THE NEWTONIAN REVOLUTION – Part One

Philosophy 167: Science Before Newton's *Principia*

Class 11

Other Developments in Astronomy from 1642 to 1684

November 18, 2014

Philosophy 167: Science Before Newton's Principia

Assignment for November 18

Other Developments in Astronomy from 1642 to 1684

Reading:

Wilson, "From Kepler's Laws, So-Called, to Universal Gravitation: Empirical Factors," pp. 103-136.

Van Helden, "The Micrometer from Huygens to Flamsteed" and "Cassini, Flamsteed, and the New Measure," from Measuring the Universe, pp. 118-143.

Flamsteed, excerpts from the Preface to Historia Coelestis Britannica, pp. 103-140.

"Römer and Huygens on the Speed of Light -- Two Excerpts," (handout) pp. 334-338 and 128-132.

Questions to Focus On:

1. What effect did the various unsuccessful attempts to replace Kepler's area rule during the period from 1640 to 1676 end up having on the evidence for it?

2. On the one hand, the ellipticity of the orbits was the most widely accepted of Kepler's three "laws" among astronomers in the 1642 to 1684 period. On the other hand, it is the only one of the three that Newton took still to be an open question in 1685. How, if at all, can these contrasting attitudes be reconciled?

3. Technological advances in astronomical equipment helped Huygens solve the mystery of the bulges of Saturn. What impact did advances of this sort have on any other problems outstanding in astronomy? Also, how were they incorporated into the design of Flamsteed's observatory at Greenwich.

4. The Royal Academy's expedition to Cayenne, along with the expedition to Uraniborg, can be regarded as among the first projects of "big science." To what extent did this project realize its objectives? Did it have any unforeseen payoffs?

5. In 1676 Römer managed to infer a value for the speed of light from vagaries in the eclipses of Io, the innermost of Jupiter's Galilean satellites. What previous results of 17th century science were required for his inference?

Other Developments in Astronomy from 1642 to 1684

I. A New "Post-Galilean" Generation of Scientists

A. "Forty Years that Shook Science"

1. With the publication of Descartes' *Principia*, the pieces that will come together in Newton's *Principia* are, in a sense, on the table
   a. Kepler's innovations -- e.g. the Sun as reference point, bi-section of the eccentricity of the Earth-Sun orbit -- and his three "laws," have at least set a new standard in predictive astronomy
   b. Galileo's new science of natural motion, including a unified, elaborate mathematical theory and the potential for a wide range of experiments
   c. Descartes' approach to conceptualizing motion, using elastic impact as a paradigm and raising the problem of centrifugal *conatus* in curvilinear motion
   d. (Also basic results in optics, several results in statics and on mechanisms, and initial results on gases, thanks to Torricelli's barometer)
2. On the standard way of viewing Newton as synthesizing Kepler and Galileo, under influence from Descartes, the forty years between 1644 and 1684 tend to be portrayed as a hiatus, awaiting the arrival of Newton's genius
   a. Nothing could be further from the truth; these years, especially starting with the mid-1650's, are among the most intense periods of development in the history of science
   b. The title of Gamow's book on the development of quantum mechanics -- *Thirty Years that Shook Physics* -- is apropos here
   c. "Forty years that shook natural philosophy" forever, pushing it toward the separate, autonomous discipline of physics
3. This is the period in which we start seeing for the first time a large amount of work that meets the standards of the best science today -- work that in every respect looks like science to us
   a. Kepler's reliance on "physics," Galileo's talk of 'impetus' and his attention to Aristotle, and Descartes' arguments for his laws look antiquarian to us in a way that Newton's *Principia* does not
   b. But this change in "scientific style" is something Newton inherited and extended, and not something he invented
   c. It developed over the course of years, roughly from 1655-1685, as we have already begun to see with Huygens's work in mechanics -- "standing on the shoulders of giants"
4. This period is also marked by the emergence of a true scientific community, setting standards, defining problems, and criticizing and even ostracizing those who work under a different conception
   a. For me, perhaps the most exciting and satisfying feature of the period is the extent to which the community pulled together and yet at the same time remained intensely self-critical
   b. Many factors combined to make this possible, but one of the most important was the dominant influence of Christiaan Huygens over these years

5. Perhaps in part as a response to Descartes, perhaps in part because of problems in replicating Galilean experiments, and perhaps in part from the challenge posed by the serious rivals to Kepler, this period is marked by a much stronger commitment to the idea that the empirical world ought to be the ultimate arbiter
    a. One way this shows itself is in closer attention to details of experimentation and observation
    b. But it also shows itself in the form of a constant open recognition of what the evidence has not yet succeeded in doing -- i.e. in a much stronger focus on ways in which specific evidential arguments fall short of settling issues
    c. With this, an increasing recognition of the difference between philosophy and empirical research and between polemics and evidential reasoning

B. The Legacy of Descartes' *Principia*

1. The legacy of Descartes that has been most widely recognized ever since is the impediment to science imposed by his restrictions on theorizing
    a. The insistence on no forces or action at a distance became a major open impediment to the acceptance of Newton's *Principia* -- an obstacle that had to be overcome with argument
    b. But the same is true, though less obtrusive, in the case of those who were looking to draw conclusions for such things as the specifics of orbital trajectories -- an added challenge that had to be overcome
2. A second part of the legacy that has often been noted is the extent to which Descartes' self-confidence -- if not arrogance -- provoked some of those who read him (especially Huygens and Newton)
    a. They may well have been challenged into finding alternatives to his conclusions
    b. In this respect Descartes left a lot of lines of thought to be pursued in response to his claims of having achieved either the best or the only possible explanations of various phenomena
3. But Descartes also had a positive impact, for while the answers he offered were almost uniformly unsuccessful in the long run, the same cannot be said of the questions he asked
    a. Descartes focused attention on new questions; by contrast, Kepler and even Galileo, to some extent, inherited their questions
    b. Even in the immediate aftermath, many people were less worried about Descartes' answers than about whether his questions were appropriate and, if so, how to get at them
    c. Furthermore, Descartes stratifies questions -- i.e. he gives reasons why some questions need to be answered before others are addressed (e.g. why are the orbits curvilinear at all)
4. One such set of new questions concerns the conceptual foundations of "mechanics"
    a. What why-questions are appropriate to ask about motion at all, where the specification of the questions includes the circumstances that give rise to them and a range of possible answers
    b. By raising the question, what are the fundamental, universal laws of nature -- i.e. the governing principles with which all explanation must stop

c. The legacy here also includes change of motion under perfectly elastic impact as the paradigm relative to which such conceptual foundations can be formulated

