this challenge
2. On Kuhn's view "science" -- no sharp line between science and philosophy for him -- is driven by the desire to form a coherent world view (or conceptual scheme)
    a. Peculiar feature of modern western science is a demand for this scheme to conform in some ways with *some* detailed empirical facts, facts that constrain but do not determine science
    b. Major events in the history of science: changes in conceptual schemes, initiated by narrow empirical difficulties with old scheme
    c. His account of Copernicus through Newton offers clear example of this view of science
3. Two primary reasons in support of Kuhn's view of science, both spelled out in detail in his widely read *Structure of Scientific Revolutions*, and both illustrated in his earlier *The Copernican Revolution*
    a. To understand e.g. Copernicus or Ptolemy, must read them through the lense of their conceptual scheme, and not ours
    b. Close examination of the way in which new theories and ideas become accepted by scientists show that they are invariably accepted long before the "evidence" gives compelling reason to think they are true
4. My view: (modern) science is driven by the desire to find ways to bring empirical evidence to bear on questions -- i.e. the desire to turn data into evidence, to turn questions into empirical ones, especially questions about which measurable details make a difference and what differences they make
    a. An extraordinarily difficult thing to do, as this course will make clear
    b. On my view, much of the conceptual apparatus attendant to science is heuristic, helping scientists to conceptualize, to talk with one another, and to popularize what they are doing

c. But, I claim, much of it is of secondary importance in the history of science -- something scientists are quick to discard (*vide*, crystalline spheres in Copernican astronomy) while retaining existing dependencies between measurable parameters and observable features of the world

5. No need for you to agree with me, for course will be a sustained effort to show how desire to bring empirical considerations to bear drove the development of Newtonian science
   a. Assign Kuhn's book in part as a corrective to me, so that you have opportunity to see another, currently more dominant view, at least among historians and sociologists of science
   b. Unlike him, will give almost no attention to process by which conceptual scheme attached to scientific developments diffuses to the general educated world -- what much of his book is about

II. *De Revolutionibus Orbium Coelestium* (1543)

A. From Basic Ptolemaic to Basic Copernican

1. Because Copernicus (like Ptolemy) tells us almost nothing about the development of his ideas, it is unclear what led him to propose heliocentrism
   a. His chief criticisms of Ptolemy -- equant, moon, factors necessitating calendar reform, failure to determine a systematic relationship between distances and periods, and residual errors in latitudes and longitudes -- have nothing as such to do with heliocentrism
   b. In particular, of these, objections to the equant and other violations of uniform circular motion seem to have been most important to him
   c. So, we are free to speculate about the origins of his heliocentrism; my preferred line is from Swerdlow because of its textual basis (Gingerich's is a simplified version of it)
2. An old idea that link between inner planets and sun can be accounted for by having them revolve around the sun
   a. Would explain why Mercury and Venus never far from sun
   b. Maximum elongations then a measure of their orbits around sun
   c. Copernicus might have considered this move in order to avoid an epicycle on an epicycle in replacing the equant for Venus
3. Suppose one tries to do this; how should Ptolemy's deferent and epicycle then be interpreted?
   a. Epicycle simply the orbit of Venus around the sun, with retrograde motion of e.g. Venus because moving around sun
   b. Deferent now the orbit of the sun around earth
4. Now suppose try to extend this idea to outer planets, just to see what happens, and again ask how the two circles should be interpreted
   a. Epicycle cannot be the orbit of e.g. Mars around the sun
   b. But as Gingerich's diagram shows, mathematically get the same result if interchange epicycle and deferent, putting epicycle on the inside
   c. Then deferent the orbit of e.g. Mars around the sun, and epicycle the orbit of sun around earth

   d. In the process explaining why the locations of the outer planets on their epicycles are always aligned with line joining earth and mean sun!

5. Problem: spheres crossing one another -- e.g. sphere of Mars crosses the sphere of sun -- so that solid crystalline sphere picture must be abandoned
   a. Solution to problem: let earth go around sun rather than sun around earth, appealing to relative motion argument; then no spheres intersect
   b. And Ptolemy's (Apollonius's) two circle explanation of retrograde motion transformed into explanation in e.g. Kuhn -- earth and planets overtaking one another (see figure in Appendix)
6. Swerdlow: in a brief aside in Book XII of the *Almagest*, Ptolemy says that epicycles not needed to account for retrograde loops of outer planets; an eccenter can do just as well, but this equivalence fails in the case of the inner planets
   a. Regiomantanus, in his *Survey of the Almagest*, shows in detail how to do this for the outer planets and then corrects Ptolemy by showing how to do it for the inner planets as well
   b. Perhaps this got Copernicus thinking about how he might get rid of Ptolemy's epicycles
   c. The one major thing then still needed is to re-locate the mean sun to (revolving) location of the eccenter -- Copernicus's major step on this account, making the five planets orbit the sun
   d. Last step of having the Earth orbit the sun rather than the sun orbit the Earth then needed to prevent intersection of crystalline spheres, as above

B. A New Result: Relative Orbital Radii

1. The Copernican system adds a dramatic new feature to Ptolemaic astronomy -- the sizes of the planetary orbits, relative to one another, are now fixed
   a. Inner planets: r/R = (mean distance from sun)/(mean distance of earth from sun)
   b. Outer planets: r/R = (mean distance of earth from sun)/ (mean distance from sun)
   c. Distances now fixed relative to distance between earth and sun
2. By contrast, Ptolemy simply set R = 60 in every case, for nothing in the planetary theory imposed any restrictions on the relations among the radii of the various deferents
   a. Theory left complete freedom on setting these radii
   b. Measured parallax for moon, parallax (wrongly) inferred from eclipse for sun, but no direct basis for any of the others
3. Let the mean distance from the earth to the sun = 1.0 -- a basic measure, called (now) the "astronomical unit"
   a. Then all other mean distances determined with respect to this measure -- indeed, can be inferred from Ptolemy's r/R values without any new observations at all
   b. Copernicus's values versus Ptolemy's and "correct": Mercury, 0.360 (vs. 0.375 and 0.3871); Venus, 0.719 (vs. 0.719 and 0.7233); Mars, 1.520 (vs. 1.519 and 1.5236); Jupiter, 5.246 (vs. 5.217 and 5.2027); Saturn, 9.164 (vs. 9.231 and 9.5719)

