THE NEWTONIAN REVOLUTION – Part One

Philosophy 167: Science Before Newton's *Principia*

Class 3

Kepler's *Astronomia Nova*: The Orbit of Mars

September 16, 2014

TABLE OF CONTENTS

I. Prefatory Remarks: Some Background on Kepler 1
A. Overview of the Class: Planetary Astronomy 1
B. Turning Data Into Evidence: Evidential Arguments 2
C. The Kepler of Legend: A Contemporary Version 4
D. Kepler: From Birth to *Astronomia Nova* 5
II. Kepler and the Crisis in Mathematical Astronomy 6
A. The Crisis in Mathematical Astronomy 6
B. Kepler's Response in *Apologia* 7
C. Kepler's Response in *Astronomia Nova* 8
III. Kepler's Discovery of his Five Revolutionary Reforms in Orbital Theory 9
A. The Empirical Problem of Determining Orbits 9
B. "Phase 0": On the Real versus the Mean Sun 11
C. "Phase 1": An Account of the Latitudes 12
D. "Phase 2": The "Vicarious Theory" 13
E. "Phase 3": Bisection of the Eccentricity of the Earth-Sun Orbit 15
F. "Phase 3" Continued: The Area Rule 17
G. "Phase 4": The Orbit Is Definitely Oval 17
H. "Phase 5": Alternative Oval Trajectories 19
I. "Phase 6": The Elliptical Trajectory 19
J. The Elliptical Trajectory and Diametral Distances 20
K. "Phase 7": A Physical Explanation 21
IV. Kepler's Original Justification for the Two "Laws" 23
A. The Context of Discovery and the Context of Justification 23
B. The Evidential Argument for the Latitude of Mars 24
C. The Evidential Argument for the Ellipse 25
D. The Evidential Argument for the Area Rule 26
E. Some Standard Objections to the Arguments 27
F. A Contrasting View of Scientific Evidence 28
G. A Defense of the Evidential Argument for Mars 30
Select Sources 32
Credits for Appendix 33

Philosophy 167: Science Before Newton's Principia

Assignment for September 21

Kepler's ASTRONOMIA NOVA and the Orbit of Mars

Reading:

Kepler, Johannes. A Defense of Tycho against Ursus. tr. N. Jardine, Preface, Chapter I, and last two paragraphs, pp. 134-158, 206-207.

Wilson, Curtis. "How Did Kepler Discover His First Two Laws?," a reprint from Scientific American in Astronomy from Kepler to Newton: Historical Studies.

--- "Kepler's Derivation of the Elliptical Path," a reprint from Isis in ibid. (preceding, written for historians)

Questions to Focus On:

1. What empirical evidence did Kepler have for the following claims:

   (a) Mars sweeps out equal areas with respect to the Sun in equal times.

   (b) Mars does not describe a circular path.

   (c) Mars describes an elliptical path.

2. Some 80 years later Newton remarked that Kepler had only guessed that the orbit of Mars is an ellipse. To what extent was Newton right?

3. What enabled Kepler to succeed with the latitudes of Mars when all mathematical astronomers before him had consistently failed with the latitudes of all the planets?

4. In Chapter I of the Apologia Kepler puts forward 11 points in reply to Ursus's suggestions that the hypotheses of astronomy should not be taken as if they were literally true or false. At the time (1600) he had yet to begin his investigations on the orbit of Mars. Which, if any, of the points could he have strengthened if he had revised Chapter I of the Apologia after these investigations had been completed in 1605?

Class 3: Kepler's Astronomia Nova and the Orbit of Mars

I. Prefatory Remarks: Some Background to Kepler

A. Overview of the Class: Planetary Astronomy

1. The Newtonian revolution, and hence this course, really starts with Kepler's efforts on Mars, and in the process on the earth-sun orbit as well, from 1601 to 1605

a. The first full reconstruction of planetary astronomy since Ptolemy

b. The first real effort to introduce physics into mathematical astronomy -- this largely in response to the crisis that had been created by competing world systems

2. The first two weeks were intended to accomplish several things, not the least of which was to eliminate some myths about Copernicus's role in the scientific revolution

a. Ptolemaic astronomy was not self-evidently absurd to anyone with modern scientific sensibilities; in many respects it was remarkably like modern science

b. The 16th century ended not just with two main competing world systems, the Ptolemaic and the Copernican, but with three; and the third, the Tychonic, raised far more serious questions about the epistemic limitations of planetary astronomy

c. Copernicus did not revolutionize science by invoking strict empirical standards where none had been in effect before; what he did was to realize that there was an evidence-preserving heliocentric mathematical transformation of Ibn al-Shāṭir's transformation of Ptolemaic astronomy

d. It was not the case that the evidence immediately made clear that the Copernican system is true and the Ptolemaic false; what the three competing systems did was to pose a rather profound evidence problem

3. The primary focus of this semester is on what those engaged in research did and did not know leading up to 1685 and Newton's *Principia*, when and how they came to know it, and how in the process certain unanswered questions became paramount

a. Not just what people believed, but what those who examined the available evidence most critically would at the time have rightly concluded about what was known

b. As you will see, that led those in the forefront of research into discussions of how evidence might be marshaled more effectively

4. The principal thing that had been known for centuries is that the planets, the sun, and the moon appear not to be engaged in uniform circular motion

a. The first inequality: a regular variation in apparent angular velocity, with period matching one sidereal revolution; e.g. Mars appears to move 40 percent faster when in Capricorn than when on the opposite side in Cancer, with the pattern repeating every 687 days

b. The second inequality: in the case of the planets, a further variation, evidenced by retrograde motion, with period matching the time between consecutive oppositions; e.g. in the case of Mars the pattern repeats every 780 or so days

c. Copernicus's main point was that the second inequality was in appearance alone -- a point taken over by Tycho

5. The 1400 year tradition in mathematical astronomy that had been initiated by Ptolemy yielded a rich set of mathematical methods
   a. Ptolemy's contribution was not using epicycles for the second inequality -- this he inherited from centuries before
   b. His contribution lay in his handling of the first inequality via bisected eccentricity, and the equant
   c. The success that this 1400 year tradition achieved with salient phenomena in the longitudes was not matched by its efforts on specific values of longitude, nor those on latitude
6. Though I haven't gone into a great deal of detail about it, this 1400 year tradition included sophisticated methods of evidential reasoning -- i.e. reasoning from observations to conclusions beyond them
   a. E.g. inferring r/R and eccentricity for the individual celestial bodies from patterns in the inequalities
   b. Or Ptolemy's reasoning to bisection of eccentricity
7. Kepler had inherited both the mathematical methods and the techniques of evidential reasoning from this tradition when he started on planetary orbits a little after 1600; the singular position he found himself in, however, was marked more by three other factors
   a. The crisis in mathematical astronomy -- at least in some people's eyes -- raised by the challenge of the apparent equivalence of the different systems
   b. Tycho's data, not only the most accurate and reliable data in the history of astronomy, but the first sustained body of data of notable extent and range since the ancient Babylonians
   c. In the light of these data, the indisputable inadequacy of any of the existing systems to match observed longitudes remotely within observational accuracy: see figure in Appendix
8. Will do three things this class
   a. Consider Kepler's reaction to the "crisis" in astronomy that developed especially after 1588, when Tycho published his system -- the crisis I laid out last time
   b. Then review the steps Kepler followed to the discovery of his first two "laws" -- i.e. to the discovery that Mars orbits the sun along an elliptical path, conforming to the area rule
   c. Finally, step back to assess Kepler's "evidential argument" for his findings on Mars

