c. So, finally get to where Horrocks was when he died in 1642

d. Horrocks's papers *Opera Posthuma*, published in separate volumes in 1672-73, edited by Wallis (I) and Flamsteed (II)

5. Streete's book proved to be influential -- in some cases the primary source in astronomy for subsequent key figures

a. Huygens bought a copy while in England in 1661, and it clearly continued to influence him, if only through making him aware of Horrocks, when the Royal Academy's Kepler-refinement project was being fashioned

b. Newton appears to have learned his astronomy from it

c. Tables outlasted Boulliau's and Wing's, into the 18th century

6. {Fifteen years later the last of the pre-Newtonian new orbital methods comparable in accuracy to Kepler's was published, Mercator's *Institutionum Astronomicarum* of 1676, employing a method he had proposed in his *Hypothesis astronomica nova* of 1664; Newton cites 1676 book in the *Principia*

a. Presents with care first the equant at the empty focus, showing it is inadequate, then both Kepler's area rule and Boulliau's geometric construction (used as well by Streete), before presenting his own geometric construction, claiming it is preferable to both of these

b. His method employs a small displacement of the circle circumscribing the ellipse (see Appendix)

c. Ends discussion with comparisons of different methods for Mars, reproducing Kepler's table of comparisons of oppositions from *Astronomia Nova*, following it with a table showing that his own values for Kepler's 28 featured comparisons are a little better than Kepler's

e. Mercator's book thus becomes the "review article" reference on the question of the area rule

d. (See Appendix for tables for the 28 comparisons from Kepler through Mercator)}

C. The Founding of the Royal Society (1660-63)

1. Regularly meeting discussion groups involving those interested in the new "experimental philosophy" had been going on in both London and Oxford from 1645 on

a. Group at Gresham College, led by Wilkins and Wallis, and a group brought together by Hartlib, a Puritan educator

b. Boyle spoke of the "invisible ... philosophical college" as early as 1647

2. The political turmoil in England during the Cromwell years -- 1649 to 1660 -- produced similar turmoil in the management of colleges and universities, turmoil that intensified with the Reformation of 1660, in which Church of England administrators regained control of the universities, after nearly two decades in which puritans had much more power than they had had before

a. Those engaged in the empirical movement felt legitimately threatened in this atmosphere

b. Turned to the newly installed King Charles with the idea of starting a new academic institution

3. King Charles agreed in 1660, and in 1662 chartered the Royal Society of London for the Improvement of Natural Knowledge

a. He gave a good deal of nominal, but not much financial support, leading them to abandon the idea of a separate college, and instead institutionalize the discussion group -- a forum for the discussion of scientific problems of all sorts
b. Meeting bi-weekly in London except during the summer, with a fully scheduled program for each meeting
c. A list of the most scientifically prominent initial (1663) Fellows, including Huygens as the sole foreigner, and some of those they elected in the following years can be found in the Appendix

4. Published *Philosophical Transactions of the Royal Society* monthly, beginning in 1666, leading to rapid publication of papers and notes, thus disseminating the substance of the presentations and discussions at the meetings
   a. Save for one brief hiatus at end of 1670s, continued publication down to today (see JSTOR)
   b. By the mid-1660's over 150 Fellows, representing all those either actively involved in or interested in empirical research in England
   c. Reaching across all of the sciences -- medicine as well as physics (the first blood transfusion, for example)
5. Henry Oldenburg, the Secretary of the Society from 1662 until his death in 1677, was exceptional in getting people to present their work and engage in critical discussion without long term animosity
   a. Great openness of discussion as well as rapid dissemination and critical-response -- a tradition continued by Oldenburg's successor, Hooke, as best he could
   b. Bi-weekly discussion and monthly publication could not help but have an enormous impact on the quality of empirical research and theoretical thinking going on in England, if only through the reduction in the time for ideas to become refined or discarded in favor of better ones