4. Another version of the same point: in Copernican system can use triangulation to infer distances from sun to planet relative to earth-sun distance
   a. From observation know geocentric longitude of planet, and from theory know heliocentric longitudes of earth and planet at the time of the observation
   b. Thus have angles SEP and ESP, and hence the triangle SEP uniquely determined, given earth-sun leg at the time of the observation
   c. In other words, if Mars is taken to be going around the sun and its heliocentric longitudes can be taken as given, have a solution to the problem of the distances of the planets from both the sun and the Earth at all times relative to the distance between the latter two
   d. In Ptolemaic, the presumption that both the sun and the planets are going around the Earth left no way of determining angle ESP; had only SEP (from observations), and that was not enough to determine the distances
5. This the most dramatic example of a feature of the Copernican system that shows up repeatedly: aspects interlock far more than in Ptolemaic, so once a certain aspect defined, entails related aspects
   a. Much more freedom in Ptolemaic: structured in a way that constantly gives freedom for superposing one aspect on another
   b. By contrast, any move made in developing Copernican tends to have ramifications blocking or constraining further moves to a notably greater extent
   c. Feature of system that Copernicans most emphasized, invoking it as evidence in favor of it
   d. Equally the feature that led to some inconsistencies in *De Revolutionibus*, where Copernicus took over numbers from Ptolemy without always adjusting them to others

C. Orbital Details: Eccentricity and the Equant
1. So far, only a first approximation to longitudinal motion, akin to Apollonius's; now have to address all the systematic anomalies in retrograde motion
   a. Otherwise, Copernican no more accurate than Apollonian -- i.e. not even comparable to Ptolemaic
   b. E.g. need to account for such things as why Mars apparently moves 40 percent faster in Capricorn than in Cancer, with retrogrades half as long in longitude in Capricorn as in Cancer
2. Copernicus takes over eccenter from Ptolemy: sun not at the center of any of the planet orbits, but off center by different amounts for each planet
   a. Two ways of measuring eccentricity now: relative to center of earth's orbit (mean sun), or relative to actual sun
   b. Copernicus adopted mean sun as the reference point
3. Copernicus rejects Ptolemy's equant, mostly because it is incompatible with uniform circular motion
   a. Indication of how much Copernicus tied to Ancient and Medieval mathematical astronomy, in contrast to modern astronomy, as initiated by Tycho and Kepler

   b. (Neugebauer and Swerdlow suggestion: Copernicus as "the most noted follower of the Marāgha School")

4. Copernicus's solution to replacing the equant from the Arabs (in particular, Ibn al-Shāţir: small (minor) epicycle of radius e/2, combined with eccentricity of 3/2 Ptolemy's eccentricity, produces the same varying motion effect in longitude, but now with uniform circular motion
   a. Preserves the effect of Ptolemy's equant, so features can be taken over from it, simply translating
   b. Actual orbit no longer a circle, but what Copernicus calls a "quasi-circle"; hence some empirical difference, though not one then immediately amenable to observation
   c. I.e., the two devices are not strictly mathematically equivalent, but they are equivalent so far as observed (geocentric) longitudes were concerned
   d. Historically Copernicus given credit for this, for Ibn al-Shāţir's work was not known in Europe
5. Notice how Copernicus's basic account of planetary longitudes ceases to be so simple once the higher order anomalies are addressed
   a. Eliminate major epicycles, but replace with minor epicycles, resulting in more or less the same number of circles for the planets as in Ptolemy
   b. But does do away with one independent ingredient, the major epicycle, and does away with the hated equant
   c. And achieves a system strictly limited to compounds of uniform circular motions

D. Copernicus's System: the Three Motions
1. Basic Copernican system of course has sun in middle, earth and other planets going around sun, moon going around earth
   a. Basic phenomena of retrograde motion explained without recourse to epicycles etc.
   b. Eccentricity, epicycles, and even epicycles on epicycles then to account for "higher order" anomalies
2. Copernicus has the earth itself engaged in three primary motions -- the "triple motion of the earth"
   a. Diurnal motion: rotation on axes tilted with respect to the plane of the earth orbit (roughly 23 deg)
   b. Annual motion of the center of the Earth, describing the ecliptic circle around the sun
   c. Conical motion of axis to explain change in seasonal position of the sun
   d. (An unnecessary addition, for didn't see that axis could just retain the same orientation in space throughout its orbit; probably from picturing axis fixed to crystalline sphere)
   e. To account for precession of equinox, Copernicus had this motion of the axis slightly asynchronous with the annual motion
3. Three motions conceptually revolutionary, for Aristotelian physics held that no body could undergo more than one simple motion naturally at a time
   a. Copernicus himself did not advocate the abandonment of Aristotle's "mechanics"

   b. Rather, suggested minimal changes to it
4. Copernicus's earth orbit far more complicated than just a circle, however, in part to account for the variation in the sun's apparent motion, but also to account for a number of other anomalies that are mostly figments arising from bad data
   a. Orbit a circle, eccentric with respect to sun, with eccentricity changing with time (over 3434 years), from 0.0321 to 0.0417
   b. One of his ways to produce this effect: center of circle is itself on a circle -- see Kuhn, p. 170
   c. Eccentricity of other planets referenced to moving center of earth orbit, the mean sun
   d. (Copernicus suffered under the burden of incorrect observations even more than Ptolemy, usually as a consequence of someone wrongly concluding that some anomaly beyond those noted by Ptolemy was entailed by various observations)
5. Copernicus's additions and changes to Ptolemy were sometimes real improvements, such as the shift from the tropical to the sidereal year as the basic unit of time and shift to trepidation for precession of equinoxes
   a. But many of the additions and changes were spurious, often resulting in complexity beyond Ptolemy, as in the case of the theory of the sun
   b. These changes notwithstanding, the vast majority of the planetary theory is primarily just a mathematical transformation of Ptolemy's system
6. Reinhold's Prutenic Tables, issued in 1551, only 8 years after *De Revolutionibus* was published, became the standard reference if only because they were more up to date than the AlfonsineTables
   a. Restarting of clock, eliminating errors in precession
   b. But otherwise not dramatically more accurate
   c. Reinhold himself not committed to heliocentrism, but thought Copernicus's other reforms of Ptolemaic important enough to warrant tables comparable to Ptolemy's *Handy Tables*