B. Turning Data into Evidence: Evidential Arguments

1. I should first say something about the phrase "evidential arguments" and related talk of turning data into evidence
   a. When I say to philosophers that the fundamental problem in doing science is to turn data into evidence, they are often surprised, asking me what the difference is between data and evidence

   b. When I say it to scientists, they usually react as if I have uttered a truism, and they are quick to grant that certain sciences have more success in turning data into evidence than others do
   c. What this amounts to, of course, is just that some sciences have more success in establishing theoretical claims than others do
2. An evidential argument consists of step-by-step reasoning from statements describing observations to a conclusion that reaches beyond these statements
   a. Such arguments in empirical science are the analog of proofs in mathematics, and like the latter they are rarely fully spelled out in scientific practice
   b. If our goal is to understand what evidence in science amounts to, then at some point we need to look at some evidential arguments in great detail to see what they really do and do not achieve
3. In spite of the fact that the course is supposed to be about the process by which successful sciences turn data into evidence, this will be the first time in it that we will be looking in any detail at the evidence behind a major scientific finding
   a. Little on the details of how Ptolemy’s working hypotheses enabled evidence on various features of the motions to be derived from observations
   b. In the case of Copernicus, went further by sketching a reason for preferring his (or Tycho's) system to Ptolemy's, but the reason did not involve an appeal to discriminating data at all
   c. Rather, the idea was that the working hypothesis that the five planets orbit the Sun potentially opened the way to converging evidence on the distances of those planets from the Sun in a.u. through triangulation
   d. The idea behind both cases is that some sort of theoretical apparatus is needed to turn data into evidence, and in the early stages of theory construction, this is often a working hypothesis
   e. But we have yet to see in detail how such a working hypothesis can pay off, and what empirical requirements have to be met to adopt one without undue risk of a garden-path
4. Kepler's evidence for his conclusions about Mars is, in many respects, a much more transparent example of the sort of evidential argument modern science has employed in the early stages of theory construction, when little in the way of theory is available to help turn data into evidence
   a. Contrasts with mere "saving the phenomena," as well as with invoking aesthetic and philosophic reasons to support theoretical claims
   b. As such, it really does engage in a process of turning data -- viz. Tycho's observational data -- into specific evidence for a series of novel claims
5. I find Kepler's evidence on Mars an especially instructive example of scientific evidential reasoning
   a. It raises most of the issues about scientific evidence that we will be concerned with during the rest of the year
   b. Issues at the heart of Kuhn's and others’ claim that evidence plays less of a role in science than has generally been thought

c. Distinctive features of this evidence: (1) limiting its dependence on specific working hypotheses; (2) remaining cognizant at all times that observations are inexact; (3) requiring plausible physics to go from conclusions about approximate to decisions about exact

6. Anyway, Kepler's discoveries about Mars are one of the great watersheds in the history of astronomy
   a. As many have remarked, rarely has a book been more aptly named, for modern planetary astronomy starts with *Astronomia Nova*
   b. And, for the first time in this course, it presents major theoretical conclusions that remain essentially intact today

C. The Kepler of Legend: A Contemporary Version

1. Rather ironic to be using Kepler as a prime example of evidential reasoning in science at its best, for historians of science sometimes use him as an example of just the opposite
   a. As someone who got several things right for the wrong reasons
   b. As someone who was persuaded by arguments that no entirely rational person then or now would have been so persuaded by
2. Indeed, the Kepler of legend is a person bordering on madness, a mystic prepared to believe in things that today seem preposterous
   a. The legend probably began with Galileo's *Dialogues*, where he takes Kepler to task for proposing the crazy idea that the moon somehow governs the tides
   b. But the legend is still being fed: e.g. Gingerich's reference to his "mathematical mysticism",
   c. And, in taking Kepler's "intense faith in number harmonies" to be typical of scientific reasoning, Kuhn turns the issue upside down by using him to argue that scientific evidence is not all that it is cracked up to be
3. Even the best historians who are looking at Kepler's work in detail -- including his manuscripts and notebooks -- tend to be critical of his evidential argument
   a. Wilson less so than, say, Gingerich, but both reflect the view (more than Stephenson does) that Kepler's evidential arguments show much less than he took them to be showing
   b. Finding faults with Kepler remains a popular sport
4. By contrast -- and I say this to warn you -- I will be defending Kepler as someone who may well have had a deeper understanding of what is involved in scientific evidence than many of those who criticize him -- especially evidence in the early stages of theory construction
   a. Few have had a keener appreciation of the value of theory in the process of marshaling evidence
   b. And few have exhibited higher empirical standards of a certain sort
5. Furthermore, as the full title of *Astronomia Nova* attests -- *A New Astronomy Based on Causation, or a Physics of the Sky Derived from Investigations of the Motions of the Star Mars, Founded on Observations of the Noble Tycho Brahe* -- Kepler himself intended the book to be a watershed in the history of "scientific method"

a. He thought of himself as showing the world how to bring evidence to bear in astronomy

b. So it is not entirely out of line to consider why he might have thought so

D. Kepler: From Birth to *Astronomia Nova*, 1609

1. Though completed in 1605 following 4 years of intense work, *Astronomia Nova* was not published until 1609 because of disagreement with Tycho's heirs on credits and on who had rights to publish Tycho's data

   a. Difficult to read, because written as if presenting the sequence of his research, including false starts and what was learned from them – see its Table of Contents and display of structure

   b. (I say "as if" because Voelkel's study of manuscripts has shown that his path to his conclusions was not the one laid out in *Astronomia Nova*)

   c. Book contains a good deal of shifting numbers, along with various calculation errors like the one on p. 167, which propagates through the rest of the book (see Neugebauer, p. 461)

   d. (The footnotes correcting prior historians in Wilson's *Isis* article are indicative of this difficulty, as was the more than decade long effort of Donahue's English translation)

2. Kepler, who was born in 1571 to a poor family abandoned by his father, struggled financially his entire life (often because his patrons failed to pay him money they owed him, but sometimes because of the Counter-Reformation)

   a. His brilliance in school gave him his education, in effect through scholarships

   b. Undergraduate, followed by a Masters from Tübingen, concentrating on theology and philosophy, but also studying astronomy under Mästlin, a leading Copernican astronomer of the time