5. A second set of new questions concerns planetary motion
   a. The primary question becomes, why are the trajectories curvilinear at all
   b. Other questions are not just secondary; whether they have any interesting answers at all depends on the answer to this question
   c. Descartes does not as such deny the possibility of discovery through detail, but he does force people to question whether various details can ever be the basis for discovery
6. Finally, Descartes' legacy includes a whole host of other questions in physics
   a. E.g. what is light, what is the difference between iron and non-magnetic substances, etc.
   b. The questions about the cosmos that came to be addressed by cosmology, including questions about what gravity is

C. The New Generation: Huygens among Others

1. A large number of figures achieve prominence in the 43 years between the publication of the two *Principia*'s, including people who will be central throughout the rest of the course
   a. In England: Wallis (1616-1703), Ward (1617-1689), Horrocks (1618-1641), Wing (1619-1668), Mercator (1619-1687), Streete (1622-1689), Boyle (1627-1691), Wren (1632-1723), Hooke (1635-1702), James Gregory (1638-1675), Newton (1642-1727), Flamsteed (1646-1719), Halley (1656-1743) -- Halley belonging in the group because, as a prodigy, he interacted with the others
   b. On the Continent: Borelli (1608-1679), Hevelius (1611-1687), Picard (1620-1683), Mariotte (1620-1684), Rohault (1620-1672), Auzout (1622-1691), Pascal (1623-1662), Cassini (1625-1712), Huygens (1629-1695), Richer (1630-1696), Campani (1635-1715), la Hire (1640-1718), Roemer (1644-1710), Leibniz (1646-1716)
2. All of these people are post-Galilean in the sense that they all came of age after his trial
   a. Whether because of the trial, or for some other reason, all of them (save for Leibniz) maintained a strict separation between their work in empirical science and other matters
   b. And Leibniz was the only one of them who made any sort of lasting contribution to philosophy
3. A post-Keplerian and post-transit-of-1631 generation too: for all of these individuals, and hence for science in their times as well, Kepler's ellipse, if not his entire orbital theory, was a starting point
4. The dominant intellect, and consequently leading figure among them throughout the 1657-1687 period was clearly Christiaan Huygens
   a. Visits to Paris starting in mid-1650's, which became his primary residence from 1666 until France turned anti-Protestant in the 1680s, although he also traveled widely -- e.g. repeatedly to England (1661, 1663, 1689, etc., FRS 1663)
   b. Personally acquainted with everyone on the above list except perhaps Hevelius, Campani, Ward, and Flamsteed, thereby replacing Mersenne as the principal unifying figure

5. Huge amount of research over 45 year period, especially from 1655 to 1665, with profound influence on others through personal contact
   a. Work in astronomy primarily in 1650's -- including lense grinding and the better telescopes in the first of these years -- culminating in *Systema Saturnium* (1659), which established him worldwide as a major figure
   b. In mechanics, from 1640's on, culminating in *Horologium Oscillatorium* (1673), which in a sense completes and replaces last two days of Galileo's *Two New Sciences*
   c. In other areas of physics -- most notably optics and light and gravity -- from the late 1660's on, culminating in *Traité de la Lumière* (1678 (draft), 1690) which presents a wave theory of light and *Discourse on the Cause of Gravity* (1669, 1678, 1684 (drafts), 1690)
   d. In mathematics, the first textbook in probability theory (1657), the theory of evolutes, and extensions of post-Cartesian geometry to numerous further curves, including logarithmic and exponential, tied to quadratures of hyperbola
   e. In technology, the leading designer of clocks, as well as several other contributions, and for a period in the 1650s the source for the world's best telescopes, with his correcting eyepieces
6. The person on the list who may have known Descartes best from his teen years and, because of his research in the third of the above categories, often thought to be a Cartesian; nevertheless, more accurately thought of as the chief follower of Galileo and Mersenne
   a. Extends the best in Galileo -- mathematical theories, telescopes, experiment, uniformly accelerated motion, etc. -- but with Mersenne's emphasis on clear empirical confirmation
   b. As such, the style-setter in science in the years between the two *Principia*'s

II. Astronomy from 1642 to 1660: Revisitations

A. Boulliau's Geometrical Orbital Theory

1. Need to start with another French priest from Descartes' generation, Ismaël Boulliau (1605-1694), who developed the first serious rival to Kepler's orbital theory
   a. Opposed not just to Kepler's physics, but to all physics in mathematical astronomy -- restore discipline to branch of geometry by insisting throughout on geometrical arguments
   b. Restore Copernican foundations by insisting on uniform circular motion, while allowing ellipse

      "To bring the motions of Mercury under numerical laws was difficult if not in fact impossible for pre-Keplerian astronomers who used only the circular hypothesis." (Boulliau, 1645)

   d. Thus with an underlying cosmology of sorts, though no physical explanation for the ellipse or for timing along it, and nothing about what resists tendency to recede from center
   c. Because area rule not geometrical, insofar as no geometrical solution to Kepler's equation, Boulliau rejected it as part of his goal of returning astronomy to branch of geometry
2. Basic idea: planet slides from circle to circle defined on a conical surface, resulting in an ellipse with one focus on axis of cone and the other at the Sun (see Appendix); in *Astronomia Philolaica*, 1645

a. Uniform motion on each circle results in faster motion (smaller circle) near perihelion, slower (larger circle) near aphelion
b. Considered geometrical grounds for concluding that oval definitely an ellipse