E. Comments on Some Other Details of the System

1. The earth's orbit is not the only example in which the Copernican system exhibits complexities or failings of a serious sort
   a. Copernicus himself keeps emphasizing the elegance of the system in Book I, but that elegance tends to get overridden with details in later books
   b. "Anyone who thinks that Copernican theory is 'simpler' than Ptolemaic theory has never looked at Book III of *De Revolutionibus*" – Swerdlow &Neugebauer, p. 127
2. Copernicus's theory of latitudes is not the least bit more successful than Ptolemy's, and from a physical standpoint it is generally worse
   a. Instead of using independent data or Ptolemy's data, used Ptolemy's calculated values!
   b. Inclinations of orbit vary in accordance with motion of earth -- this to replace Ptolemy's inclination of the epicycle

c. A messy, unsuccessful account, largely developed around 1514 and then never improved

d. Kepler especially critical of this aspect of Copernicus

3. Does succeed in eliminating the implication that the moon comes much closer to the Earth than it obviously does by devising an alternative way to deal with the higher inequalities

a. Basic model of moon like Ptolemy's -- minor epicycle

b. But now adds, following Ibn al-Shāţir, an epicycle on top of this minor epicycle to account for anomalies Ptolemy discovered in the quadrants and octants

4. Copernicus apparently attempted to get better observations of Mercury, but failed, and hence ended up transporting Ptolemy's account of Mercury into his system with appropriate transformations

a. Uses a minor epicycle to replace equant, but then adds epicycle on epicycle and has radius vectors vary in length to accomplish the same thing that Ptolemy's inner circle did

b. Thus the worst "Rube Goldberg" aspects of Ptolemaic planetary theory – latitudes and the theory of Mercury -- carried over into Copernican, though in the form of Ibn al-Shāţir

5. One really must feel some sympathy for Copernicus, spending 30 years trying to achieve improved accuracy over Ptolemy, but having to introduce more and more complexity simply to match Ptolemy in accuracy

a. Of course, what was really needed was a total reform of astronomy from the ground up

b. With entirely new, highly reliable observations as a key element of that total reform

c. Something Tycho came to realize in his early 20's, after finding that the Alfonsinetables mis-predicted the conjunction of Jupiter and Saturn in 1563 by around a month and the Prutenic tables mis-predicted it by several days

F. Copernicus’s Triangulated Distances of the Planets

1. Where Ptolemy had used observations within retrograde loops and hence near opposition to determine his ratios of epicycle to deferent radii, Copernicus used observations away from opposition

a. The observations in question allowed him to use triangulation to determine the ratios, in the process yielding distances, at the time of observation, of planets from both the sun and Earth

b. Illustrated (see Appendix) by the triangle ELF with his first example, for Saturn

2. In his figure E represents the mean sun, L the Earth, F the planet, EL the radius of the Earth’s circular orbit about the mean sun, AD=BD=CD the radius of the circular deferent of the planet, and AF= e/2 = ED/3 the radius of its minor eipicycle

a. Observation gives the location of F along the zodiac as seen from L, i.e. the geocentric longitude of F; Copernicus’s theory, with ED already established, gives him the location of F along the zodiac as seen from E, that is the heliocentric longitude of F with respect to the mean sun

b. The difference between these two gives angle EFL; his heliocentric longitude for F together with the heliocentric longitude of L from his theory for the Earth gives him angle LEF

c. Therefore observation plus his theoretical heliocentric longitudes determines the triangle ELF

3. From that Copernicus obtains the ratio of the mean distances of the planet and the Earth from the mean sun: 1090/10000 in the case of Saturn, "very little different" from Ptolemy's 0.1083
    a. Taking the Earth-Sun radius to be 1.0, it also gives him the distances of Saturn from the mean sun and the Earth at the time of observation: 9.601 and 9.254; and given the eccentricity of the true sun from the mean sun in the Earth orbit, the distance of Saturn from it as well
    b. Ptolemaic astronomy could obtain such a relative distance from the Earth, but had no means of obtaining a relative distance from the mean (or true) sun
4. Still, the comparatively good agreement with Ptolemy for the radius ratio for Saturn should not be surprising, for it was essentially built into Copernicus's theories of heliocentric longitudes
    a. The triangulation presupposes those theories, making them theory-mediated in a manner that comparison with Ptolemy amounts to just a check on Copernicus's transform of Ptolemy
    b. For that reason, even repeated triangulations with different observations, yielding a trajectory of Saturn around the sun, cannot show that Saturn, contrary to Ptolemy, describes a nearly circular orbit about the mean sun
    c. What the comparison with Ptolemy showed, therefore, was that the added complications still left the overall system observationally consistent with Ptolemy's
5. As the Copernican account of the distance to Saturn (in Appendix) displays, the combined orbits of the Earth and outer planets involved complications absent from Ptolemy's account
    a. These made Copernicus's account difficult to understand, witness whereunto is the struggle Kepler had in the 1590s, turning to his teacher Maestlin for help
    b. Maestlin's account, published as an Appendix to Kepler's first book, was likely the best explanation for Copernicus's individual orbital theories from the time, even though strictly speaking it was an exposition of Rheinhold's calculations for the Prutenic Tables
6. But what if there were some independent way of verifying Copernicus's theories of heliocentric longitudes, or even better some account of those longitudes that does not presuppose those theories
    a. Then any nearly circular trajectory for Saturn determined by triangulations using sequences of observations would be evidence that Saturn describes a nearly circular orbit around the mean sun, and not at all so around the Earth
    b. And observations of sufficient precision might even provide evidence deciding between his minor epicycle and a Ptolemaic equant for that heliocentric orbit

G. Philosophic Issue: Grounds for Preferring It?

1. Given all these features and shortcomings, the obvious question is why anyone ought to have preferred the Copernican system before, say, 1600
    a. Several key astronomers did, often with intensity, and they managed to persuade some of their best students to become Copernicans
    b. E.g. Rheticus, Digges, Reinhold, and most notably Mästlin, Kepler's teacher

c. Though some of these -- e.g. Reinhold -- not committed to the reality of heliocentrism, only to the many other reforms