3. Though he would have preferred a position in theology, ended up as professor of mathematical astronomy (in Roman Catholic Austria) upon graduation, leading to his first book, *Mysterium cosmographicum* (1596), which attracted some attention

   a. In part because he sent copies to everyone prominent in the field, eliciting their remarks -- e.g. Galileo, Tycho, and Ursus -- and also perhaps because the Appendix Mästlin added provided such a clear account of the Copernican distances in the *Prutenic Tables*

   b. (All his life Kepler sought approval and recognition from more prominent figures, usually not receiving it)

   c. A somewhat heroic figure who maintained his enthusiasm in the face of great adversity: first wife died, as did 8 of his 12 children, and his mother was prosecuted as a witch

4. In pursuit of better data to bring to bear on the ideas of *Mysterium* Kepler asked to become Tycho's assistant after the latter came to Prague

   a. Tycho insisted that Kepler first write the *Apologia* in order to undercut Ursus's appeal to Kepler in his disputes with Tycho

   b. Not published at the time because of Tycho's death in 1601 -- bad enough form to publish such a polemic when one of the principals was dead, and hence totally inappropriate once both dead

c. Because it was not published until the 20^{th} century, did not become part of science; but still useful in giving Kepler's views of the goals and status of mathematical astronomy

5. On his death-bed Tycho apparently exacted a promise from Kepler to figure out the "true path" of the planets from the data
   a. Kepler kept the promise, working relentlessly on the problem from 1601-1605
   b. The "war on Mars" -- four years of 6 digit calculations (without the benefit of a "computer"), not knowing whether anything was going to come out of it
   c. (Romanticized account in Arthur Koestler's *Sleepwalkers* and *Watershed: A Biography of Johannes Kepler*; see also John Banville's novel, *Kepler*)

II. Kepler and the Crisis in Mathematical Astronomy

A. The Crisis in Mathematical Astronomy

1. The crisis in mathematical astronomy reached its fullest proportions in the last decade of the 16th century, following publication of Tycho's alternative system in 1588
   a. The very years in which Kepler was a college student and beginning professor of astronomy
   b. (Conceivably the thing that swung him away from theology and permanently into astronomy)
2. Outwardly, crisis took the form of challenging the exalted status of the discipline within universities
   a. Does astronomy really deserve its exalted place if it is unable to determine which of three such different systems -- the Ptolemaic, the Copernican, and the Tychonic -- is true?
   b. Does astronomy amount to anything more than just clever calculation schemes for approximating, not all that well, observed locations of celestial objects?
3. Those within the discipline could appreciate even better than those outside that such challenges had a legitimate basis
   a. For they appreciated the extent to which the systems could be mathematically transformed into one another
   b. And hence they understood the extent to which each system could be adjusted to accommodate empirical considerations
   c. And of course they more than anyone saw how the generic Copernican and Tychonic systems appeared to be observationally indistinguishable
   d. Added to which, those astronomers who had access to Tycho's observations were aware of the magnitude of the discrepancies between observations and all the prior systems
4. The issue, then, was whether and how empirical data could be brought to bear to determine which, if any, of the systems was the true one
   a. How is the dispute over the systems to be settled in a principled, empirical way?
   b. An issue that fed, and fed off of, the broader issue that dominated 17th century epistemology -- *how are any questions to be resolved in a principled way on the basis of empirical information, especially given the problems of separating appearance from reality?*

5. During the first decade of the 17th century Kepler gave much thought to this issue within astronomy
    a. Along with other methodological questions: *On More Certain Foundations of Astrology* (1602), *Astronomia pars Optica* (1604), and *Dioptrics* (1611)
    b. *Astronomia pars Optica* covers research Kepler conducted while working on Mars in an effort to get a better handle on atmospheric refraction than he suspected Tycho had; the research led him to read Apollonius's *Conics*, in the process introducing 'focus' as a new word in mathematics
    c. The answer Kepler gave to the fundamental issue of choosing among the three systems on a principled basis was not nearly so influential as his specific astronomical findings were
    d. But in some respects it anticipates Newton's answer

B. Kepler's Response in the *Apologia*

1. Kepler's *Apologia*, originally entitled "Tract on hypotheses," is a direct response to Ursus's claim that astronomical hypotheses should not be taken as true and false, but as mere calculational devices
    a. View now known as "instrumentalism": theories are merely calculation devices which are only required to agree properly with the data, but otherwise make no claims about what is really true
    b. Contrast with the position known as "realism": theories are making claims about what really underlies observed phenomena
    c. Various intermediate positions between these two
2. Kepler asks the key question, the question with real bite:

    "Why, then, you may ask, given that they all demonstrate the same motions of the heavens, is there nevertheless so great a diversity of hypotheses?" (p. 140)

    a. Basic answer (pp. 140-142): equipollence may be illusory, arising from failure to allow for further forms of evidence, like the parallax of Mars; moreover, ultimately no equipollence, for

        "Even if the conclusions of two hypotheses coincide in the geometrical realm, each hypothesis will have its own peculiar corollary in the physical realm." (p. 141f)

    b. Further answer (pp. 142f): two hypotheses that are contradictory may nevertheless not be contradictory, but equivalent, relative to some one set of conclusions being derived from them
    c. Conclusion (bottom of p. 143) Popperian: "... Nor can it happen in astronomy that what was originally founded on a false hypothesis should be true in every respect ...."
3. In his point-by-point reply to Ursus, Kepler emphasizes how hard it is to come up with any hypotheses that allow calculation of the observed motions (p. 147)

    No one denies that there are still some flaws in even the best-constructed astronomy, and hence in the hypotheses also. (p. 147)

    Hypotheses are sought which will correspond to the motions of the heavens. The Alphonsine hypotheses are found to err, likewise the Copernican. But the skillful practitioner, having made a comparison of the two and having removed the sources of error, establishes some third [hypothesis] which avoids all error in the prediction of the motions of the heavens and in that way corrects both hypotheses. (p. 150)

a. An emphasis on precision of agreement, if not on exactitude, which was missing from Ptolemy and Copernicus, along with open admission that not yet there

b. A criterion for preferring one hypothesis to another, other things remaining the same: the one that is more accurate

4. But calculational accuracy not the sole criterion or constraint:

> There are two distinct tasks for an astronomer: one which truly pertains to astronomy, is to set up astronomical hypotheses such that the apparent motions will follow from them; the other, which pertains to geometry, is to set up geometrical hypotheses of whatever kind... such that from them those prior astronomical hypotheses, that is, the true motions of the planets unadulterated by the distortion of the sense of sight, both follow and can be worked out. (p. 154)

a. Astronomical hypotheses required to give the true motions -- the trajectories

b. And required not to entail physical falsehoods -- i.e. not as such required to include an account of the underlying physics, but required not to imply things false of the underlying physics

c. Contrasting equivalent devices like the eccenter and a minor epicycle, while geometrically different, are astronomically the same in that they yield the same trajectory -- alternative calculation devices

