monument on his grave after he died in 1642

4. Another long investigated and somewhat disputed question: why did Galileo, a devout Catholic, go ahead with the *Dialogue* when he could see the very distinct possibility of what ultimately happened (see Fantoli)
   a. Wanted to free "science" -- a word he championed -- from the narrow-minded dogmatism that surrounded it in universities and that he had spent much of his lifetime fighting
   b. Wanted to save the Church from the mistake of interposing itself against the new science, in the process undercutting its intellectual respectability
5. Galileo succeeded on the first score, probably beyond his wildest imagination, in no small part thanks to the Church
   a. Wonder if he might have toned the book down if he had realized that it was going to have the impact on Catholicism that it did
   b. Equally, if he had realized that it was going to be the primary source for the educated public's conception of the birth of science
      (1) He was too good a scientist not to be uncomfortable with the picture of science he conveyed
      (2) But then too he was too much of a polemicist not to receive some pleasure from the fact that his greatest polemic could even distort the whole world's picture of history
6. A final question: was Galileo sincere in recanting
   a. Most outspokenly think not, for they cannot see how Galileo could have brought himself to reject the truth of Copernicanism
   b. But don't forget that perjury in such circumstances was a mortal sin, condemning one to eternity in Hell, and Galileo was a devout Catholic

III. Assimilation of the Two Revolutions in Astronomy from 1630 to 1642

A. The State of "Predictive Astronomy" in 1630

1. As remarked earlier, in retrospect we can see that Kepler was years ahead of everyone else in mathematical astronomy when he died
   a. Not just in substance, having identified Keplerian motion, determined methods of calculating such motion, and defined elements for all of the orbits from Tycho's data supplemented with some of his own
   b. But also in his understanding of where his astronomical efforts stood -- i.e. what was comparatively well established, what was more shaky, what was largely conjectural, etc.
2. Other sets of tables had been devised during the 1620's, besides Kepler's, and not surprisingly their authors made claims for them akin to Kepler's claims, giving the community a problem
   a. Longomontanus (1622), the other assistant to Tycho in 1600, in the manner of Tycho
   b. And van Lansberge (1630), predicated on the Copernican system and its uniform circular motion, and presupposing the integrity of ancient observational reports (in direct opposition to Kepler and Longomantanus) claiming a more secure long-term foundation

3. The "arguments" for Keplerian motion in the *Epitome* derive it from a physics that was far from established (even, one would think, in Kepler's mind)
   a. Kepler was aware of the conjectural character of the physics, and the extent to which it had been devised to conform with the astronomical results, rather than vice-versa
   b. And, as we shall see, its invocation of magnetic forces acting at a distance was in violation of the prevailing "mechanical philosophy"
   c. And even if it wasn't, there was the question of reconciling Kepler's magnet mechanisms with known magnetic phenomena -- e.g., no empirical grounds that a magnetic flux from a rotating body can drive another body in (or into) orbital motion
4. One could go back to the reasoning in *Astronomia Nova*, or attempt to arrive at the area rule and ellipse independently, but doing so was sure to reveal the hypothetical character of the reasoning
   a. Reasoning built on a Ptolemaic scaffolding which, though ultimately discarded, is crucial -- e.g. vicarious theory
   b. At some key steps Kepler makes moves that reach beyond the specific numbers he is basing them on -- e.g. bisected eccentricity in the case of Solar theory, the assumption of exactly equal and opposite discrepancies in support of the ellipse, and the assumption of the exact harmonic diametral distance rule
   c. Reasoning to the ellipse presupposes the area rule, which itself was introduced as a mere calculational approximation, then later justified on physical grounds that were open to doubts
   d. And ellipse and area rule make a clear empirical difference only in the case of Mars and Mercury, with the latter problematic because of limited, poorer quality observations
5. Of course, Kepler was aware of the large number of things he had done to double-check his conclusions and otherwise protect himself from being misled, but at the same time he could appreciate some residual problems better than anyone
   a. Still not entirely within observational accuracy, raising worries about whether the orbital elements were as exact as needed
   b. Questions about scale -- in particular, the solar parallax -- raising worries about whether Tycho's observations needed different corrections for parallax and atmospheric refraction
   c. Conflicting schemes of planetary sizes (from telescopic observations, together with issues of scale, raising questions about his harmonies and physics)
   d. Inequalities in the lunar orbit, and "instabilities" in the elements of Jupiter and Saturn (and he thought Mars), raising questions about second-order effects and hence about whether Keplerian motion was an idealization or just not true: is astronomy "perfectible" at all?