3. Claimed his method provided a direct solution to problem of finding true anomaly from mean anomaly, but at last moment realized solution resulted in excessive geocentric longitude errors (> 7 min)
   a. Hence inserted Kepler's equation of center (i.e. area rule) at last moment in 1645 book
   b. In 1653, however, Seth Ward showed (1) that uniform circular motion about conical axis equivalent to an equant on that axis and (2) Boulliau's method not consistent with his own claim of uniform circular motion
4. Boulliau, who knew that the simple elliptical hypothesis (equant at other focus) won't work, offered a modified method in (1657) in response to Ward's critique: *Astronomiae Philolaicae fundamenta clarius explicata et asserta*
   a. Straightforward new geometrical construction to determine true anomaly ("Boulliau's method")
   b. Claimed this is consistent with uniform circular motion, for reflects a small additional inequality due to "translation of the motion of the planet from a circle into an ellipse"
5. Resultant orbital theory of the same level of accuracy as Kepler's even though it replaces the area rule by a computationally more tractable alternative (using the same 28 comparisons with Tycho's data for Mars near opposition that Kepler had used, as shown in the Appendix)
   a. Raises questions about the indispensability of the area rule, even though the alternative could be viewed as nothing more than a computational contrivance, akin to devices others (including Horrocks) had suggested for approximate solutions to Kepler's equation
   b. At same time, however, success of both original and corrected versions lent further weight to conclusion that the orbit elliptical

B. Other Alternatives to Kepler's Orbits

1. Boulliau's orbital theory the principal rival to Kepler's in the 1640's and 1650's, for no other was both comparable in accuracy and had at least the pretense of an underlying cosmology
   a. But there were several other rivals to Kepler's orbital theory put forward as well, along with some approximate solutions replacing the area rule (e.g. Cavalieri)
   b. More often than not in an effort to avoid having to face Kepler's equation in determining true anomaly from mean anomaly
   c. (In *Rudolphine Tables*, "eccentric anomaly" used, with direct solutions then for both mean and true, but requiring interpolation in former, and hence not strictly geometric)
2. Riccioli's *Almagestum Novum* was published in 1651, containing not only his work in mechanics, but also a complete orbital system, with Jupiter, Saturn, and the sun orbiting the earth
   a. Rejected elliptical orbits on grounds that the evidence for bisected eccentricity inadequate at the time; in process was putting greater demands on the evidence

   b. In 1665 switched to elliptical after Cassini's efforts in Bologna provided high quality empirical evidence for bisected eccentricity, in the process removing one of the shaky steps in Kepler
   c. System not a serious contender for various reasons, among them a large number of calculation errors; but book of interest because of its extensive review and critical analysis of others
3. The simple elliptical hypothesis, with equant point at the other focus, continued to be put forward in spite of Kepler's explanation in the *Epitome* of why it does not work
   a. Ward, ironically, was criticizing Boulliau in order to justify resorting to equant, as he did in 1656
   b. Boulliau's 1657 reply showed that the equant is not empirically satisfactory
   c. Pagan nevertheless published Keplerian elements with equant at focus that same year
4. Wing (*Harmonicon coeleste*, 1651; *Astronomia instaurata*; 1656, Ephemerides for 1659-1671, 1658; *Astronomia Britannica*, 1669) adapts Boulliau's original method of calculating the equation of center, while abandoning completely Boulliau's geometrical cosmology and cone ("a mere supposition")
   a. "No such thing in nature as mean motion" -- an openly calculational approach, with no concern for underlying physics in 1651
   b. Actual construction akin to an oscillating equant point in 1651 (just as Kepler said was necessary), yielding reasonable agreement with observation (Wing's first method)
   c. Shifts to different method in 1656 and 1669, in which an empirically based geometrical correction term used to relocate planet, different from Boulliau's, but in same spirit
   d. (Tries to conflate Kepler and Cartesian vortex in 1669)
5. Two other important approaches eschewing the area rule published in England between 1660 and 1676, by Streete and Mercator, will be discussed below
6. One thing to notice in all these attempts is that nothing emerges to show Kepler wrong
   a. Ellipse becomes conceded, constituting a form of assimilation of Kepler, as does accuracy comparable to area rule, which requires some special contrivance or other in each case
   b. Notice also that Tycho's data the empirical base for these efforts, with no attempt to use either new data or discrepancies between Kepler and observation to generate better accounts, in the way Horrocks did, making these efforts less an assimilation of Kepler than his was

C. The Development of the Pendulum Clock

1. The limited accuracy of clocks -- e.g. Tycho's observations involve as much as 1/4 hour error in time -- was holding back astronomy in two respects:
   a. Some observations were simply being misstated -- direct measurements of latitude and longitude at a specified time (as opposed to measurements relative to certain nearby stars)
   b. Lack of standardization impeded simultaneous measurements at different sites, as well as comparison of measurements at slightly different times
2. Although Galileo had proposed ways of turning the pendulum into a clock, Huygens was the first to produce a completely functioning pendulum clock in 1656 (announced in his *Horologium* of 1658)

a. Unlike Riccioli, no need for a human to count the number of pendulum arcs out loud -- a complete mechanism, with the pendulum driving gears and the gears driving the hands of a clock
b. Some key features: an "endless chain" that allows the clock to be wound without disturbing its time-keeping, and an easily actuated means for making small corrections to the period
c. Immediately reduced the error in time from as much as 15 min per day drift down to 10-15 seconds per day

3. Huygens continued to improve his 1656 clock over the next few years, inventing a series of variations to it; throughout these efforts he generally turned his designs over to professional clock-makers, who then produced and marketed the clocks
a. He measured the non-isochronism of his basic pendulum clock, finding that it deviated by 5 sec per day with a 1 to 2 deg arc and 18 sec per day with a 5 to 6 deg arc
(1) This led him to try curved walls along the pendulum chord, effectively shortening the length at larger arc
(2) This increased accuracy so long as the arc remained true, but lateral displacement of the arc re-introduced inaccuracies
(3) He then reverted to a circular pendulum, introducing a mechanism restricting it to small arcs
b. In 1659 Huygens discovered the theoretical shape of the curved wall needed to make the period independent of the arc length, namely a cycloid
(1) Specifically, cycloidal cheeks produce an isochronous cycloidal path, as explained in his *Horologium Oscillatorium*, published in 1673
(2) After 1659 Huygens always employed cycloidal cheeks on his pendulum clocks, yielding accuracies within a few seconds per day
(3) Cheeks also on his maritime clocks, which he developed in an effort to solve the problem of determining longitude at sea
c. In the late 1670s Huygens also invented the spring-balance clock, apparently in an effort to get around the problem of ships' motion disturbing his pendulum clock
(1) Was about to conduct sea trials with this when he discovered that spring-balance sensitive to variations in temperature
(2) In spite of 40 years of effort, Huygens never solved the problem of keeping accurate time at sea, though his failure was not entirely clear to him at the time he died in 1695