5. Remainder of the *Apologia* reviews the history of astronomical hypotheses, showing not only that Ursus's historical claims are false, but that the view that hypotheses are to be taken seriously was held by ancient astronomers as well

a. Ends with defense that Tycho did not steal his system from anyone else, including Copernicus

b. And calls attention to the fact that Tycho has added features (that could be added to the Copernican)

C. Kepler's Response in *Astronomia Nova*

1. As the full title of *Astronomia Nova* suggests, the idea that the physical cause of the actual motions is directly germane to astronomy even more in the forefront there

a. The "physics" generally appealed to is derivative from Gilbert's *De Magnete* (1600), which attracted a good deal of attention

b. Not physics in our sense, but a thorough description of the phenomenology of magnets, including pole effects, the earth's magnetic field, etc.

c. "Naturalistic" in contrast to "theoretical" science

2. As you will see in reading the Introduction for next week, Kepler starts from an open statement that the three chief systems are, at least up to a point, observationally equivalent

> The three opinions are for practical purposes equivalent to a hair’s breadth, and produce the same results. (p. 48)

a. Qualification because they are not physically equivalent -- i.e. each has physical implications incompatible with the others

b. Still, Kepler acutely aware of the observational equivalence problem

3. Primary purpose is to correct astronomical theory of Mars to remove discrepancies with observation

   > My aim in the present work is chiefly to reform astronomical theory (especially of the motion of Mars) in all three forms of hypotheses, so that our computations from the tables correspond to the celestial phenomena. (p. 48)

   a. E.g. Prutenic tables off by almost 4 deg in August 1608, and almost 5 deg in August and September 1593
   b. Note the claim that he is correcting Mars for all three systems: knew that his results for Mars and earth could be compounded into a Ptolemaic account

4. Secondary purpose is to show, from consideration of the underlying physical causes, that "only Copernicus's opinion concerning the world (with a few small changes) is true, that the other two are false, and so on." (p. 48)
   a. Openly admits that much of the physics is (and he says always will be) conjectural -- indeed, has to be, given the state of physics at the time!
   b. Conjectures in which the Sun plays a central role
   c. But also directly challenges the physical plausibility of the motion attributed to Mars by Ptolemaic and Tychonic systems, displaying the "pretzel" shape of the motion in Chapter 1 in the process of reviewing restrictions in the traditional approach taken to the two inequalities (see Appendix)
5. Kepler's response to the crisis, then, is that the three systems are not empirically equivalent once one attacks the matter properly
   a. Through a combination of demanding full agreement with observations, on the one hand, and considering possible lines of physical causation, will be able to show that Copernican is, if not correct, is at least the most plausible of the three
   b. Key thing to note here is the idea of playing off precise agreement with observation, on the one hand, with some sort of physical considerations, on the other
   c. This last was the primary respect in which Kepler's approach anticipated Newton's

III. Kepler's Discovery of his Five Revolutionary Reforms in Orbital Theory

A. The Empirical Problem of Determining an Orbit

1. Observed geocentric longitudes (and latitudes) cannot be brought to bear on questions of planetary trajectories and motions -- i.e. orbits -- in the absence of some theory or working hypothesis
   a. E.g. the classic working hypothesis adopted by Ptolemy and Copernicus that the motions are compounded out of uniform, or at least equiangluar, circular motions
   b. Upon abandoning this hypothesis, Kepler had to come up with other hypotheses in order to derive any conclusions about the orbit of Mars (and of Earth) from Tycho's observations
   c. One worry with any such hypothesis was to avoid its begging the question of the orbit from the outset; another worry was a need for different mathematics from the known geometry of circles

2. Kepler's approach was to try to use discrepancies between provisional hypothesized orbits and observation as evidence to reach the correct orbit -- i.e. via successive approximations
   a. In addition to hypothesized orbits for Mars, he used and refined Tycho's earth-sun orbital theory, as well as assumptions that authorized his interpolating among Tycho's observations
   b. To constrain his hypotheses, he always demanded of them a plausible physical mechanism
3. One difficulty in trying to use discrepancies as evidence was the variety of sources potentially contributing to them besides inadequacies in the motion hypothesis then under consideration
   a. Tycho's observations had margins of uncertainty of at least 2 min of arc
   b. Kepler's approaches to interpolating among them widened their bounds of uncertainty
   c. The supplemental provisional theory -- of the earth-sun orbit when working on the orbit of Mars and of Mars when working on earth-sun orbit -- added still further uncertainty
   d. Kepler often could not make rigorous calculations for hypothesized motions, but had to resort to novel approximations, adding still more uncertainty
   e. (Not to mention calculation errors, from working with six significant figures, or simple arithmetical mistakes of the sort mentioned above and illustrated in the Appendix)
4. Another difficulty: the orbit of Mars is so nearly circular that highly discriminating evidence is needed to establish an alternative to equiangular motion along a circle
   a. Mars as of 1600 had an eccentricity of 0.09304 and a mean distance from the sun of 1.52369 a.u., resulting in a major axis of 304,738 in Kepler's units (based on 100,000 for mean sun-earth distance) and a minor axis of 303,416, so that the oblateness amounts to only 0.43 percent
   b. A hypothesis of equiangular motion along a circle with bisected eccentricity gets within a few min of arc, requiring observations with uncertainty much less than 10 min of arc to establish an alternative to it
5. Thus the problem Kepler took on was extraordinarily difficult, and his success deserves the praise heaped on it by such figures as Charles Saunders Peirce (his exemplar of "abduction")
   a. Kepler's successive approximations involved him in several false starts and frequent need to step back and assess whether extraneous sources of discrepancies were invalidating conclusions
   b. This made *Astronomia Nova* extremely difficult to read, for the evidence often depended on the specific false start, and hence they could not be ignored by the reader
   c. Symptomatic of this was the ten years Bill Donahue worked on the translation, having to re-derive, as best he could, the numbers Kepler gives in the book
   d. All of this, especially the convoluted line of evidential reasoning through the book, helps to explain why it seems to have persuaded no one but Kepler himself
   e. Still, historically that was all that mattered, for he then found other ways to connect with others
6. Wilson's reconstruction of Kepler's reasoning, focused as it is on the question of how Kepler reached the ellipse, drops some of the complications of the argument in *Astronomia Nova*

a. That is, it drops some of the pathways that Kepler reported and inferences drawn from them; also several of the cross-checks he pursued in order not to be misled by discrepancies he had derived; and, in rearranging the logic a little, it glosses over some of the arithmetical errors
b. Save for its understating how much use Kepler makes of triangulated distances (corrected here), we can think of Wilson's reconstruction as the sort of thing a good reader at the time might have extracted from *Astronomia Nova* in laying out the central argument of the book for the ellipse
c. Save for its focus on the ellipse, this is what we want, for we are interested more in the development of evidence for the community than in biographical details concerning Kepler himself