D. The Royal Academy of the Sciences (1666)

1. A tradition of regular meetings of discussion groups in Paris extended back into the 1630's, originally organized by Mersenne, but continued after his death in 1648 by Gassendi and Rohault
   a. Gassendi the central figure until his death in 1655, after which Huygens was the primary star
   b. Huygens initially presented his discoveries, e.g. regarding Saturn, to this group at its regular meetings
   c. This group included some brilliant women (subsequently satirized by Molière)
2. After the Royal Society was established in London, Louis XIV was successfully prevailed upon by Colbert to form the Académie Royale des Sciences in Paris in 1666
   a. Unlike Charles, however, he supplied generous funding, allowing the Academy to become much more than a discussion group
   b. Money to support individuals full time (16 academicians) as well as for superior equipment and for special projects and expeditions
   c. Housed in the Royal Library

3. The Academy brought in the top people from throughout the Continent to join the French
   a. Huygens accepted a charter appointment in 1666, and with it became the intellectual leader of the Academy, along with the physicist and astronomer Auzout, the outstanding French observational astronomer, Picard, and the experimentalist, Mariotte
   b. Cassini joined in 1669, at Huygens's urging, and Roemer two years later, at Picard's urging
   c. Like the Royal Society, not restricted to physics, though its greatest successes in the early years were in astronomy and experimental physics, with Mariotte the chief experimenter
4. In conjunction with the Academy, the Royal Observatory was established, in the garden of the Royal Library, in the late 1660's
   a. Cassini became the Royal Astronomer in 1669 -- starting a family tradition of Cassini's as Royal Astronomers of France
   b. He brought with him the finest Campani telescopes, giving the Academy the best equipment in the world -- e.g. a 17 ft and a 34 ft telescope with Campani lenses
   c. In effect, the first fully functioning observatory since the death of Tycho, with a group of the very top people in observational astronomy working closely together -- Huygens, Picard, Cassini, Richer, Roemer, la Hire -- and discussing details with one another all the time
5. The *Journal des Sçavans* ended up providing the vehicle for rapid publication for those associated with the Academy in much the way that *Philosophical Transactions* did so for the Royal Society
   a. Close communication between the leading Fellows of the latter and the Academicians, in part because Huygens was a member of both
   b. Both journals read on both sides of the Channel, and the most important articles were often translated to appear in the other journal -- e.g. Cassini's second and third satellites of Saturn
   c. {*Mémoires* started in 1690s}
6. Thus, in both England and France, science breaks off from the rest of philosophy with the emergence of professional organizations in the 1660's, out of the reach of university politics
   a. Free to set their own standards, define their own problems, and isolate themselves from the sorts of concerns that Galileo's trial had given rise to
   b. More important than even this, having two such organizations in supportive competition with one another, yet with open communication, produced an international scientific community
   c. Not just the loosely connected community of a single academic discipline spread over many universities, in the manner of astronomy from well before Copernicus, but a tightly integrated community, with great communication and fast turn-around time on ideas and criticisms
   d. Thus, sociologically as well as in content, science starting to look distinctly more like it is today
7. Until early in the 18th century, when the Basel school emerges, science largely a "tale of two cities"
   a. Some drop-off in Italy when early death of Torricelli left the Galilean experimental institute weakened, not to mention effects of trial of Galileo and departure of Cassini to Paris

b. In rest of Europe, scientists spread out among universities, working too much in isolation, versus what was happening in England and France