2. Definitely no reason for preferring it before 1600 on the basis of its being more accurate than a correspondingly updated Ptolemaic theory
   a. Comparatively little interest in specific inaccuracies before 1575, so no collection of growing discrepancies until Tycho and his followers begin developing one
   b. But do not need comparison of observation and theory to realize that Copernicus not more accurate, for to too great an extent just a transformation of Ptolemy, as every trained astronomer could see (especially after Mästlin's explanation in Kepler's *Cosmographicum Mysterium*)
   c. Though should note some corrections, like treatment of moon; but these irrelevant to heliocentrism
3. Usual reason given from 17th century on is that Copernican theory more simple than Ptolemaic, and hence preferable
   a. Philosophic worry: why should more simple theory be preferable
   b. Willing to put this worry aside for the moment, and trust intuitive sense that simpler theory preferable
   c. Don't gain much, for still have to face further philosophic question: what do we mean when we say one theory -- e.g. Copernican -- is simpler?
4. Some, like Galileo and even Copernicus in his opening passages, argue that Copernican simpler in the sense that the basic phenomenon of retrograde motion can be explained without (major) epicycles
   a. I.e. to the extent that we ignore real complexities in the observed motions, Copernican theory is simpler, at least in that it requires fewer circles and hence has fewer degrees of freedom
   b. But as soon as we consider the further anomalies, Copernican ceases to be clearly simpler: at least as many circles, though eliminating the equant, and often more circles
   c. And do not fail to notice that the moon now adds a further kind of motion with consequent question: why does the moon circle the Earth when everything else circles the sun?
   d. And the earth itself is engaged in three separate perpetual natural motions
5. Copernican not simpler from a calculational standpoint, nor is it simpler in the sense of raising fewer worries about the underlying physical mechanism
   a. Eliminating equant allows truly uniform circular motion throughout, which may have seemed to pose less of a physical problem through appeal to crystalline spheres
   b. But note that epicycles on epicycles would have provided the same thing for Ptolemy, as shown by Ibn al-Shāţir, and Copernicus allows this in his theory of the moon
   c. And with all the eccentricities and special devices, no reason to think easier to give an account of the underlying physics
6. Copernicus himself emphasizes another "aesthetic" feature that is at least related to simplicity,

namely the way in which different aspects interlock to form a system, so that many effects that have to be individually built into Ptolemaic theory are obtained "for free" in Copernican

a. E.g. why planets brightest during retrograde, why Venus and Mercury never far from sun, why motions on epicycles of outer planets have to be keyed to mean sun, etc.

b. A type of appeal that still carries weight in science today, and certainly was a major factor among converts in the century after *De Revolutionibus*

  (1) The "Pythagoreanism" of Copernicus (a term applied derogatorily by the Church at the time)

  (2) But methodological principle can be stated independently of appeals to classical authority

c. Principle: a theoretical move put forward to account for some one phenomenon gains support when it provides, as corollaries, answers to why-questions regarding other phenomena

  (1) The more such answers to why-questions "for free" and the wider the range of phenomena so covered by the answers, the better

  (2) Theoretical moves that do this preferable to ones that do not

d. An intuitively universally accepted methodological principle, but controversy in philosophy of science over why it is a proper principle

  (1) On view of science as inference to the best explanation: a unified explanation of many separate features better than separate explanations for separate feature

  (2) On a Popperian view of science: wider the range of items covered by a theoretical move, the more opportunites to falsify it

H. Another Answer: Opening a New Path for Research

1. Let me suggest an alternative, extremely sophisticated reason why Copernican ought to have been preferred to Ptolemaic before 1600

  a. Doubt that anyone at the time ever came close to verbalizing this reason, for too much at odds with how people talked about astronomy etc. at the time

  b. But still might have been what tacitly persuaded several of the most sophisticated astronomers to abandon Ptolemy well before decisive empirical evidence to do so started coming in

2. If one adopts the Copernican system, even provisionally, then in a position to use triangulation to infer at least rough sun-planet distances from observations, which ought to coincide with distances inferred from retrograde motions

  a. Inference theory-dependent, for need to use heliocentric longitudes from theory, and need to include eccentricity and varying distance from earth to sun

  b. At first glance, then, question-begging

  c. But suppose Ptolemaic true; then extremely unlikely that distances obtained via triangulation, using heliocentric longitudes that do not beg the question, will be well-behaved at all, much less will support conclusion that planets basically in circular orbits about sun

   d. Then over time can use observations to keep checking distances inferred from retrograde loops, with expectation that if as far off the track as Ptolemaic, difficulties will emerge

3. More important, if heliocentric longitudes can be made precise and a large number of careful observations are then used to obtain triangulated sun-planet distances, may be able to bring evidence to bear on the precise trajectories of the planets
   a. E.g. a circle, as equant would have it, or a flattened circle, in accord with minor epicycle
   b. Difficult for two reasons: small errors in observations can lead to significant errors in computed distances; and small errors in orbital parameters can have the same effect
   c. Even so, by adopting Copernican, even provisionally, have at least a hope for beginning to assess basic circular motion hypothesis, as well as minor epicycle versus equant
4. Nothing like this in any way possible on Ptolemaic, for no way to use triangulation to look for whether distances conflict with circular motion assumption
   a. Circular motion assumption a working hypothesis, underlying both Ptolemaic and Copernican
   b. But with Copernican, a working hypothesis that in the long run may be open to systematic empirical assessment and refinement through triangulations
   c. In terms of its potential for developing further empirical evidence that will allow refinements of initial assumptions, Ptolemaic at a dead end in a way that Copernican is not
5. Reason for preferring Copernican, then, is not that it is true or more likely to be true, but that (1) it can be safely adopted and (2) by doing so, open the possibility of bringing empirical data to bear that will address some underlying assumptions
   a. Safe because, if Ptolemaic right, triangulated distances with independently determined heliocentric longitudes will likely be so poorly behaved that will see this promptly
   b. Of value because for first time potentially less at mercy of an initial assumption
   c. In other words, by adopting Copernican, just as a working hypothesis, there is a promise that everything will come out in the wash -- a promise that is not offered by Ptolemaic
6. Suggested methodological principle: if a theoretical claim opens the way to bringing (theory-mediated) empirical evidence to bear on questions that have heretofore resisted empirical answer, then the claim ought to be accepted as a working hypothesis and ongoing research be predicated on it, provided that there are adequate safeguards against being systematically misled (down a garden path) by the research in question
   a. Theory as tool in research, even when not exactly true
   b. Evidence accrues to it from the success of the research predicated on it in yielding stable convergent results
   c. Becomes entrenched in science, usually in a refined form, not because of the initial evidence for it, but because of this accruing evidence
   d. (The beginnings of a response to Kuhn's claim that evidence plays not so great a role in science)