B. "Phase 0": On the Real versus the Mean Sun

1. From a quick glance at its Table of Contents, you can see that *Astronomia Nova* has five main parts
   a. On the relationships among the hypotheses
   b. An initial approach to the first inequality, in the manner of the past astronomical tradition
   c. Towards a new approach to the second inequality, through a new account of the earth-sun orbit
   d. The new theory of the first inequality for Mars: the ellipse and area rule
   e. The new theory of latitudes, verified and explained
2. Wilson glosses over the first part, which takes the important step of showing that the choice between using the mean sun and the actual -- i.e. visible -- sun as reference point is potentially important
   a. Astronomically significant by yielding different sun-planet distances
   b. Empirically detectable, though only with a change in evidence practice
3. Kepler himself had shifted from the mean to the actual sun in his *Mysterium cosmographicum*, for reasons of physics, independently of any compelling empirical evidence for doing so
   a. Once one abandons crystalline celestial spheres, the center of the Earth's (or Sun's) orbit ceases to have any physical significance; it becomes a mere point in space, echoing Copernicus's complaint about the equant
   b. The step to the actual sun is thus abetted by a conceptual shift; Kepler, being of the new, post-Copernican generation, saw the mean sun differently
   c. Instead of crystalline spheres, Kepler assumed a physics of forces acting between actual bodies in the manner described in Gilbert's *De Magnete*, generating motions
4. Tycho had challenged Kepler on using the actual sun instead of the mean sun, arguing that, with his theory of the sun, employing the mean sun as reference point, he was able to achieve good agreement with observed longitudes of planets, and hence there was no reason to switch
5. Kepler's reply, in Chapters 5 and 6, argues that Tycho's good agreement may well be misleading (see figure in Appendix)
   a. Chapter 5: So long as one restricts oneself to acronychal observations -- i.e. observations when near opposition, so that Mars rises in evening and sets near dawn -- difference in longitude for the actual and the mean sun will be small, as in the case of X and Y in the figure

   b. But this is because these observations eliminate distance from central to orbiting body as a factor
   c. Chapter 6: By contrast, data in which the earth, sun, and planet are not aligned will reveal large observable differences in longitude resulting from the different distances
   d. Kepler goes through the exercise of comparing the orbit in reference to the actual versus the mean sun first for the Copernican, next for the Ptolemaic, and then part way for the Tychonic (leaving the rest to the reader), identifying in each case a maximal observable difference in longitude and showing it would be greater than 1 deg -- i.e. more than two Moon diameters
   e. That is, he forms what later became known, thanks to Francis Bacon, as an *experimentum crucis* – an “experiment of the cross” or "cross-roads" experiment -- for each of the three systems
6. Even though this is just a hypothetical argument, as it occurs in Part I (postponing further confirmation until Part V), it contributes significantly to the overall evidential argument in three ways
   a. First, when the reference point is switched from the mean to the actual sun, and no such discrepancies show up when theory and data are compared, one will have an empirical argument for using the actual sun -- i.e. having lines of apsides pass through true sun
   b. Second, when a classical orbit about the actual sun yields comparatively small discrepancies in acronychal longitudes, one can infer that a significant fraction of the longitude errors in past theories results from having used the mean sun
   c. Third, the difference implies that one must look to longitude observations removed from periods of retrograde motion to determine the true orbit -- a change in astronomical practice that Kepler takes to heart

C. "Phase 1": An Account of the Latitudes

1. What Wilson calls "Phase 1" of Kepler's "War on Mars", the account of the latitudes, is in Chapters 12-14, with a second final pass in Chapters 62-66, very late in the book
   a. Chapters 12-14: three different methods of determining inclination of Mars orbit with line of nodes passing through actual sun
   b. Inference to specific inclination angle in each method presupposes heliocentric longitudes, whence the refinement at the end of the book using his new account of longitudes
   c. Also need earth-Mars distances to infer geocentric latitudes from heliocentric latitudes
2. Basic result: orbit of Mars is inclined at a constant angle of 1 deg 50 min vis-a-vis the ecliptic
   a. Claim: no variation as Mars goes around orbit
   b. Result initially using a pre-Keplerian model of the orbit, but same result at the end of his book after he reaches his new model
   c. Claim: result confirms line of nodes through true sun
3. Using the true sun, instead of the mean sun, as reference point is the key to the breakthrough
   a. The first example of a payoff from Kepler's "physics" -- use an actual physical body as a reference point, and not the preferred mathematical point that everyone else had used

b. Ptolemy's and Copernicus's treatments of latitude so complicated, and so unsuccessful, in large part because of this

c. Kepler ends up offering an explanation of the inclination in terms of an interaction between the (hypothesized) magnetic actions between the sun and Mars

4. Kepler's approach was to use certain privileged observations -- e.g. when the Earth is on the line of nodes and the line from Earth to Mars is perpendicular to the line of nodes (Wilson, Fig 4)

a. Used a number of privileged observations of this sort, obtaining stable values for the inclination

b. Then at end, after orbit defined and inclination corrected to 1 deg 50 min, 30 sec, compared calculated and observed geocentric latitudes for a large number of observations at opposition, concluding, contrary to Copernicus, that no other element needed to account for latitudes

c. Finally, takes the trouble to check Ptolemy's observed latitudes (for fear of changes over long periods of time): consistent with little change (Ch. 68-70)

d. (First pass needed because Kepler had to locate the nodes of Mars preparatory to using Tycho's data to determine oppositions to the actual sun in deriving his first theory of the orbit)

5. A tremendous step forward in the history of planetary astronomy

a. E.g. comparison of calculated and observed latitudes for the 12 oppositions used by Kepler shows several in the 2-5 min range and one of 13 min -- owing to a mistake in calculation: 3 deg 20 min should be 3 deg 26 min (p. 388)

b. Attributes remaining discrepancies to uncertainties in parallax and atmospheric refraction

D. "Phase 2": The "Vicarious Theory"

1. To use triangulation to infer Mars-sun distances, need earth-sun distances and, more important, heliocentric longitudes for Mars and earth

a. Tycho's (improved) theory for the sun was known to give accurate heliocentric longitudes for earth -- this via comparison of theory and measurement for Tycho's large number of observations of midday altitudes of the sun

b. Worst problem, then, was to obtain trajectory-independent heliocentric longitudes of Mars