4. Once the promise of the pendulum clock became clear, many other inventors refined and developed it, leading to a large number of variations of the basic idea
a. For example, the clocks at Flamsteed's Greenwich Observatory were designed by Tompion, who became the leading clock designer in England
b. The Greenwich clocks used 13 ft adjustable circular pendulums, giving a 2 second arc (4 sec period)

c. {Few followed Huygens in using cycloidal cheeks; instead they restricted the motion to small or constant arcs}

5. By 1670, the pendulum clock had become standard throughout astronomy in one version or another, allowing extreme high confidence in measurements of time; 15 arc second per second error in time
   a. Most of the clocks could maintain accuracy to within a few seconds per day, and they were easily correctable, allowing them to be reset by astronomers as called for
   b. Note Flamsteed's remarks about the Tompion clock (p. 140): in March it was found to lose 18 sec per day, in September, to gain 13 sec per day -- e.g. a 0.02% error
   c. Careful calibration -- via resetting of the pendulum length -- on the best of these clocks -- e.g. Huygens's -- could reduce the error another order of magnitude

D. Advances in the Astronomical Telescope

1. During the 1640's the Keplerian or astronomical telescope had been made longer and longer, each increase in aperture leading to an even greater increase in length
   a. Long wooden tubes, but could be focused to eliminate lens misalignment effects
   b. Their long focus permitted much higher magnifications, with reduced chromatic effects
2. Huygens made a major breakthrough in extending the length of telescopes in the mid 1650's when he invented the aerial telescope, abandoning the long wooden tube and instead using two separate pieces, aligned with one another, separated by open air
   a. A 123 ft telescope, with a 7.5 inch aperture: 50 power with comparatively little aberration
   b. In part because of the open-air effects of this arrangement, Huygens was the first to discuss "seeing" phenomena -- i.e. visual disturbances due to temperature oscillations in the air
   c. Huygens added light dusting of lenses with coal dust to reduce aberrations
3. Just as important as the improved optics, Huygens in the late 1650's also added markings allowing direct measurement of angular distances between objects
   a. Gascoigne had invented the micrometer earlier, but it had been lost, and Hooke invented one at roughly the same time as Huygens, but Huygens's micrometer as announced in *Systema Saturnium* had more impact
   b. Combination of higher magnification and micrometer allowed precise measurements of observed sizes, though still handicapped to some extent by the glow around the edges from chromatic aberration
4. Huygens added the compound negative eyepiece still named after him in the early 1660's -- i.e. he put two convex lenses together in the eyepiece of his aerial telescope
   a. With suitable spacing between the two lenses, get a reduction -- more accurately, a correction -- of chromatic aberration
   b. Net effect was that the astronomical telescope had become a developed technology by the mid-1660's allowing not only much higher magnifications, but clearer images too

5. As with the clock, others picked up Huygens's inventions, extending and improving them
    a. The screw micrometer was developed in Paris in the mid 1660's by Picard and Auzout, allowing a very precise measure of subtended arcs
    b. Cross-hairs were introduced, which together with proper collimation allowed precise measurements of observed positions
    c. Improved lenses were being offered by many, with the best ones by Campani (initially in Rome)

E. Huygens's *Systema Saturnium* (1659)

1. Using telescopes incorporating his initial improvements, Huygens made two key discoveries concerning Saturn in the mid-1650's -- the first truly major discoveries since those of Galileo in the second decade of the century
    a. Saturn has a satellite -- Titan (1655)
    b. Bulges in Saturn are in fact rings (1656)
2. The discovery of the first satellite of another planet offers a further opportunity to pursue empirical cross-checking through developing orbital elements
    a. Huygens himself publishes careful data on "the uniform movement" of the Moon of Saturn (p. 264)
    b. Titan's eccentricity small (0.029), but not so small as those of the satellites of Jupiter
    c. No opportunity to check Kepler's third "law" until after Cassini discovers two more satellites, in early 1670's (not confirmed in England until after 1685)
3. Huygens's discovery of Saturn's rings was more a matter of clever detective work, using the varying descriptions of his predecessors over a 40 year period, than it was a product of the superiority of his telescopes
    a. An example of the interpretive element in observation, for once learn to see the protrusions as rings, they appear to us to be rings
    b. Huygens's detective work summarized in diagram (p. 309) showing the different appearances of the rings, vis-a-vis the Earth, when Saturn is at different positions in its orbit
    c. Significantly improved telescopic observation of the rings, using Campani telescopes, plus right timing, revealed the Cassini divide in 1675
4. Huygens's discoveries were initially presented as evening papers to the famous Rohault discussion group, helping to make him the lead figure in this group following the death of Gassendi in 1655 (the group Molière fictionalized in his satire *The Learned Ladies* in 1672)
    a. *Systema Saturnium* published in 1659, including the results on Saturn and a description of the micrometer he had incorporated (pp. 228-231)
    b. Follow-up publications supporting the original in 1660, adding subsequent observations of Saturn in 1668, and determining orbital characteristics of the three known satellites in 1673
5. Few of Huygens's subsequent efforts lay within observational astronomy, but his contribution on

Saturn, much like those of Galileo in 1610-1620, showed that advances in the telescope had opened the way to a new round of discoveries

a. All the technical complications and headaches associated with new telescopes worth the effort
b. And, although comparatively few measurements, enough to provide a major impetus toward the telescope becoming an indispensable instrument of measure in astronomy -- the beginning of the end of Tycho's standard