III. Tycho Brahe and Observational Astronomy

A. From Simple Copernican to Simple Tychonic

1. Not surprisingly, given the nature of academics, Copernicus's new system led others to propose further alternatives, giving rise to a whole host of new systems
    a. E.g. systems in which just the inner planets orbit the sun, while everything else, including the sun, orbits the earth
    b. Most of these denied the triple motion of the Earth, on grounds both empirical -- no evidence for any motion -- and philosophical -- only one simple natural motion to any body at a time
2. The most important of these new systems was Tychonic, which Tycho put in print in 1588
    a. Five planets orbit the sun, with Venus and Mercury moving in opposite direction from the others
    b. Sun and moon orbit the earth, with Copernicus's moving eccenter of the mean sun shifted to an equivalent minor epicycle on top of the epicycle replacing the equant
    c. Result: all eight bodies always in the same relative position as in the Copernican system, ignoring small differences in their respective orbital elements
3. There are several different paths of thought by which to arrive at the Tychonic system, especially following the Copernican, so not surprisingly, several different people claimed to have thought of it
    a. Tycho himself was accused of having stolen it from various people, including from Copernicus -- accusations which he vehemently denied
    b. Based on Copernicus's notebooks, he almost certainly considered it at one point (see above, and Gingerich or Swerdlow)
4. Let me propose one way of arriving at it, given the Copernican system: suppose that one becomes really impressed, for whatever reason, by the way in which the Copernican system fixes relative planetary distances
    a. To allow that there is a substantial grain of truth to the Copernican distances, even provisionally, is to grant that the five planets are orbiting the sun
    b. But, as noted earlier, it does not entail that the Earth is also orbiting the sun, for perhaps instead the sun, accompanied by its five planets, is along with the moon orbiting the Earth
5. Tycho himself seems to have arrived at his system from one with only Venus and Mercury orbiting the sun by measuring (via parallax) the comparative distances of Mars and the sun in 1582
    a. Concluded that Mars closer to earth at opposition than the sun, contrary to Ptolemaic theory
    b. Still resisted Copernicanism because saw no evidence of movement of the earth
6. The obvious problem with the five planets orbiting the sun and the sun orbiting the earth is that the orbits in question cut across one another in a way inconsistent with solid celestial spheres
    a. Earlier we suggested that this was what had led Copernicus to his system
    b. Tycho tells us that abandoning solid celestial spheres was the hard step for him to take
7. But in mid 1580s Tycho developed what he thought was good evidence against solid celestial spheres

through his and others' careful measurements of the comet of 1577 and his reconstruction of the path it was following

a. Strong evidence from parallax inferred by him and by Mästlin that it was extra-lunar: from 150 to more than 1500 Earth-radii

b. But 1500 Earth-radii beyond the number inferred (mistakenly) from lunar eclipses for the distance to the sun, so that must be crossing at least Venus's orbit

c. But if comets can cross planetary orbits unimpeded, then no solid crystalline spheres

d. (Notice here the willingness to abandon the entire underlying conceptual scheme in spite of having nothing to replace it)

B. Tycho Brahe and His Alternative System

1. Tycho (Tygge) Brahe (1546-1601), a child of one of the most wealthy and powerful noble families in Denmark, was the foremost figure in astronomy in the second half of the 16th century, and not just because of his system

> For as long as histories of astronomy have been written, heliocentrism has been regarded as the hallmark of modern astronomy. In accordance with this tradition, Nicholas Copernicus (1473-1543), as the effective originator of heliocentric doctrine, has been hailed as the founder of modern astronomy. In fact, however, except for the motion of the Earth, the revolutionary element in Copernicus's work is very small; in most respects his *De Revolutionibus* (1543) follows Ptolemy's *Almagest* so closely that he can equally well be regarded ... as the last great practitioner of ancient astronomy. On this view, it was the seventy-year period following Copernicus's death in 1543 that actually saw the transition to modern astronomy. And insofar as any such development can be attributed to the influence of one person, that transition was wrought by the ideas and efforts of the Danish astronomer, Tycho Brahe. (Thoren, *Cambridge History*, p. 3)

2. Tycho first became a recognized major figure in astronomy when he "discovered" and announced a new star -- a supernova -- first noted on 11 November 1572

a. Completely in conflict with Aristotelian view that celestial realm is unchanging, and hence a conceptually revolutionary step

b. Followed briefly thereafter by the brilliant comet of 1577, his studies of which further undermined the old cosmology

3. Tycho's cosmological efforts, the first of his three major contributions to astronomy, reached print in 1588 in his 800 page *De Mundi Aetherei Recentioribus Phaenomenis*

a. Mostly on the comet of 1577, including detailed observations, a carefully argued determination of its path, and long critiques of many of the more than 100 other books that had been published on the comet

b. A chapter hastily added at the end presented the Tychonic system

4. Tycho's second main contribution was a revolution in observational astronomy

a. In 1576 King Frederick of Denmark offered to set aside the island of Hven for an "observatory" and provide money for instruments and annual stipends to support those working there

b. Over next 9 years observatory developed, and numerous special observing instruments designed by Tycho and crafted, first by others, and then in his own shop -- accurate to within 1 min of arc

"By 1585 he had established the modern prototype of the scientific research institute, featuring housing, instrument-making works, instruments, observatories; a collection of artisans, students, unpaid assistants, and salaried co-workers to staff his manifold activities; and even papermaking and printing shops to publish his results." (ibid., p. 3)

