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)