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