III. Astronomy in a New Context: 1650s to 1670s

A. Cassini on the Sun and on Jupiter and its Satellites

1. Huygens was not the only person to be taking advantage of the improvements in the technology of the astronomical telescope in the late 1650's; Cassini was doing so too, along with other things
   a. Cassini joined Bologna faculty in 1650, where he was a colleague of Riccioli and Grimaldi
   b. During the 1650's he initiated a careful effort on the motion of the Sun, measuring meridian altitudes throughout the year using a specially constructed large gnomen at San Petronio
   c. As part of this effort, carried out impressively precise measurements to confirm Kepler's bi-section of the Earth-Sun orbit (convincing Riccioli, as well) (see Heilbron, pp. 102-119)
   d. These results revealed a discrepancy in the position of the celestial equator that led him to question both the solar parallax and refraction corrections used by Tycho
   e. (Horrocks had questioned these for reasons having to do with discrepancies in Kepler's orbits)
2. In the late 1650's Cassini began using telescopes by Campani, with truly superior lenses -- the highest quality of the era (along with Divini's), which others tried in vain to match
   a. In the early 1660's established that Mars, Venus, and Jupiter rotate on their axes, with Mars having a period a little longer than 24 hours and Venus a little under 24 hours (1666)
   b. Also confirmed a conjecture by Hooke that Jupiter is slightly flattened -- he estimated by 14/15
3. In 1650 undertook the project of working out detailed orbits for the four Galilean moons of Jupiter
   a. Others had determined periods and some elements, but precise distances from Jupiter could not be established without a micrometer; Kepler's suggestion that his third law holds for these satellites amounted to nothing more than that the periods are somewhere between the first and third power of the radii
   b. 15 years of observations, beginning with a copy of Torricelli's telescope in 1652, but making his most rapid progress in 1664 with the aid of 17 foot and 34 foot telescopes by Campani
   c. Able then to observe shadows of the satellites on Jupiter, from which he could determine velo-cities to a much higher accuracy
4. Cassini's tables giving ephemerides of the satellites of Jupiter were published in 1668, the first detailed accurate account of these orbits; useful for determining longitudes from eclipses
   a. Adopted circular orbits with uniform circular motion throughout, which he could get away with in the case of these four (e=0.000, 0.000, 0.002, 0.008)

b. Success in predicting eclipses depended mostly on his account of latitudes, which included an approximately 6 deg movement of the line of nodes per sidereal revolution of Jupiter

5. These tables attracted a good deal of attention in both England and France, where published reviews confirmed their accuracy, helping to stamp Cassini as at the forefront of observational astronomy

a. So far as I have been able to tell, Cassini does not address the question of Kepler's third "law," which Wendelin had said holds exactly for these satellites in a letter to Riccioli (in 1640's)

b. (Question left for Flamsteed to resolve in 1670's and 1680's, prompted in part by his knowledge of Streete and Horrocks)

B. Streete's *Astronomia Carolina* (1661)

1. A step forward with the publication of Streete's *Astronomia Carolina* in 1661, written in English and named in honor of newly restored monarchy of King Charles of England

a. The best among the several British works on planetary astronomy in the twenty year period starting and ending with Wing's books

b. The most eclectic, picking and choosing in pursuit of the most accurate predictive system

2. Elliptical orbits, using Boulliau's 1657 method of determining true from mean anomaly, not the area rule, but with superior orbital elements, in large part under the influence of Horrocks

a. (Boulliau's method attributed to Streete's friend, Robert Anderson, in the book)

b. As Table (from Wilson) shows, Streete comes closest to "correct" elliptical elements at the time

c. Flamsteed remarks in 1669, "I esteem Mr Streete's numbers the exactest of any extant."

d. (See graphs in Wilson (1989) showing discrepancies in ephemerides for the 1650-1690 period)

3. Follows Horrocks's *Venus in sole visa* in reducing the solar parallax to about 15 sec and using Kepler's third law to determine mean distances from periods

a. Significant improvements for Mercury and Venus, as we already know from Horrocks

b. Adapts a procedure of Herigone's (1637) for circular orbits to simple elliptical orbits to obtain eccentricity and aphelia

c. Denies that aphelia and nodes move, provoking a major controversy with Wing that extended across the 1660's, focusing on solar parallax and correct precession of the equinoxes; whether orbits are stationary (unlike Moon's) later to become an important issue

d. Invokes magnetism as a physical basis rather than a geometrical basis for defending (see Appendix)

4. Streete important because he shows the potential for refinement through revision of some of the assumptions underlying the *Rudolphine Tables*

a. Makes Horrocks's discoveries public, in process calling attention to Horrocks, whose *Venus in sole visa* is published in 1662 by Hevelius, to whom Huygens had sent a copy of the manuscript

b. Streete the first of the group in the 1650's and 1660's to pursue empirical improvement over Kepler, and not just comparability

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

include micrometers

   a. Cassini's review of the results, combined with (in some ways) more useful results obtained from time-synchronized measurements in Europe, led him to propose a value of solar parallax of 9.5 sec (21,600 earth radii), though not published until the 1680s
   b. Flamsteed, working by himself in England, but with great care, obtained essentially the same value, reinforcing the finding and giving welcome support to Cassini

5. The net effect of the expedition, then, which was not fully reported until 1684, was to institute a substantial reform needed for precise measurements
   a. A new obliquity of the ecliptic, the line of reference for latitude and longitude; a sufficiently small value of solar parallax to make parallax corrections less important; and a standardized correction for refraction (influenced by Snel's law, as published by Descartes)
   b. Also such side benefits as Richer's discovery that the carefully calibrated pendulum clock he took with him lost around 2 and 1/2 min every 24 hours in Cayenne
      (1) Implying a 0.35% decrease in the acceleration of gravity between the equator and Paris, contrary to Galileo
      (2) Which Richer then confirmed via repeated measurements with a 1 sec pendulum over several months, revealing a need to shorten the pendulum by 1.25 lines
   c. Richer's report giving the observations was published in the late 1670s, a few years before Cassini's on the conclusions drawn from the expedition

B. Newton on Refraction: the Newtonian Reflector

1. Newton appears publicly on the empirical science scene for the first time during the expedition to Cayenne, submitting two papers (letters) to the Royal Society
   a. Lucasian Professor of Mathematics at Cambridge, following Barrow's resignation in 1669
   b. Had not published his work in math, but had allowed it to circulate among some British mathematicians, establishing him as one of the leading, if not the leading mathematician in England
2. First paper in 1672 describes some extraordinary experiments in refraction, using prisms and yielding compelling empirical evidence that white light is composed of light of the several colors
   a. Brought the constituents of the spectrum back together to form white light in an extremely delicate experiment, though one successfully duplicated by Hooke
   b. Part of the basis for his particle theory of light -- i.e. for the conjecture that light is composed of different kinds of particles, corresponding to different colors
3. Paper also explained the phenomenon of chromatic aberration -- a consequence of different refractions of the different colors, resulting in misaligned focus
   a. Incorrectly concluded that chromatic aberration not correctable in a refracting telescope -- an over hasty conclusion, since proper use of Huygens's eyepiece will permit correction
   b. But still a major breakthrough, for now know what source is

