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