E. New Standards in Experimentation: Hooke

1. The Royal Society was outspokenly committed to the so-called "experimental philosophy" -- i.e. the idea that questions should be settled via experiment and observation
   a. Two of the well-springs for the Society were the influence of Bacon's philosophy in certain circles and the (neo-Epicurean) corpuscularean school of the mechanical philosophy inherited from Gassendi, in part through the writings of Charleton, and pushed by Boyle
   b. The distinction between theory and experiment was drawn sharply and, at times, the prevailing attitude seemed to be that virtually all new knowledge came out of experiments
2. The only full-time employee of the Society was called the Curator of Experiments -- for forty years, Robert Hooke
   a. His job was to further experimentation, by developing experiments, by reviewing and criticizing experiments being done by others in and outside the Society, and by developing equipment and techniques that could be used
   b. In addition to being expected to report on experiments, he was obligated to have an experiment actually presented at each bi-weekly meeting, if need be by devising one himself
3. This put Hooke in a pivotal spot in the development of science in England for the forty years from 1660 to 1700, involving him in a huge number of projects
   a. Hooke is the second major figure in this course -- Kepler is the other -- who was not financially secure and hence had to survive off his scientific work
   b. He is often referred to as a mechanical genius because of his great cleverness in designing experiments and equipment; yet he was also given to a good deal of theorizing, though his mathematical skills were not up to those of many of the others
   c. Probably because of the incredible demands on his time, he often did not perfect experiments or equipment to the extent he might have, and when others did, leading to new results or advances, he tended to claim priority
   d. Indeed, Hooke was constantly involved in priority disputes, perhaps in part because of his personality, but also because he really did have at least some early thoughts about virtually every major scientific discovery of the time
4. At the time Hooke became most widely known from his *Micrographia* (1665), a compendium of observations made with the microscope, in which he added the word 'cell' to the lexicon of science (the microscope served him well in meeting his bi-weekly obligation -- see figures in Appendix)
   a. But he also worked on the equipment used in Boyle's experiments in pneumatics, built a (not terribly successful) mural arc for Greenwich, and built one of the first reflecting telescopes, based on Newton's ideas, that was used in astronomical research

   b. And he devoted a great deal of effort to optics, in which he has claim to being a co-founder (with Huygens) of the (longitudinal) wave theory of light, among other things
5. The emphasis on experimentation, the bi-weekly experiments before an intensely critical audience, and Hooke's own genius in developing experiments raised the standards of experimentation in England to a much higher level, generating a series of experimental "paradigms"
   a. One example is the series of experiments on ballistic pendula performed in the late 1660's, using knowledge of pendular motion to investigate the effects of impact
   b. Experiments were criticized, refined, and once perfected then exploited, in other investigations
   c. The upshot was an experimental tradition that has ever since remained part of English science
6. {Mariotte and Huygens were similarly raising experimental standards in the Academy, though with less immediate dissemination}

F. Post-Cartesian Efforts in Celestial Physics

1. Whether because of Descartes' vortex theory or because the books by Streete, Wing, and Ward openly discussed celestial physics, serious interest in the physical mechanisms underlying celestial phenomena, especially planetary motion, developed again
   a. Streete suggests in passing that Moon held in orbit around Earth by quasi-magnetic gravity (see Appendix)
   b. After years of pushing Kepler's physics off to one side, and running only geometrical and phenomena-saving arguments, the idea that many questions were going to be settled only through an underlying physics finally took hold
   c. And, at least in England, this meant a physics solidly founded on experiments
2. Wilkins (1614-1672), one of the central figures in London in the years leading up to the Royal Society, had kept the tradition of the "magnetical philosophy" of Gilbert going in England
   a. Christopher Wren -- then a professor of astronomy -- and Hooke, both protegés of Wilkins at Gresham College in London, began looking at a 'magnetic' gravitation to account for planetary motion in the late 1650's
   b. Wren lectured on Keplerian astronomy in the late 1650's, expressing the view that "the perfection of ... the Elliptical Astronomy" was most worthy of inquiry
   c. (Wren's shift to architecture occurred during the 1660s, following the London fire of 1666 and his winning the job of designing and building the new St. Paul's)
3. Starting in early 1660's Hooke began trying experiments to reveal how gravity varies with radial distance from the center of the Earth, an issue that had become prominent in some circles years earlier
   a. Huygens had established that the acceleration of gravity could be measured via pendular motion to high accuracy by 1660
   b. Tales of reduced gravity in deep mine shafts led Hooke to use pendulums to measure the acceleration of gravity in mines

c. Though his initial results were unsuccessful, he continued such experimental efforts, reporting on them in a major paper before the Society in 1666