4. Followed by a paper in the very next issue announcing the reflecting telescope and arguing that it will provide a way around chromatic aberration
    a. Newton's reflecting telescope used in Cambridge from 1668 on, but this the first public announcement
    b. Sharp edges and clear images, impressing all
    c. Nevertheless had little impact on astronomy over the next 25 years, while it was being technologically developed; but had major impact in the 18th century
5. One unfortunate by-product of these two papers was a sharp, public dispute with Hooke, and various others (including Huygens, though more subdued), who rejected Newton's interpretation of his results (within the particle theory of light)
    a. More specifically, ignored Newton's distinction between what the experiments established as fact -- white light composed of light of the several colors -- and its conjectured explanation
    b. Newton was already maintaining a sharp distinction between conjectured hypotheses and experimentally established fact, something others did not maintain
    c. Left Newton thoroughly displeased with Hooke, whom he probably regarded as a fool, and reluctant to participate further in the sort of critical give-and-take of the Royal Society
    d. No more contributions after Newton withdrew from the controversies in the mind 1670s until the "De Motu" manuscript in 1684, the forerunner of the *Principia*

C. Flamsteed and the Greenwich Observatory

1. The other key figure to gain prominence at this time was Flamsteed, who because of illness had not gone through university, but had instead taught himself astronomy during the 1660's
    a. From a wealthy family in Derby, and hence able to acquire some telescopic equipment and pursue the subject in his spare time
    b. Began communicating with others in the late 1660's
    c. Established himself as a first-rate observer, at least in Cassini's eyes, in 1672 when he reported his measurements of the parallax of Mars to him
2. At Flamsteed's instigation, and to some extent at his expense, the Royal Observatory was founded in 1675, under the aegis of the Royal Society, and he became the first Royal Astronomer
    a. Building designed by Wren, and equipment purchased with his own money and generous support of Sir Jonas Moore
    b. Carefully designed in spite of limited funds, as attested to by his own description
3. Flamsteed's observatory never had the quality of equipment of Paris -- causing him to leave planetary astronomy primarily to them, since he could not compete, and instead to concentrate on a star catalogue
    a. Had a 7 ft sextant, two telescopes (7 and 15 ft long), a 10 ft mural arc designed by Hooke that never worked especially well

b. Continued to add improved equipment, usually at his own expense, over the years -- e.g. 7 ft mural arc in 1688

4. What Flamsteed lacked in the way of excellence of equipment, he more than made up for with his painstakingly high standards as an observational astronomer
   a. Enormous care and dedication, coupled to great patience, over a 44 year career
   b. Throughout that time recognized both in England and abroad as one of the two top observational astronomers along with Cassini
5. A falling out with Newton and Halley in the early 1700's led them to attempt to discredit him via a premature publication of part of his Star Catalogue, purloined from him
   a. Crosthwaite published his full *Historia Coelestis Britannica* posthumously in 1725
   b. It remained the basic catalogue worldwide for the next 100 years

D. Changing Attitudes in Observational Astronomy

1. Thus by the late-1670's there were two Royal Observatories -- one in Paris and one in Greenwich -- that were professional in every sense of the word
   a. Headed by exceptionally capable astronomers, Cassini and Flamsteed
   b. Professionally designed to serve the purpose, with fully modern equipment, even if not the best in the case of Greenwich
2. Flamsteed and Cassini had the highest respect for one another as observational astronomers, and remained in close communication from the early 1670's on
   a. In effect, allowing the two observatories to cross-check one another, providing independent support of any exceptional findings
   b. This, of course, had the effect of insuring high standards at both observatories -- something that probably would have occurred anyway, given Cassini's and Flamsteed's predilections
3. This interaction between the two observatories and Royal Astronomers accordingly raised the standards in observational astronomy throughout the world
   a. A new sense of joint endeavor, with obligations to the discipline itself since sloppy work was rightly viewed as something that would just set everyone back
   b. A new guardedness in the statement of conclusions, with great attention given to ways in which findings were still open to further revision and refinement, if not outright rejection
4. This was especially true of Cassini and Flamsteed themselves as individuals, both of whom were always preoccupied with not overstating the case
   a. Constant attention to the potential implications of any imprecision of measurement and continual cross-checking using alternative approaches
   b. Staying up-to-date so far as possible with what was going on at other observatory and elsewhere
   c. Both much more preoccupied with observation than with theory
      (1) Flamsteed a Copernican, Cassini apparently a Tychonist

(2) But for both this irrelevant to their work

5. The resulting new attitude had benefits for all, for one could now turn to either observatory and get extremely reliable information about what was and was not known

   a. Newton, for example, could write Flamsteed rather than having to search through books and journals or do observations himself

   b. Helped make possible increasing attention to discrepancies between prediction and observation as a source of evidence, for could now rely on statements about the discrepancies themselves

E. Observational Anomalies: The Speed of Light

1. The increased attention to precision in observational astronomy during the 1670's revealed a number of small anomalies that were taken at the time to be a basis for further empirical discovery

   a. E.g. Picard had discovered the "movement" of the North Star in his expedition at Uraniborg

      (1) Hooke detected a similar movement in the 1670s, announcing that it was the long sought annual stellar parallax, but didn't follow it up with supporting measurements and others did not replicate

      (2) An anomaly that was not resolved until after 1725 with Bradley's discoveries of the aberration of light followed by the nutation of the Earth

      (3) This anomaly limited the level of precision in astronomy until then

   b. Also Flamsteed's observations of Jupiter and Saturn, the vagaries in the movement of which he initially thought could be accommodated through improved orbital elements, but whether they could remained open

2. One such anomaly was a perceptible delay in the onset of eclipses of Jupiter's innermost satellite, Io, versus Cassini's tables

   a. This was first noticed by Cassini in the early 1670's, with delays in the range of 10 min (of time)

   b. Cassini apparently at first suggested that a speed of light effect was involved, but dropped this idea because no similar anomaly was noticed with the other three Galilean satellites

   c. Cassini instead concluded that there is an irregularity in the movement of Io, a view he continued to hold long after others had become persuaded by Roemer

   d. (Important because the eclipses of Io were providing a simultaneously observable phenomenon that could be used to determine longitude differences around the Earth, as originally proposed by Galileo, but brought to fruition in expeditions supported by the Royal Academy)