5. Third main contribution: starting from 1576 on, but especially from 1585 until 1597, when conflict with the new young King led him to move, a huge collection of observations to a level of accuracy beyond anything ever before

   a. Observations by himself and by trained assistants for roughly 85 nights per year over 12 years, supplementing daytime observations that had extended from 1576 on

   b. Four large volumes listing observations in Dreyer's edition of his works

   c. Nothing remotely like this body of data ever before

   d. Began setting up a second observatory in Prague in 1599, but died unexpectedly in 1601

6. In addition to these main contributions, a large number of lesser contributions

   a. An much improved theory of the sun, involving simply an eccentric circular orbit

   b. Discovery of a new important inequality of the moon (Tycho's), as well as three other lesser inequalities -- resulting in a much improved lunar theory (jointly with Longomontanus)

   c. A star catalog with 777 stars, to which planetary observations could be referred, finally replacing Ptolemy's after 14 centuries

C. The Empirical Impasse in Astronomy

1. The Tychonic system has all the sun, moon, Earth, and planets at all times in exactly the same positions with respect to one another as the Copernican system

   a. Hence any observation made not just from Earth, but from the moon, the sun, or any of the planets of one another will have exactly the same evidential import for both systems

   b. Contrast this with the Ptolemaic, for which observations made from other planets would distinguish it from the Copernican

2. Tycho nevertheless devised an empirical test to distinguish between his system and the Copernican: annual parallax of the stars

   a. Made several careful measurements, including with instruments good to within 1-2 min of arc, and observed no parallax at all

   b. Concluded that either the earth is not moving around the sun or that the stars are incredibly more distant than Saturn -- more than 3500 a.u. vs Saturn's 9

3. Copernican response, already formulated by Copernicus, was to accept the second alternative

   a. Idea seemed crazy to Tycho -- why would God have created this vast empty space between the orbiting bodies and the stars?

b. Nevertheless, as he well recognized, this was not an empirical argument, and once the vast gap to the stars was accepted as a possibility, no astronomical observation within the planetary system would distinguish between the two systems

4. A classic example of the difference between data and evidence: same datum evidence for no motion for Tycho, and evidence for great distance to stars for Copernicans

5. Thus at an impasse: both systems in effect make -- with suitable values of elements do make -- the same observational predictions, and hence the primary evidence is exactly the same for both of them

   a. Every key factor or consideration favoring the Copernican was equally a factor or consideration favoring the Tychonic

   b. Any revision or refinement of the Copernican could immediately be incorporated into the Tychonic, and vice-versa

   c. So two seemingly "empirically equivalent" systems that are by no means physically equivalent: the physical mechanisms underlying the one would almost certainly be totally different from those underlying the other

6. Kuhn talks of the Tychonic system as "a compromise", which it may well have been for a great many of those who adopted it over the next half century

   a. But it was not a compromise in Tycho's mind at all

   b. Rather, it offered all the advantages of the Copernican, with none of the drawbacks

D. The Value of More Precise Observations

1. Tycho more than anyone appreciated the empirical impasse that had been reached between the two systems, but this in no way suggested to him that extremely accurate observations were of no interest

   a. Perhaps no one before him was ever so committed to empirical evidence -- to the idea that empirical evidence should be the ultimate arbiter

   b. And surely no one before him showed a similar appreciation for the value of extremely precise observations

2. Had come to appreciate latter from efforts on comet of 1577, and then subsequently while setting up the observatory on Hven

   a. Painstaking observations of successive comet positions on 30 cloudless nights, then a determination of the trajectory in which he made -- and reported -- 7 trials for each element -- an example of the modern practice of using redundant data and admitting scatter in observations

   b. Reached conflicting values for the latitude of Hven, using two different methods to high precision, which made him realize not only the need for redundancy in observation, but also the need to correct observations

3. In particular, Tycho began correcting observations not only for the effects of parallax (not observing in line with the center of the earth) -- something that Ptolemy had done as well for the moon -- but also for refraction of the atmosphere

a. Parallax corrections require at least an estimate of distances from the earth in earth-radii, which Tycho (and all before him) grossly underestimated

b. Had to infer what the magnitude of the refraction effect was from discrepancies within data after correction for parallax

c. Ended up with good corrections for anything above 45 deg (where the true correction is less than 1 min), but over-corrected for things below 45 deg (because of excess parallax correction)

4. Saw value in precise measurements of planetary positions, in spite of the empirical equivalence of the two systems, because he saw the possibility of determining "the true motion" of the five planets

   a. Both systems have them going around the sun, and, as Tycho knew better than anyone, neither system gave anything like values of latitude and longitude correct within observational error

   b. Had good reasons to be suspicious of past data, and hence to be suspicious that one source of shortcomings in all the accounts of planetary motion was bad data

   c. Saw bad data equally as a possible source for the complexities of Copernicus's and his systems

5. A reform of astronomy from the ground up, in large part because he saw the added potential for compelling empirical arguments that truly precise measurements would yield

   a. And with it a reform of observational practice, based on careful study of observational practices and their shortcomings

   b. And a reform in the use of instruments and the quality of their preparation

E. Tycho's Observational Program: 1576-1597

1. Tycho's overall observational program extended to many different areas

   a. E.g. "From 1578 until well into the 1590's, he recorded meridian altitudes for more than a hundred noons a year, usually with several different instruments." (Thoren, op. cit., p. 12)

   b. From 1581 to 1597 "Tycho averaged some eighty-five night-time observing sessions annually,...four-fifths of them...during the dark months of September to March" (ibid. p. 14)

2. "Perhaps ten first-line (but variously specialized) instruments, and about the same number of less successful ones which would still have been the pride and joy of almost any astronomer before 1700." (ibid., p. 12)

   a. All sorts of special precautions -- e.g. in second observatory built in mid 1580s, instruments mounted below ground to protect against the wind

   b. The best were capable of measuring to within 1 arc min

   c. Including, for example, a 7 foot quadrant that was used mostly to check clocks allowing him to maintain time to within about 15 min

3. Trained observers and used them to cross-check one another, as well as insisting on repeated observations

   a. Based on his own studies concluded that observations were within 2 min of arc

   b. Not always that good, but usually so, and fairly consistently within 4 min of arc

c. Errors from wrong parallax and atmospheric refractions corrections no more than 1½ min