4. A comet that appeared in December 1664 led Wren and Hooke together to propose a theory of comet motion based on 'magnetic' gravity (see Wren's figure in the Appendix)

"For Hooke, or for Wren, a comet's uniform rectilinear motion made physical sense as an unencumbered inertial motion, and any deviations, indicated by a less-than-perfect fit with observations, were naturally explained by gravitational influences of bodies within whose 'magnetic' range the comet might pass." [Bennett, p.227]

a. They proposed to investigate such motions via pendular motion, more specifically the conical pendulum, which was known from 1640's on to yield elliptical orbits when the apex is made to oscillate along a line

b. Hooke continued work on such ideas throughout the 1660's and 1670's, spurred on by such things as a proposal by Wallis to complete Galileo's proof of the motion of the earth by deriving the tides, now having the common center of gravity of the Earth and Moon orbiting the Sun, with each moving with respect to one another

5. Borelli's *The Theory of the Medicean Planets Deduced from Physical Causes* (1666) proposed that elliptical orbits result from interaction of centrifugal force and a force directed towards central body

a. Borelli a founding member in Galilean *Accademia del Cimento* -- Academy of Experiment

b. Ellipse, or quasi-ellipse, instead of circle because of disequilibrium between two forces

c.. Note that this book, which Newton read, stressed centrifugal tendency in manner of Descartes

6. The interest in gravity in London may have been part of why the Academy of Sciences devoted a series of sessions to it in fall 1669, inviting papers and theories, which were then subject to criticism

a. Various proposals put forward, including the idea that gravity is simply one of the fundamental phenomena of nature, not to be explained further (Roberval)

b. But the only theory to yield any comparatively detailed explanations of distinctive phenomena was Huygens's much advanced, refined version of the sort of mechanism put forward in Descartes' vortex theory

G. Steps Toward a Resolution in Orbital Theory

1. One of the principal projects the Academy of Sciences undertook, led by Picard, but undoubtedly with strong support from Huygens, was the systematic refinement of Keplerian orbits

a. From the outset Picard was set on raising observational astronomy to a new level of precision, taking advantage of improving technology and financial resources available to the academicians

b. The decision to put their effort into the *Rudolphine Tables*, presumably reflected the view that none of the rivals had improved on them

c. They excluded Boulliau from membership in the Academy, apparently because of objections to e.g. his 2 min solar parallax and his artificial equation of center