B. The Transit of Mercury in 1631

1. Kepler's ephemerides for 1629 to 1636 (*Admonitio ad astronomos rerumque coelestium studiosos*, 1629) display his concerns in the big deal he makes of requesting that the transits of Mercury and Venus predicted for 1631 be carefully attended to

a. Would provide the first direct observation of Mercury's heliocentric longitude, in the process checking the Tables and providing a basis for refinement

b. Would provide information about the size of Mercury, and hence about Kepler's conclusions regarding relative planet volumes and densities (reflecting his harmonies)

2. Transit was observed by Gassendi, with confirmation from observations by Remus (in Alsace) and Cysat (in Ingolstadt), all projecting the image through a telescope

   a. Predicted for November 7, but Kepler had warned of possible inaccuracies, so Gassendi had started his vigil on November 5

   b. Cloudy and rainy, but a break on the morning of November 7, allowing him and the other two to observe it -- the first observed transit of a planet across the face of the Sun!

3. (Fr.) Pierre Gassendi (1592-1655) subsequently became a prominent professor of mathematics and philosophy at the University of Paris, teaching scholasticism while openly opposing it

   a. One of the key figures in the development of modern empiricism and atomism

   b. The major opponent of Descartes in their generation (see *Meditations*, fifth "Objections")

   c. A good second-rank astronomer, who together with Fr. Mersenne made University of Paris a hotbed of the new "science" from the 1630's on

4. Gassendi's observation, reported in a published letter in 1632, (*Mercurius in Sole Visa et Venus Invisa*) showed Kepler's prediction to have been accurate to within 13 min in longitude, 1 min 5 sec in latitude, 5 hours and 49.5 minutes in time, and 14 min 24 sec in longitude at egress

   a. The Ptolemaic tables were off by 4 deg 25 min at egress, the Copernican by 5 deg, Longomantanus's by 7 deg 13 min -- "a matter of days rather than hours" (Wilson, p. 164)

   b. And van Lansberge's tables off by 1 deg 8 min in longitude and 17 min in latitude at entrance and 1 deg 21 min at egress

5. Though but one observation, the contrast in relative accuracies was so great that the *Rudolphine Tables* were at once put into a class by themselves, thereby setting a standard for all others

   a. Mercury a good test for Kepler since the most elliptical of the orbits

      "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, in Wilson, p. 100)

   b. From Gassendi's emphasis on the *Rudolphine Tables* in his announcement of the transit, Kepler (at last) begins to receive recognition, leading to the re-issue of the *Epitome*

   c. Though keep in mind that both Ptolemy's and Copernicus's net trajectories for Mercury, compounded out of circles, were oval in shape

6. Notice the logic here: if Mercury is elliptical and Mars may well be, so must all the rest be, whether their ellipticity is empirically detectable or not

C. Impact of the Transit on Predictive Astronomy

1. The message from the transit of Mercury was clear to all: whether Kepler's astronomical and physical theories are true or not, one best use the *Rudolphine Tables* for practical calculations

   a. Practical calculations by astronomers like Gassendi looking to observe a comparatively ephemeral event like a transit or an occultation
   b. Even more so practical calculations by astrologers, who had a much greater need for tables permitting calculations for remote times

2. But this had the effect of highlighting the one serious calculational problem in using Kepler's tables, the need for an iterative solution of Kepler's equation -- $M = E + e \lceil \sin E$
   a. To find a heliocentric longitude at a given time, t, start with time T at which planet was at aphelion ($-e \lceil \sin E$, if perihelion)
   b. Determine mean anomaly $M = 360/P \lceil (t-T)$ -- longitude of planet were it to proceed in uniform circular motion about center of "eccentric" circle
   c. Next, solve Kepler's equation for the eccentric anomaly E -- longitude of planet such that fraction of area of eccentric circle planet would sweep out in t = fraction of area swept out in ellipse (i.e. area ASQ/area of circle = area ASP/area of ellipse)
   d. Drop perpendicular from Q on circle to line of apsides; distance from center to point of intersection = $a \lceil \cos E$, and hence distance from sun = $a \lceil (e+\cos E)$
   e. From $SP=a \lceil (1 + e \lceil \cos E)$ can now determine true anomaly= arc $\cos[(e+\cos E)/(1+e \lceil \cos E)]$, and P just the point where SP touches perpendicular -- an ellipse
3. Those finding the problem step excessively cumbersome called for an alternative calculation system (or system of motion) yielding comparable accuracy, but bypassing the need for an iterative solution
   a. Did not really care whether alternative was true, so long as it yielded a reasonable approximation for purposes of calculation
   b. Main concern was to return to direct determination of longitudes, without the need for an iterative solution step
   c. (For the history of efforts on dealing with Kepler's equation, see Colwell, *Solving Kepler's Equation over Three Centuries*)
4. This in turn spurred mathematical astronomers to consider the possibility of replacing the area rule altogether, for it was the source of the need for Kepler's equation
   a. E.g. try an equant at the other focus of the ellipse, or if need be an equant in a movable location, so long as the calculation could be done directly with little loss in accuracy
   b. But keep the ellipse, insofar as Mercury, the most elliptical, was successfully predicted
5. And this in turn led some of the more theoretically minded mathematical astronomers to question whether the ellipse and area rule together were yielding the true orbit, or just a very close approximation
   a. Kepler's argument for the area rule scarcely compelling, for tied to a physical principle that seemed quite hypothetical
   b. And no independent verification of area rule being exact, for it must be verified in combination with a trajectory