3. Cassini's predictions of eclipses for August to November of 1676 were published in the *Journal des Sçavans* in August, and Roemer then predicted, on the basis of his theory that the effect was due to a finite speed of light, that the 16 November eclipse would be 10 minutes late

   a. The prediction was successful, and the December issue of the *Journal* carried Roemer's brief paper, announcing the view that the speed of light is finite and using the delay to measure it (see Appendix for *Phil Trans* translation of paper)

b. Claimed a speed of light corresponding to 11 min from the Sun to the Earth (versus our mean value of 8 min 19 sec), though it turns out his data would have supported a conclusion of 9 min
c. No attempt at a precise value in terms of an earthly measure because he knew that the solar parallax was still at issue

4. Notice here how the marked increase in precision in orbital astronomy led not only to a fundamental discovery in physics, but to a measurement that could not at the time be done on the ground
   a. Galileo's protegés at his center for experimental science in Florence had tried and failed to measure the speed of light, as noted by Descartes in his letter criticizing Galileo
   b. Roemer one of the first examples clear to everyone at the time that planetary astronomy had progressed to a point where it could provide "experimental" measurements of a much higher quality than comparable experiments on earth
   c. Roemer's measurement presupposed not just Cassini's accurate tables for Io, but also an extremely precise value of Jupiter's heliocentric longitude, as well as precise values for the Earth's longitude and Jupiter-Earth distances
5. Roemer's result, which was accepted right away by Huygens, Flamsteed, and Newton -- and more generally as it continued to account for the variation in the eclipses -- had important implications
   a. In astronomy it entails a new round of corrections of observations of planetary position -- e.g. observed oppositions of Mars as great as 7 minutes (in time) off the true opposition
   b. In physics it strikes at the heart of Descartes' theory of light in just the way that Huygens describes, opening the way to alternative accounts of the physics of light, including both Newton's particle theory and Huygens's wave theory
6. By 1684, enough had been learned about how to correct planetary observations -- for atmospheric refraction, parallax, and the speed of light -- to permit a substantial improvement over Tycho's level of accuracy
   a. Still limited by the "movement" of the North Star, so that full advantage of the telescope could not be taken until after the 1740's
   b. But major anomalies leading to potentially conflicting results and hence confusion had been eliminated -- in no small part in the way Kepler had envisaged, by drawing conclusions from discrepancies between observation and increasingly refined theory

V. Astronomy 70 Years After Kepler's *Astronomia Nova*

A. Mathematical Astronomy at the End of the 1670s

1. By the end of the 1670s seven distinct approaches to calculating the motions of the planets were known to be of the same general level of accuracy, all of them mathematically neutral between Copernicus and Tycho, all of them known to Newton in 1684
   a. Kepler's original approach, and Horrocks's variant in which 3/2 power rule used to determine mean distance; of the seven, only Horrocks's did not include full tables for all of the orbits

b. Boulliau's approach of 1657, after rejecting his initial approach and the equant

c. Streete's approach, combining Boulliau's method for location vs. time and Horrocks's approach for mean distance

d. Wing's approaches, with either his oscillating equant or his subsequent geometric device

e. Mercator's approach of 1664 and 1676

2. The one thing all these approaches had in common was that their calculated planetary trajectories were ellipses with the central body at a focus

   a. The ellipses were more or less the same, though specific values of the elements differed and there was some dispute over whether aphelia were precessing, with Streete saying no

   b. Triangulations supported the oval shapes and (to reasonable accuracy) the eccentricities

   c. Evidence insufficient to claim that they were exact ellipses, especially given uncertainties about changing elements of Jupiter and Saturn

3. The primary difference among the different approaches was the method used to locate the planet versus time, making the "true" rule for that the largest open question at the time

   a. Mercator had shown that, whatever approach is used, it will yield excessive errors for an elliptical Mars trajectory unless it closely approximates the area rule

   b. The alternatives to the area rule had the virtue of being computationally simpler, but they did have somewhat the character of computational constructs, at least as seen by some

   c. The area rule alone offered a promise of a physical account through the invariance of $rv_{\perp}$, though defenses for the other approaches were offered, as illustrated by Mercator's

   d. Question left open by the alternatives to area rule was whether some other no less accurate alternative might offer both a geometrical solution and have no less promise of a physical account

4. The question whether the 3/2 power rule should take precedence over more direct ways of determining mean distance gained importance from Streete's success and the publication of Horrocks's papers

   a. Does 3/2 power rule hold only in high approximation for the solar system or does it hold exactly

   b. Main argument for latter is Horrocks's demonstrated increase in predictive accuracy for Venus and Streete's high accuracy generally when rule used to determine mean distance

   c. Does the 3/2 power rule hold universally -- e.g. for satellites as well

   d. Question not openly addressed in the literature; Cassini's 1669 tables for satellites of Jupiter gave support, but Roemer's findings had put these tables under some question

5. Moreover, mathematical astronomy had yet to achieve an adequate lunar theory

   a. Kepler's and Boulliau's complex lunar models fell well short of observational accuracy

   b. Publication of Horrocks's papers had made public a more accurate model, but still inadequate

   c. Raising questions about the contrast between the Moon's motion and the comparatively well-behaved motions of the planets

6. A no less perplexing contrast between the prominent inequalities in the Moon's motion and their seeming absence from the motions of the satellites of Jupiter and Saturn
    a. Borelli's 1666 book inadvertently underscored this question when it used our Moon as the basis for a physics applying to the satellites of Jupiter, contending that the same complexities had to be present with the latter even though they had not been observed
    b. Cassini's 1668 tables, by contrast, had yielded very simple orbits, though the inequality he introduced rather than accepting the finite speed of light had complicated the orbits a little
    c. Cassini also had their lines of nodes precessing, just as our Moon's nodes precess
    d. The point is that the question was open about the relationship between our Moon's motion and that of the satellites of Jupiter and Saturn
7. And finally agreement had yet to be reached on the question of the trajectories of comets
    a. Hooke's lectures on comets had them describing a linear or near linear path, following Descartes
    b. Hevelius's *Prodromus cometicus* (1665) and *Cometographia* (1668) also offered physical causes to bend Kepler's rectilinear paths; latter book includes a catalogue of known comets to antiquity
    c. In 1681 Flamsteed proposes from symmetry of trajectory that what appeared to be two separate comets were in fact one
        (1) Comet had approached close to the Sun and then away from it
        (2) First time anyone had suggested anything like this
    d. Newton was at first excited by Flamsteed's proposal, but on reflection decided it was mistaken; three years later he changed his mind