2. The approach they took to refining Kepler was one of proceeding from the ground up, first establishing better founded values of the astronomical parameters used in measuring and correcting "observed" positions
   a. For example, probably reflecting the influence of Horrocks's *Venus in sole visa* (1662) -- which Huygens had known since 1660 -- they knew that the solar parallax had to be reduced, and that in turn called into question such things as tables of refraction and the obliquity of the ecliptic
   b. Picard introduced telescopic sights on graduated arcs in the late 1660's and adopted new observing procedures, taking advantage of the pendulum clock and of his discovery that the brighter stars can be observed in daytime (so that their right ascensions could be determined from their meridian transits versus those of the sun)
3. Picard undertook an expedition to Uraniborg to check Tycho's value of latitude and its longitudinal difference from Paris -- this in order to make the best use of Tycho's data (Wilson)
   a. Note the attitude: no longer going to rely on Tycho's data -- a new reform of observational astronomy from the ground up -- but still going to take full advantage of the data to cross-check, to raise questions, and to extend the time line of the data
   b. Measurement of longitude difference via determination of time of an eclipse of satellite of Jupiter at both places, using clocks set to local mean time
      (1) Extremely accurate result: 42 min 10 sec (in time), versus 40 min 26 sec today
      (2) I.e. an error of 26 min of arc out of 10 deg 32.5 min
      (3) Method used by Picard to determine other lengths in France
   c. Large scale of the undertaking helps explain the invitation (initiated by Huygens) to Cassini to join the Academy in 1669, and Picard's decision to bring Roemer back from Denmark with him during the trip to Uraniborg
4. 1669 is also the year in which Mercator was prompted to deliver the final blow to the simple elliptical hypothesis -- i.e. to an equant at the other focus -- in response to a paper by Cassini in the *Journal des Sçavans*
   a. Article in 1670 *Philosophical Transactions* showing clearly that equant must lead to 7 min errors in octant of Mars; result repeated in this 1676 *Institutionum Astronomicarum* (read by Newton)
   b. Showed that, once the ellipse adopted, nothing beside the area rule or some calculational device closely approximating it could yield observational accuracy in the case of Mars
5. So by 1670, forty years after Kepler died, the fundamental astronomical tenets of his orbital theory had become recognized and accepted as holding at least to a high degree of approximation; the assimilation was complete
   a. The ellipse and the area rule (or a close approximation to it) were recognized to achieve more or less what Kepler had claimed for them in *Astronomia Nova* and the *Epitome*, though virtually all tables after *Rudolphine Tables* did not use the area rule

b. James Gregory had even devised an infinite series solution to Kepler's problem, based on work by Wren on cycloids (and Newton was soon to follow with another such solution)

c. And Horrocks's idea of taking Kepler's third "law" to hold exactly and using it to define mean distances was acknowledged (by some) to yield improved orbital elements

6. Question then becomes, how near to exact do Kepler's "laws" hold -- a question that can best be answered by pushing Keplerian orbits for all they are worth, using data of the highest possible quality

a. In other words, the right conclusion finally gets drawn from Kepler's efforts: focus shifts to determining (refined) residual discrepancies and assessing their implications

b. New tables based on this effort do not finally emerge until well into the 18th century (ultimately by Cassini's son and Halley) -- i.e. a concerted effort spread over more than a half century

IV. A New Standard in Astronomy: 1670 to 1684

A. The Royal Academy's Expedition to Cayenne

1. Cassini's efforts on the Sun while still in Bologna had shown him that the Academy's program in orbital reform could not go ahead until a proper way of correcting for refraction and solar parallax had been established

a. Two different approaches for correcting for refraction, one of which (Cassini's) used a single table with corrections all the way up to the zenith

b. Measurements at tropical latitudes needed to choose between these two, leading to the legendary expedition to Cayenne of Richer in 1672-73

2. Richer's measured solar declinations at Cayenne over a period of months (covering two equinoxes) showed that Tycho's corrections yielded a different obliquity of the ecliptic from the one measured in Europe, while Cassini's corrections did not

a. Result was a change in the obliquity of the ecliptic from Tycho's 23 deg 31.5 min to 23 deg 29 min, with comparable adjustments to solar eccentricity and the locations of the equinoxes

b. The new values also entailed that the horizontal solar parallax could not be greater than 12 sec -- even smaller than Horrocks' 15 sec, proposed following his work on the orbit of Venus

3. The timing of the expedition to Cayenne was based in part on the fact that Mars would be in opposition while near perigee in 1672, giving a special opportunity to measure its horizontal parallax

a. Since all orbital distances of the planets locked into one another, a successful measure of the horizontal parallax of Mars would establish the horizontal solar parallax as well, at last yielding celestial distances in terms of an earth measure

b. Tycho and Kepler had been unable to detect a Mars parallax, but equipment had improved, and the expedition would allow comparison of time-synchronized measurements between Paris and the western hemisphere

4. As Van Helden describes, the attempts to obtain the Mars parallax through the expedition were confounded by too much measurement error, in part because the telescopes taken to Cayenne did not