6. The state of predictive astronomy as of 1642: suffer with the *Rudolphine Tables* when accuracy really needed, but hope for something else (which had yet to surface)

D. The Issue of Planetary Dimensions

1. The most heralded aspect of Gassendi on the transit of Mercury, however, was not its implications for the *Rudolphine Tables*, but its evidence that Mercury is far smaller than expected
    a. Apparent diameter only around 20 sec of arc (Cyset, 25 sec; Remus, 18 sec), roughly 1/6 the size Gassendi had expected
    b. Only Galileo at the time was arguing that the planets were in fact much smaller than telescopic observation suggests (see *Dialogue*, pp. 388-395)
    c. Many failed to witness transit because they had used pin-hole camera, thinking telescope not needed
2. Traditional planet sizes and distances, e.g. from Al-Farghani (ca. 850 A.D.) had Mercury's apparent diameter at 1/15 of that of sun, Venus's 1/10 (see Table in Appendix), while Gassendi had conclude that Mercury's is around 1/90
    a. Relative apparent sizes from relative distances (known via Copernican reasoning) and relative actual sizes (unknown)
    b. Sizes and distances in terms of an earthly dimension -- e.g. earth's radius -- a further issue
3. As indicated last time, Kepler's account of the physics underlying his third "law" had led him to the claim that planet densities vary as 1/⌈ SP
    a. Based on (not very accurate) observations of Jupiter and Saturn (by Remus), had concluded that planet volumes proportional to distance from Sun
    b. Gassendi's observation compatible with Kepler's view – one thing motivating the latter's concern with the transit
4. Ensuing dispute over whether Gassendi's observation some sort of optical illusion led to first empirically based -- i.e. telescope based -- table of relative apparent diameters (*Hortensius in De Mercurio in sole visa*, 1633) supporting Galileo's claims
    a. "Actual" values here based on van Lansberge's solar distance of 1500 earth radii (while correct value is nearer 23,000 earth radii)
    b. But notice the listings of values for apogee and perigee
    c. In this case telescope used not to extend vision, but to correct observational distortions
5. Transit of Mercury thus had the impact of directing empirical attention to the problem of planet sizes, and hence indirectly to the problem of the scale of the whole system (in terms of earth dimensions)
    a. Still substantial work to be done, but now being addressed empirically instead of "philosophically" or via "harmonies"
    b. Thanks to telescope, though telescopes with micrometers would have helped improve the apparent values even more

E. The Problem of the Solar Parallax

1. Since distances of planets from sun known relative to distance of earth from sun -- the astronomical unit -- and apparent diameters reasonably determinable empirically, all that is needed to fix the scale of everything is the distance from the sun to the earth
    a. I.e. the solar parallax -- the difference in the angle to the sun from a point in line with the center of the earth and a point on the tangent line from the sun to the earth
    b. A value that is much smaller than tradition would have had it, and consequently proved hard to pin down (8.8 arcsec)
2. Determines actual sizes of planets from apparent diameters, for once sun-earth distance known, can infer earth-planet distance at any time from orbital theory, and then get actual planet diameter versus earth's via simple trigonometry
    a. Hence of interest from Apollonius and Hipparchus on, though only successful determination was moon's size versus earth's
    b. Ptolemy's value of sun-earth distance: 1210 e.r., 19 times the distance from the earth to the moon (solar parallax = 2.84 min)
3. Tycho had adopted a solar parallax of 3 min, slightly greater than Ptolemy's value
    a. Had used this value as a basis for making parallax corrections to observations, reflecting the latitude of the observer -- corrections that were then offset by estimated corrections for atmospheric refraction
    b. In particular, then, Tycho's solar theory -- most notably, its eccentricity -- ultimately was based on his value for solar parallax
4. Kepler adopted half of Tycho's value of solar eccentricity -- 0.018 – for his bisected eccentrcity of his earth-sun orb it in both *Astronomia Nova* and the *Rudolphine Tables*, but he had also found the parallax of Mars to be undetectable
    a. This had led him to conclude that the Solar parallax had to be no more than 1 min of arc, a value he announced in the *Epitome* and in the *Rudolphine Tables*
    b. But did not go back and alter Tycho's corrections to his observations, nor Tycho's solar eccentricity
    c. (Nor did he incorporate his corrections for atmospheric refraction into the *Rudolphine Tables*, but stayed with Tycho's set of corrections)
5. Thus, as was clear to a variety of astronomers working on questions of celestial scale after the 1631 transit of Mercury, the whole issue of scale was somewhat up in the air until the Solar parallax was determined with greater confidence
    a. A central concern in astronomy over the next decades, affecting even Newton -- another evidential problem, though in fact tied to the classic problem of distances
    b. Raising immediate questions about the exactness of some of the observations on which tables were being based
    c. (An issue not entirely resolved until 1740s)

F. Horrocks on Venus: *Venus in sole visa* (1662)