    d. Table in Appendix shows the advantages of doing this, though when Horrocks tried it for Saturn, encountered difficulties raising questions about perfectibility of astronomy

6. These results, along with his observation of the 1639 transit of Venus, reported in his *Venus in sole visa*, which was finally published in 1662
    a. Found that the apparent diameter of Venus during transit was 76 sec (versus 12 min predicted by Tycho); and from this concluded that both Mercury and Venus subtend 28 sec of arc when viewed from the sun
    b. Using this same value for earth, obtained a horizontal solar parallax less than 15 sec -- one of the first to offer a half-way right value!
    c. (The Flemish astronomer Wendelin had proposed 15 sec of arc in 1630)
7. Notice Horrocks's research strategy here: faced with discrepancy between observations and theory, don't immediately abandon the theory, but push it for all it is worth
    a. Assume theory correct, and see whether discrepancies telling one something about data used to fix the numerical values of the elements
    b. Regardless of whether theory is right, this way can characterize the discrepancies in a manner that exposes exactly how the theory falls short
    c. Kepler, of course, had done this; but Horrocks unique in doing it with Kepler's theory in the decades immediately following Kepler's death
    d. Horrocks working on Mercury, and still concerned with problems he had in achieving the same success with Jupiter and Saturn, when he died in January 1641
    e. In process made clear that Keplerian orbits more promising even than Kepler himself had shown

G. Horrocks and the Problem of the Moon
1. Interesting to speculate how much more progress astronomy would have made between 1630 and 1660 if Horrocks had not died at the tender age of 22 (give or take a year) or had not been working almost by himself (save for correspondence with Crabtree, who died in 1644, at the not much less tender age of 34)
    a. The one person at the time who was making progress by building directly on Kepler's efforts, as evident throughout the second volume of his Posthumous works (1673), which includes a large array of observations and comparisons of different Tables
    b. (Others pursuing paths parallel to Kepler's that in time lent confirmation to his work)
2. Horrocks's preoccupation with the perfectibility of astronomy led him to reconsider Kepler's lunar theory, attempting to avoid appeal to any extraordinary "intensions and remissions"
    a. Reported by Crabtree to Gascoigne in summer of 1642, distributed privately in 1672, and finally published in 1673 (*Opera Posthuma*)
    b. At Flamsteed's urging, became a key starting point for Newton, and continued to influence people as far afield as Euler throughout next century
3. Horrocks first cleans up Kepler's lunar parameters, initially using observed lunar eclipses and

then observations of the moon outside of the syzygies

   a. Small changes in parameters governing the inequalities -- e.g. 2 deg 40 min for menstrual equation -- 10 min more than Kepler -- and 34 min 40 sec for the maximum value of the Variation -- 15% less than Tycho's value
   b. Small (45 min) change in Kepler's apogee too, in process eliminating an asymmetry in Kepler's theory

4. Subsequently finds that revised theory still outside the bounds he has set, leading him to three objections to Kepler's basic theory
   a. Too many distinct inequalities in Kepler's (and earlier) lunar theories, leading to excessive amounts of calculation -- nature is simpler than this
   b. Kepler's treatment of longitudes and latitudes not consistent: a wobble of orbital plane in account of menstrual inequalities in latitude, but no wobble in account of those in longitude
   c. In point of empirical fact, moon's motion away from syzygies does not conform with ellipse and area rule, the latter of which Horrocks is reluctant to abandon given that it holds for the planets
5. Horrocks's solution -- the final new theory -- has both the line of apsides and the eccentricity of the lunar orbit oscillating (with period of 2 times per year)
   a. Orbit is an ellipse with oscillating apse and eccentricity, and motions of moon on this varying ellipse conform with area rule -- while in Kepler's treatment of 2nd inequality, area rule violated (Horrocks's oscillation of apse saves area rule)
   b. A physical explanation, in analogy with conical pendulum, appealing to Sun's forces and inertial properties of matter; includes solar attraction, but no repulsion
   c. Significantly higher predictive accuracy than any previous lunar theory -- from discrepancies above 20 arcmin to ones around 10 arcmin (1/3 the moon's diameter)
6. Upshot again: more reason to take Kepler's "laws" to be (in some sense) exact than Kepler himself gives
   a. Horrocks can be viewed as engaged in a systematic exploration of Kepler's "laws", trying to develop empirical answers to the questions about them that we posed last time
   b. His successes in this regard ultimately began having influence 20 to 30 years after he died
   c. Newton's phrase, "as expostulated by Kepler" applies here too: Kepler's orbits as expostulated by Horrocks

H. Telescopic Innovations and their Impact

1. No real advance over Galileo's Dutch telescope until mid-to-late 1630's, when Kepler's proposed (1611) design developed (see Figure in Appendix)
   a. Let converging rays from objective be allowed to come to a focus, and resultant image then be magnified by means of a second convex (eyepiece) lens (yielding an inverted image)
   b. Advantage: rays converging on eye, so that more of them can be taken in by the eye, yielding a wider field of view, and allowing considerably greater magnification (Thompson, p. 4)

2. Meanwhile Snel's law of refraction (1621) published (without credit to Snel) in Descartes' *Dioptrique* (1637), reducing a wide range of questions about lenses to mathematical precision
    a. For example, Descartes identifies the phenomenon of spherical aberration and indicates that hyperbolically ground lenses (which Kepler had suggested in 1611) will correct for it
    b. Inability to ground aspherical lenses prevents this from helping for a decade
    c. Also Descartes wrongly confounded chromatic aberration with spherical aberration -- former explained by Newton (1672)
    d. Key point, however, is that new science of optics tells us which things seen in telescope are real and which are not, thus providing a supporting physics of observation
3. Fontana apparently the first to make extensive use of a Keplerian telescope, in the late 1630's
    a. His observations of Saturn and the moon circulated in letters (with Galileo denying that they were adding anything new)
    b. Published "picture book" in 1646, including phases of Mercury, belts on Jupiter, and perhaps surface markings on Mars
    c. (Lots of drawings of the moon at this point, including a full project by Gassendi and Peiresc in the mid-1630's, though van Langren's first true lunar map did not appear until 1645)
4. One other virtue of the Keplerian (or astronomical) telescope is that it allows the introduction of micrometers for measurements
    a. Gascoigne apparently first to introduce cross-hairs and micrometer in eyepiece, ca. 1641
    b. Another of the group of young midland-England astronomers who, like the others, died prematurely (in 1644, in the English Civil War), delaying the adoption of his advances
5. In short, a whole new generation of observational astronomers were coming of age at this time, with new instruments promising much larger magnifications; and with them a whole new range of discoveries and improved observations
6. Perhaps I should explain why telescope was so slow to offer advances in accuracy over Tycho's data for longitude and latitude
    a. Part of the problem is need to develop telescope, provide cross-hairs, and devise adequate mountings and “divisions of the circle” (to adapt Alan Chapman’s title)
    b. More important: uncertainties about systematic errors and corrections made for them -- parallax and refraction corrections
    c. Until these uncertainties were addressed and the systematic errors were known to be less than 1 min, not much reason to pursue extremely high accuracy in raw data

IV. The State of Astronomy as of Christmas Day, 1642

A. The "Copernican Revolution" -- 100 Years

1. Newton was born on Christmas day, 1642 (old calendar), 12 months after Galileo died, 12 years after Kepler, and just over 99 years after the publication of Copernicus's *De Revolutionibus*
    a. Galileo's *Dialogue* had become the chief instrument in effecting the Copernican revolution of world view, and with it a major transformation of university curricula