4. Laid out a whole program of observations -- planets, stars, sun and moon -- that would have taken decades to complete, and consequently was not completed

   a. In part because of his leaving Hven for Prague, where facilities were never comparable, but also because of his early death

   b. And also because he delayed the start of some observational programs until he had instruments he was satisfied with

5. Astronomy changed forever by this effort, not just because of his data and what Kepler was able to do with them, but also because others followed him, yielding other growing bodies of first-rate data

   a. Many of those who followed him either assisted him at Hven or had ties to those who did, so that the practices and standards Tycho instituted diffused throughout Europe well before his data were published (see Christianson's "Biographical Directory")

   b. Data themselves, not merely because of Kepler's use of them, changed the goal of mathematical astronomy from giving an account of the principal orbital phenomena to one of devising an account that agrees with latitudes and longitudes to within observational accuracy!

   c. Tycho's data remained the standard for most of the 17th century in spite of the introduction of the telescope into astronomy in 1609

   d. Many decades before technology of telescope reached the point of yielding more accurate observations of latitude and longitude than Tycho's

IV. The Crisis in "Mathematical" Astronomy

A. The Three Chief World Systems in 1600

1. By 1600, three chief (generic) world systems, the Ptolemaic, the Copernican, and the Tychonic

   a. Other systems as well -- e.g. hybrids such as only inner planets orbiting the sun, some pre-dating Tycho's publication of his system -- but of less interest then and now

   b. Different versions of these three systems -- e.g. Copernicus's own version, like Ptolemy's and Tycho's, versus variants of them, so that phrases like 'the Tychonic system' were ambiguous

   c. (The "semi-Tychonic system" in which Earth rotates diurnally)

2. Philosophic and aesthetic considerations were adducible in support of each of the three, especially the Copernican and the Tychonic, with theological considerations against Copernican

   a. The Copernican: the principal reasons given by Copernicus himself, viz. the way in which aspects interlock and motions compounded out of uniform motion on circles

   b. The Tychonic: the very same reasons, plus no movement of Earth, though also no crystalline spheres and hence need for a new cosmology

   c. The Ptolemaic: for 14 centuries the standard, with a cosmology of sorts behind it, and still setting the standard, for no decisive evidence against it and no alternative notably more accurate

3. As of 1600, there was no decisive empirical evidence against any of the three (vis-a-vis the others)

a. Not clear to anyone even how to go about developing empirical evidence against either the Copernican or the Tychonic versus the other

b. But not yet any direct empirical reason to discard the Ptolemaic in favor of either of them

c. All three could equally well accommodate any set of observed (geocentric) longitudes and latitudes, for with respect to latitudes and longitudes each could be mathematically transformed into either of the others to yield exactly the same calculated longitudes and latitudes

4. At the same time, as was becoming especially evident to Tycho and hence increasingly evident to the number of professional astronomers in contact with him, no version of any of the three came remotely close to being within observational accuracy

   a. Errors of 1-2 deg, and even larger, in latitude and longitude not uncommon

   b. This versus an old observational standard of 10-20 min, and the new standard of within 5 min

5. Finally, the three systems make different claims about what would be observed from fixed stars, and hence too different physical claims, requiring substantially different underlying physics

   a. Some who held that all motion is relative were prepared to say that the Copernican and Tychonic were but one system, with no fact of the matter distinguishing them (e.g. Leibniz)

   b. But most were not willing to say that there is no fact of the matter about which objects are at rest and moving (relative to fixed stars), and for them all three systems were physically incompatible

   c. Worse, it was unclear what the physics was in each case, once the full detailed model was taken into account, for each one was mercilessly complicated in one respect or another, with no apparent way of eliminating the complications

B. Crisis: Epistemic Status of Astronomy

1. Picture the situation from the point of view of a professional astronomer, typically someone very bright who had found the intellectual challenge of mathematical astronomy exciting

   a. The most difficult field in the curriculum led to its drawing people enamored with the challenge

   b. And with it enamored with the prestige of the discipline

2. For 1400 years astronomy had been the "highest" discipline, the most advanced of the technical fields, setting the intellectual standards for the others

   a. Even in Plato's *Republic* the highest technical field, beyond geometry and simple mathematics

   b. And in the 16th century the highest along with theology and philosophy in some people's eyes

3. By 1600 the discipline was being openly ridiculed by people in other disciplines -- particularly people in the by then beleaguered discipline of theology

   a. Standard criticism: merely engaged in mathematical play, with no element of substantive truth behind any system at all

   b. I.e. astronomers were doing nothing more than inventing neat ways of computing approximate representations of celestial phenomena, and there is an indefinite number of different such representations approximating the phenomena to more or less the same level of accuracy

c. So talk of truth no more appropriate than talk of truth with a game

4. Those trained in astronomy had the keenest appreciation of the bite of this line of criticism, for they were in the best position to realize how hard it was to bring any decisive evidence to bear against any one of the systems

    a. They knew the extent to which each of the systems could be mathematically transformed into the others, for they had been doing such transformations

    b. They fully appreciated the way in which the Copernican and Tychonic systems were, at least in effect, observationally equivalent

    c. And they knew how easy it was to adapt any one of the systems to any new finding -- e.g. the Copernican response to the lack of annual parallax

    d. And those with access to Tycho's observations knew how much the longitudes and latitudes calculated in all the systems tended to deviate from observations

5. Thus from the point of view of those in the field, astronomy was not only in a state of crisis, but the principal question raised by the crisis was whether the field had any legitimate claim to elevated epistemic status at all

    a. Is mathematical astronomy anything more than a form of game playing, with no principled basis whatever for selecting among different mathematical systems?

    b. If no principled basis, then really making no epistemic claims at all beyond being able to represent the phenomena

C. The Crisis in Historical Context

1. This crisis in astronomy occurred in a broader historical context in which the epistemic status of all sorts of disciplines was coming to be challenged