B. The Underdetermination of Theory by Data

1. So many different orbital theories agreeing comparably with Tycho's data is an example of what philosophers have come to call the underdetermination of theory by data
    a. Philosophers now talk of the underdetermination of theory by all possible evidence, but in practice the situation that arises is underdetermination by available evidence
    b. We had earlier seen the underdetermination of the choice between Copernican and Tychonic theory by data consisting of geocentric longitudes and latitudes
    c. Now raising the possibility that those same data cannot select among competing orbital theories
    d. (As we can see retrospectively, the data were also underdetermining Galilean-Huygensian theory at least to the extent that they were compatible as well with inverse-square vertical acceleration)
2. In fact, while all the approaches were achieving more or less the same level of agreement with Tycho's data, none of them was falling entirely within what was thought to be the accuracy of those reduced observations
    a. (See graphs from Wilson in Appendix giving a modern assessment of typical inaccuracies)
    b. Unclear what to make of this so long as questions about the obliquity of the ecliptic and corrections for parallax and atmospheric refraction remained unsettled

   c. Finite speed of light and the seeming motion of the North Star observed by Picard at Uraniborg and Hooke's similar claim about a different star called attention to the potential need for still further corrections to observations

3. The long-term project of reconstructing observational astronomy telescopically from the ground up by the French Academy and Observatory offered some prospect of clarifying just how inaccurate the existing tables were
   a. But even then the question would remain whether the inaccuracies were coming from inadequate orbital elements or from the fundamental calculation rules used
   b. And, given the open questions about the motions other than those of the planets, the question of which calculational system had claim to truth might still remain open
4. Kepler had originally proposed that the underlying physics inferred from precise orbital motions would resolve the Copernican vs. Tychonic issue
   a. The multiplicity of calculational systems was now making it look like the physics underlying orbital motions might be needed to resolve questions about the precise orbital motions!
   b. Even the ellipse was open to question insofar as the most that had been shown was that it holds only to high approximation, with vagaries in the motions of Jupiter and Saturn raising questions
   c. And indeed a few years later Cassini proposed his "Cassinoid" as an alternative to it as part of his continuing goal of restoring the equant
5. The challenge was to establish the relevant physics without in the process having to beg the question of the actual motions
   a. Otherwise might end up with different mathematical systems with different underlying physics, all agreeing with the same body of celestial data
   b. In other words, underdetermination of theory by data all over again

C. Emerging Interest in Inverse-Square Forces

1. One final development in regard to underlying physics that had a major impact on planetary astronomy, as well as on Newton's *Principia*, requires mention
2. In 1673 Huygens published his masterpiece *Horologium Oscillatorium*, to which he appended without proof the theorems on centrifugal force
   a. They formed the theoretical foundation for his conical pendulum clock, though he apparently felt that the proofs were too far afield from the main subject
   b. Once published, the theorems were granted by many even though no one but Newton appears to have proved them before the *Principia*
3. One key theorem says that the centrifugal force in uniform circular motion -- as evidenced by the tension in the string holding the object -- is proportional to the weight of the object, its linear velocity squared, and inversely proportional to the radius

a. I.e force varies with v^2/r, equivalent to $r*\omega^2$, and hence to r/P^2, where ω is angular velocity and P is the period of rotation

b. Introduction now of Kepler's third "law" yields by trivial substitution that the centrifugal force involved in uniform circular motion conforming to Kepler's third "law" varies inversely with the square of the radius

c. (Huygens made no mention of this result, but Newton called attention to a topic related to it in a letter to Oldenburg in 1673 forwarding thanks to Huygens for his complimentary copy of the *Horologium Oscillatorium*; Oldenburg did not forward that letter to Huygens)

4. In England, where Streete's influence (i.e. Horrocks's) had produced stronger interest in Kepler's third "law," many people besides Newton noticed this result

   a. Most notably Wren, who saw it as a basis for proposing that the 'magnetic' gravitational forces preventing the planets from going off in a straight line vary inversely with distance squared

   b. Hooke had put forward a detailed set of hypotheses on 'magnetic' gravitation and celestial motion at the end of his monograph in 1674 announcing stellar motion (see Appendix)

   c. By 1679 he was in a position to add an inverse-square variation

5. Hooke's gravitational hypothesis therefore now took the form that the planets are deflected from straight line motion by an inverse-square gravity-like force aimed toward a central body

   a. The question Hooke then posed is, what trajectory will a body follow if it enters into the gravity-like influence of some other body with a given velocity and direction

   b. His conjecture was that it is some curve approximating an ellipse, but different -- "an Elleptueid" -- though still with a circle as a limiting case

6. Interest in this hypothesis by Wren and Hooke stimulated a good deal of discussion in London from the mid 1670's on

   a. Wren had a discussion with Newton on forces governing curvilinear planetary motion during a visit to Cambridge in 1677

   b. Hooke put his problem to Newton in a famous series of letters at the end of 1679, contending that Newton's superior skill in mathematics would enable him to determine the answer

   c. These letters initiated Newton's work that led to his *Principia*

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<u>Credits for Appendix</u>

Slide 2: Wilson (1970)
Slides 3, 4, 25: Boulliau (1657)
Slides 5, 21, 29, 48, 49: Wilson (1989)
Slides 6, 27: Wing (1669)
Slide 7: Huygens (1986)
Slides 8, 43: King (1955)
Slide 9: Van Helden (1989)
Slides 11, 13: Heilbron (1999)
Slides 19, 20, 26: Streete (1661)
Slides 22, 23, 28: Mercator (1676)
Slide 24: Kepler (1609, *Gesammelte Werke*, vol.3)
Slide 30: Bennett (1989)
Slide 31: https//royalsociety.org
Slides 32-37: *Phil. Trans*., no. 1 (1666)
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