2. Approach: use observations at opposition, when heliocentric longitude of Mars is the same as that of earth -- i.e. when heliocentric and geocentric longitudes of Mars coincide

a. Calculated 12 oppositions from groups of observations made roughly at the times of opposition -- extracting an "observation" from Tycho's observations

b. Took opposition relative to true sun, and not to mean sun (as had been the customary way to define it, in keeping with the mean sun being the reference point for the basic time unit)

c. Not just redefining "opposition", but then also inferring the time when opposition occurs from observations near, but not at opposition

3. Assumed a quasi-Ptolemaic model for Mars -- an eccentric circle, with an equant at an independent eccentricity along the line of apsides

a. Knew the radius of the circle, but had to determine line of apsides, locations of eccenter and equant, and the time of aphelion
b. I.e. four unknowns requiring four observations and solution of what amounted to a 16th-order equation
c. No direct calculational methods then available, so had to proceed by trial and error (first requiring the four to lie on a single circle of known radius and then requiring the center of the circle to lie on line between sun and equant)
d. Selected four observations from the 12 and proceeded through 70 trials until requirements met
e. Then checked result against the other 8 observations, finding an average discrepancy around 50 sec, with a maximum of 2 min 12 sec

4. Upshot was a model -- he called it his "Vicarious Hypothesis" -- that predicted Mars's heliocentric longitudes to within the accuracy of Tycho's observations everywhere around the zodiac, provided that Mars orbits the sun
   a. Could henceforth use this theory in place of observations to determine heliocentric longitudes for Mars at any time under the proviso
   b. Thus freeing him from having to depend on specific observations that were primarily acronychal -- i.e. near opposition
   c. If instead of the proviso a Ptolemaic account of Mars is adopted, the vicarious hypothesis gives the longitudinal position of the center of the Mars epicycle on its deferent at all times
5. The trouble, however, was that the vicarious theory was demonstrably false
   a. Angles in earth-sun-Mars triangle known from Tycho's solar theory, Kepler's vicarious theory, and observation
   b. Earth-sun distances known to reasonable accuracy from Tycho's solar theory; Kepler confirmed this, by using parallax observations, to show earth-sun distances do not change very much
   c. Can thus calculate Mars-sun distances from observations; Kepler did so, and found that the center of Mars's orbit falls near the midpoint between the Sun and the equant, and not at a little more than 0.6 of the distance between the two as the vicarious theory had it
   d. Changing the center in the vicarious theory to the midpoint yielded heliocentric errors in longitude as large as 8 min, well outside the error-bands of Tycho's observations
   e. (This was the second cross-check; the first revealed discrepancies in latitude near opposition, discrepancies that could be removed by bisecting the eccentricity)
6. (From parallel reasoning, the violation of bisected eccentricity when the vicarious hypothesis is taken to give accurate longitudes along Mars's deferent shows its inadequacy in a Ptolemaic theory as well)
7. Upshot: the model underlying the vicarious hypothesis must be wrong -- either equant or circular trajectory or both wrong (see quote from end of Chapter 20 in appendix); this freed Kepler from having to stay within the constraints of a 1500 year tradition in astronomy

a. Corollary: if trajectory a circle, no point of equiangular motion at all (see Appendix); at best a point oscillating in location along the line of apsides

b. Obvious question: how can the theory give heliocentric longitudes within observational accuracy

c. Kepler took the trouble to answer (Chapter 21), showing that the location of the equant is more critical than the location of the center

8. Notice finally that without Tycho's accurate measurements, no Keplerian reform of trajectories, for modified vicarious theory would have been found accurate to within 10 min of arc -- the old observational standard

a. Names and dates in the history of science would be different

b. Kepler's view of the relative accuracy of Tycho's observations was also crucial here

E. "Phase 3": Bisect the Eccentricity of the Earth-Sun Orbit

1. Kepler chose first to abandon the equant, not just because it had long been criticized, but also because he saw no hope of giving a physical explanation of equal angular motion about a mere point in space

a. Note here that two separate elements involved in any planetary theory, the trajectory and the variable rate of motion along it

b. Really then two separate assumptions being adopted in prior theories

2. From before he had begun with Mars, he had conjectured that the (arc length) velocity of the planets was inversely proportional to their distance from the sun -- in keeping with his conjecture that a magnetic flux from a rotating sun drove all the planets, a flux that diminished inversely with distance

a. He showed that this variation in velocity is approximately correct, via comparison with planets

b. Moreover, with Ptolemy's bisected eccentricity, exactly correct at two ends of lines of apsides (on the deferent) for each planet, though not elsewhere

c. Thus reconcilable with classic approaches to fixing apsides and eccentricity

3. Problem: in prior theories of the sun, including Tycho's superior theory, no bisected eccentricity of earth-sun orbit; instead equiangular motion about the center

a. Therefore a direct empirical objection to hypothesis that planet velocities vary inversely with distance from the sun (taking earth to be a planet)

b. Had to dispense with this objection before proceeding

c. Provided multiple arguments from different observations, considering Ptolemaic, Copernican, and Tychonic theories, as well as his own, and ended with an argument laying out his physical conjecture

d. (A numerical error made the first of these arguments appear better than it was)

4. In his main effort to show that bisected eccentricity should hold for the earth-sun orbit too, Kepler used combinations of three observations 687 days apart so that Mars (presumably) in the same place each time (or, on Ptolemaic view, center of Mars's epicycle in the same place on its deferent)

a. (Note the tacit assumption, which amounts to counting on nature being regular in a certain way; also the assumption that Mars is in orbit around the sun, for on Ptolemaic theory it is not in the same place every 687 days, only the center of its epicycle is)

b. Could then use triangulation to infer ratios of three earth-sun distances in each case, from which could calculate center of presumed circle

c. Calculated distances subject to errors from observational inaccuracies

d. Not surprising, then, that he obtained varying results, ranging from 0.025 to 0.01653 using his vicarious theory of Mars's heliocentric longitudes, and from 0.01837 to 0.01530 using the preliminary Copernican-type theory Tycho had developed for Mars about the mean sun in the 1590s

e. But all showing near middle between Sun and equant, and definitely not coincident with latter

f. Also compared apogeal and perigeal apparent diameters of sun (30/31), giving a value of 0.0164

5. Transporting this same reasoning to a Ptolemaic system showed that Mars's epicycle requires a point around which equiangular motion occurs that is removed correspondingly from the point at which it is attached to the deferent

a. That is, the vicarious hypothesis and observations of geocentric longitudes of Mar again defined three distinct triangles every 687 days between the earth, the point of attachment of the epicycle on the deferent, and Mars on the epicycle (see figure in Appendix)

b. These three defined a circular trajectory for Mars on its epicycle showing that its point of attachment and point around which motion is equiangular straddle the center of the circle, at least to reasonable approximation

c. This, of course, is a conclusion about Mars's epicycle, not about the earth-sun orbit, but that did not stop Kepler:

> That these characteristics belong to the Ptolemaic epicycle, is properly demonstrated. But that they are carried over from the epicycle to the theory of the sun is shown by a probable argument only, pieced together from Ptolemaic opinions (Chapter 26, p. 145)

d. Arguing that whatever is true of Mars's epicycle should be true of those of Jupiter and Saturn as well, Kepler offers a diatribe against Ptolemaic systems (see Appendix), while nevertheless granting that his bisected eccentricity reform can be incorporated within them

e. Having shown that the reasoning from observations (and the vicarious hypothesis) can be transported from one system to another, Kepler from here on reasons in terms of the Copernican

6. On this basis hypothesized exact bisection for a circular earth (or sun) orbit, contrary to a tradition dating back to Hipparchus: 0.018, half of Tycho's value, 0.03584, rounded

a. (Note: did not use average of calculated values; hence an idealization)

b. Checked by comparing heliocentric longitudes of earth calculated with new model against Tycho's original at the quadrants and octants of anomaly, finding good agreement (9 sec, but correcting for calculation error, 1 min 7 sec)

c. Then carried through a mathematical analysis to explain why the longitudes would be so much more sensitive to the distance between the sun and equant than to the location of the center of the circle, thus explaining Tycho's success with the sun (Chapter 31)

7. The combination of the actual sun and the bisection of the eccentricity of the earth-sun orbit reduces the discrepancies in Mars's orbit from greater than 4 degrees to a few minutes of arc -- a reform that can be introduced just as well to the Ptolemaic system (see Voelkel and Gingerich)

   a. In effect, an order of magnitude-plus reduction in discrepancies between observation and Ptolemaic theory when latter revised for actual sun and epicycles have bisected eccentricity

   b. Had these two reforms been carried out earlier, a very high standard of observational accuracy would have been required to give reason to pursue the further refinements of the area rule and the ellipse

F. "Phase 3" Continued: the Area Rule

1. Now adopts new hypothesis in place of the equant -- arc length velocity everywhere varies inversely with distance from the sun

   a. Kepler had long believed that the sun provides the motive power driving the planets, and thought it must diminish with distance in keeping with the longer periods of outer planets

   b. In Ptolemaic type orbit as in vicarious theory, with equant but with bisected eccentricity, velocity exactly inversely proportional to distance from sun at perigee and apogee

   c. So, now replace the equant with this feature of it, but generalizing across entire orbit: a minimal move beyond the vicarious theory

2. But now finds this new rule for locating Mars versus time calculationally taxing (needed calculus)

   a. Substitutes an approximate method, dividing circular orbit into equal 1 deg segments, computing distance of each arc from sun and adding up these distances, so that the time in each arc determined by the ratio of its distance to the sum of the distances

   b. Verifies this simplification against Tycho's solar theory (within 9 arcseconds)

3. Then happens upon a still simpler approximation to the inverse distance from the Sun rule: equal areas in equal times (Chapter 40: "An Imperfect Method ...")

   a. I.e. area of sector as a measure of all the distances within the sector (which were being summed on above method): assume areas proportional to times for the equal arcs

   b. Again verifies against Tycho's solar theory (within 34 arcseconds)

   c. Note the reasoning here: so long as within observational error bands, both methods okay

4. Proceeds through remainder with two separate motion rules to replace the equant hypothesis, the inverse distance rule and the area rule, though he never states the latter in a fully perspicuous manner until after *Astronomia Nova*

G. "Phase 4": The Orbit is Definitely Oval

1. Given rule (in fact two rules) for motion, now ready to address question of trajectory

a. But not in a position to infer distance from sun via motion rule alone, for directional orientation of each small arc not determined

b. I.e. still had to make some assumption about trajectory

2. Asked what physical factor might conceivably cause an eccentric circle, as in revised "solar" theory, if sun controlling the velocity (via magnetic effect)

   a. Concluded that planets must have independent source of motion superposed on sun effect

   b. This representable by means of a small epicycle superposed on circle with sun at center, to produce a circle with sun off center (a classic Apollonian move, as discussed in *Apologia*)

   c. For orbit to be circle and area rule to be satisfied, motion in epicycle must not be uniform; but proceeded anyway

3. I.e. proceeded to use assumed circular trajectory and the area rule to determine heliocentric longitudes of Mars, comparing them with values obtained from the vicarious theory

   a. Result: good agreement in apsides and quadrants, but error in octants

   b. +8 min 21 sec for first octant, -8 min 1 sec for third (see figure from Wilson in Appendix) -- i.e. planet moving too rapidly in apsides, too slowly in quadrants

   c. Verify that these discrepancies not just from using area rule by confirming that comparable discrepancies emerge as well with the 1/r rule

   d. To satisfy area rule, then, orbit must be oval rather than circular, for need less area around the quadrants; same true with 1/r rule as well

4. Triangulation calculations of the sort described last week (using the modified earth-sun theory) confirmed that the orbit is an oval of some sort (see Appendix), but sensitivity to observational errors prevented him from concluding what specific oval

   a. These triangulations used heliocentric longitudes from the vicarious theory, earth-sun distances from the modified solar theory, and geocentric longitudes from Tycho's observations -- all elements that had not been available e.g. to Copernicus

   b. Calculations difficult, given need to control for observational errors; Kepler tried several ways

   c. Conclusion: orbit comes in around 800/152,500 parts, with estimated errors of 100 to 200 parts

5. Two upshots: (1) orbit some kind of oval; and (2) area rule survived a test, for it predicts an oval and the distance calculations, though inexact, confirm an oval

   a. (Moreover, the conclusion that it is some kind of an oval is theory-dependent to a sufficiently large extent that some would have seen it as piling hypothetical conclusions on top of hypothetical conclusions in just the way that elicits objections and complaints in courtrooms

   b. Maybe why Kepler hesitated for two years before finally abandoning the circle)

6. Did manage to get some valuable conclusions out of the triangulations (see Appendix):

   a. To within the bounds of uncertainty, the oval is bi-laterally symmetric with respect to the line of apsides (Chapter 51)

b. Only a line of apsides through the true sun has its end points maximally near and far from the true sun, and a line of apsides through the mean sun does not have its endpoints thus maximally near and far from it

c. Confirmation of the location of the aphelion, with aphelial distance = 166510, perihelial distance = 138173, eccentricity near 14169 (0.093 vs earlier 0.09265) for earth-sun orbit radius = 100000

7. Finally, notice that the combination of using true sun as a reference point and the area rule has eliminated almost all the error from a classic eccentric circular model for Mars! (see table)

a. Why then is Kepler more famous for the ellipse than for these two steps?

b. Suspect the answer is twofold:

(1) The shift from using the circular geometries of the 2000 years of previous astronomy

(2) No one worked through *Astronomia Nova* sufficiently to realize how little work the ellipse was doing for Mars