2. Protestant reformation got underway during the 30 years Copernicus was working on his system and had reached a fever pitch by the late 16th century

    a. Luther's Bull of Condemnation -- 1521

    b. Henry VIII and the Church of England -- 1534

    c. Calvin's Institutes of the Christian Religion in 1536

3. Sextus Empiricus's *Outlines of Pyrrhonism* had re-appeared in print in 1562, stimulating strong interest in skepticism

    a. Main tenet: everything a matter of opinion, and we ought to learn to live with this, for only pain from thinking otherwise

    b. In a climate in which theology was increasingly appearing to be purely a matter of opinion, since no one was finding any universally accepted basis for resolving controversies within it

4. The crisis within astronomy and the tendency of the educated to be skeptical of knowledge claims fed on one another, in no small part because of astronomy's long standing claim to being the highest science

a. Consider, for example, the following comment by Montaigne, the leading Pyrrhonist of the age, published between 1575 and 1580, before Tycho had announced his new system

> The sky and the stars have been moving for three thousand years; everybody had so believed, until it occurred to Cleanthes of Samos or (according to Theophrastus) to Nicetas of Syracuse, to maintain that it was the earth that moved, through the oblique circle of the Zodiac, turning about its axis; and in our day Copernicus has grounded this doctrine so well that he uses it very systematically for all astronomical deductions. What are we to get out of that, unless that we should not bother which of the two is so? And who knows whether a third opinion, a thousand years from now, will not overthrow the preceding two? -- "Apology for Raymond Sebond", p. 429

b. Within 10 years had the apparently completely equivalent Tychonic system to drive Montaigne's widely read point home

5. Pyrrhonian skepticism put special emphasis on dismissing the possibility of any sort of "theoretical" knowledge of the empirical world
    a. Completely committed to the relativity of motion, and hence in position to say "I told you so" with the equivalence of the Copernican and Tychonic
    b. And always ready to take on the most prestigious "sciences", trying to show that they are ultimately unable to separate truth from mere appearance and hence they are a sham

D. The Challenge: Empirical Evidence

1. In short, the Renaissance rebellion against Aristotelian and Scholastic dogmatism -- against the view that many profound questions had been settled once and for all -- had come to threaten the most basic Aristotelian claim of all, that we can have real theoretical knowledge of the empirical world
    a. This was the claim that had separated him from Plato
    b. But the challenge to it was threatening to extend to neoplatonism as well, for the fundamental question was how are we to resolve disputes about what is true of the world in a principled way
2. A significant number of people at the time -- philosophers and "scientists" -- were not prepared to abandon the idea that we could have real theoretical knowledge of the empirical world
    a. Not just people like Tycho, Kepler, and Galileo, but philosophers like Bacon, Descartes, and Gassendi
    b. Typically figures in universities who saw the situation as imperiling not just their field, but learning as a whole
3. The question, how are we to gain knowledge of the empirical world, came to be in the forefront for these people, and consequently in the forefront of most philosophy and science throughout the 17th century
    a. Replace dogmatism and appeal to higher or ancient authority with some way of bringing evidence to bear to settle questions about the world
    b. Virtually every philosopher and "scientist" in the 17th century was centrally preoccupied with this question

c. And hence everyone we will be reading in this course

4. Any answer to this question had to come to grips with the crisis in astronomy, for it was in many ways spearheading the broader crisis, not just because of the deep empirical problem posed by the three systems, but also because of the former status of the discipline as the most advanced of the true sciences

    a. The question, how are we to gain knowledge of the empirical world, thus included a corollary: such that we can resolve the dispute between the three world systems in a principled way, in the process determining the true trajectories of the orbiting bodies (at least within observational precision)

    b. For those in astronomy, the resolution had to restore the discipline to its former place

    c. In other words, the crisis in astronomy became part of a larger crisis concerning the possibility of empirical knowledge, but a part that greatly added to the seriousness of the larger crisis

    d. The most widely read book at the time of four of the five central figures of this course -- Kepler, Galileo, Descartes, and Newton -- claimed to have ended this crisis by having found a way to provide decisive empirical evidence for Copernicanism

5. One slight oddity in the crisis developing only after Copernicus is that the epistemic -- in contrast to social -- sources underlying it were clearly already present in the *Almagest*

    a. All of Ptolemy's empirical reasoning presupposes what I called "working hypotheses" at the beginning of this class, and his defense of those hypotheses in Book 1 invokes nothing more than plausible reasoning that does little or nothing to exclude alternatives to them

    b. As Ptolemy emphasizes time and again throughout the rest of the work, if only because of Apollonius's theorem, there are representationally, though not physically, equivalent alternative models to the ones he adopts, and hence, even granting his working hypotheses, the observations he relies on in his empirical reasoning are unable to select one among these alternatives

    c. Both of these limitations in Ptolemy's empirical reasoning had to have been apparent to Ibn al-Shāţir, if not long before him

6. It is commonplace to say that the scientific revolution began with Copernicus; but the scientific revolution this course will be about -- the Newtonian revolution that led to modern advanced science -- really began in the last years of the 16th century, following the publication of Tycho's *De Mundi*

    a. I.e. it began when the question -- is theoretical knowledge of the empirical world possible at all, and if so how are we to achieve it? -- reached crisis proportions when the main exemplar of such knowledge, mathematical astronomy, could no longer maintain its claim to knowledge

    b. Newton's *Principia* is a response to this question just as much as it is a response to the questions, which system is the true one, the Copernican or the Tychonic, and what trajectories do orbiting bodies in our planetary system truly describe

    c. This course thus really begins with this crisis, and hence really begins around 1600.

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Credits for Appendix

Slides 2, 22, 23: Evans (1998)

Slide 4: Saliba (2007)

Slides 5-7: Swerdlow (1990)

Slides 8, 9, 13: Swerdlow (1973)

Slides 10, 11: Abbud (1962)

Slide 12: Ptolemy (1998)

Slide 15: Kuhn (1957)

Slides 16-21: Copernicus (1992)

Slide 24: de Santillana (1955)

Slide 25: Copernicus (1995)

Slide 27: Thoren (1989)

Slides 28, 30, 31: Thoren (1990)

Slide 29: Moore (1994)

Slide 32, 33: Pafko (2000)

Slide 34: Woolard & Clemence (1966)

Slide 35: Thoren (1989), Schofield (1989)

Slide 36: Montaigne (1957)