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)