H. "Phase 5": Alternative Oval Trajectories

1. One might naturally expect Kepler at this point to adopt the classical oval from geometry, the ellipse, and see how it does in conjunction with the area rule in yielding heliocentric longitudes

a. But not what he does, undoubtedly because saw no physical reason why orbit might be elliptical

b. Not engaged in just finding a geometrically familiar trajectory that agrees within observational limits, but wants one with some physical basis

2. Thus tries same sort of epicyclet model as before, but now with uniform circular motion on epicycle

a. This together with area rule yields a slightly egg-shaped oval, with bulge end at perihelion

b. Uniform motion on epicycle less physically objectionable than former non-uniform motion

3. Difficulties in carrying through the area calculations led him to approximate this oval by an ellipse (his "auxiliary ellipse", as shown in the figure from Gingerich in Appendix)

a. Result: good agreement again in apsides and quadrants, but error in octants -- errors essentially the reverse of before

b. -8 min for first octant, +7 1/2 min for third (Fig 9) -- i.e. planet moving too slowly in apsides, too fast in quadrants

4. Upshot: auxiliary ellipse yields excessive correction versus circle, roughly twice the amount of correction needed; proceeds to check, for several chapters, whether approximations, including auxiliary ellipse, might be responsible for the excessive discrepancies

5. The auxiliary ellipse an idealization, but one not prompted by idea that nature will conform with mathematics; rather, purely to ease computation, which is recognized throughout to involve uncertainty owing to observational inaccuracies, and hence is at best only approximate to begin with

I. "Phase 6": The Elliptical Trajectory

1. Working under the assumption of the area rule, the discrepancies at the octants between the circle of "Phase 4" and the "auxiliary ellipse" of "Phase 5" are opposite, and almost exactly equal

a. Indeed, equal to within bounds of uncertainty from multiple sources

b. But then nothing empirical standing in the way of simply saying that they are equal and opposite

c. I.e. an idealization of the data, but one within bounds of uncertainty

2. Once this move is made, then orbit must be precisely midway between the circle of "Phase 4" and the "auxiliary ellipse" of "Phase 5"

a. That is, it must be an ellipse!, ingressing by 429 out of 100,000 parts (the value I gave above)

b. Notice here how the combination of the area rule and Tycho's observations is entailing that the trajectory is an ellipse, at least to very high approximation

> In effect the area law controls the shape of the orbit. The areas swept out around the sun are assumed to be proportional to the times. Variously shaped orbits distribute the total area of the orbit in different ways; only one shape of orbit will get the planet to the right place at the right time. On the assumption of the area law the right orbit can differ only negligibly from the intermediate ellipse. (Wilson, p. 102)

3. Still using bisected eccentricity in a circular earth-sun orbit, predicted observed positions of Mars from the Earth for 28 of Tycho's observations bracketing seven oppositions from 1583 to 1595

a. Elliptical theory of Mars gives heliocentric longitude and distance of Mars from sun versus time; bisected circle gives earth-sun distance versus time: two sides and angle determine triangle

b. As Table (p. 341) displayed in the Appendix shows, average discrepancy less than 3 min and maximum less than 6 min

c. 20 of the 28 points within 3 min, 15 within 2 min

4. Of the four worst residual discrepancies in this table, three are primarily from bad observations, according to Gingerich's computer program, as used by Harper and Smith:

a. 30 Dec 1582: correct locus 16.4.14 and discrepancy 2 min 6 sec

b. 13 May 1591: correct locus 2.17.53 and discrepancy 2 min 17 sec

c. 10 Jun 1591: correct locus 26.0.47 and discrepancy 2 min 50 sec

d. 28 Jun 1591: correct locus 21.9.39 and discrepancy 5 min 18 sec

5. This is more than an order of magnitude improvement on all prior accounts of the orbit; indeed, more than a factor of 20 improvement

a. The first real advance in modeling planetary motion since Ptolemy -- 1450 years earlier

b. A totally new standard set by this table, replacing the one that had held sway since Ptolemy

c. Any alternative theory of Mars was going to have to do at least this well versus Tycho’s data

J. The Elliptical Trajectory and Diametral Distances

1. Kepler now knew that an ellipse midway between his circle and his auxiliary ellipse would yield heliocentric (and geocentric) longitudes within more or less his bounds of uncertainty

a. But so too, undoubtedly with some other trajectories approximating it

b. Moreover, the reasoning to the ellipse was predicated on the area rule, and it had been introduced as merely an approximation to a preferred rule, giving added reason to question the ellipse

2. The comparison between the circle and the auxiliary ellipse, both of which were within the bounds of uncertainty at apsides and quadrants, indicated that the 100000 circular radius of the orbit at the quadrants needed to be decreased from 858 units to half that value, 429
    a. He says he then stumbled on the fact that the secant of the angle (in the circle), CQS, = 1.00429
    b. That is, get the desired distance CM at the quadrants by setting SM to 100000 there
3. Now generalizes this: the right way to measure the required distances from the Sun to Mars is by taking the projection on the diameter, TP, of the distances to points on the circle
    a. I.e. the SM distances everywhere are given by the rule, $r(1+e\cos x)$, where r is radius of circle and x called the "eccentric anomaly" -- see figure from Wilson in Appendix
    b. Kepler calls these the diametral distances: the "diametral distance" rule
4. Checks this rule against the triangulated distances he had derived from Tycho's observations before
    a. Table (in Appendix) shows that rule gives correct distances within the bounds of uncertainty
    b. Notice that this rule and its confirmation do not presuppose either the area rule or the ellipse; the evidence presupposes only the heliocentric longitude curve-fit of the vicarious theory and Kepler's earth-sun theory with its bisected eccentricity
5. Now asks how the distances in question should be laid off from S, that is, as radius vectors extending from S, under the requirement that the resulting heliocentric longitudes vs. time be correct
    a. First try, consistent with the 429 shortening at the quadrant: intersection between radius vector of appropriate length and radius from center of circle for each value of the angle x
    b. Result: a "puff-cheeked" orbit not symmetric about the diameter at the quadrants, with calculated heliocentric longitudes (using the area rule) outside bounds of vicarious theory uncertainty
    c. Second try, consistent with the 429 shortening at the quadrant: intersection between radius vector of appropriate length and a perpendicular to the line of apsides
    d. Result: an exact ellipse, with the 429 shortening at the quadrant, and one for which the area rule holds exactly; by earlier comparison of discrepancies for circle and auxiliary ellipse, eliminates the discrepancies (vis-à-vis the vicarious theory) in the octants and everywhere else
6. On this construal of Kepler's reasoning, played off triangulated distances against heliocentric longitudes: any two of the three rules -- ellipse, area rule, and diametral distance rule -- if taken to hold exactly, has the vicarious theory entailing that the third holds as exactly as that theory holds!

K. "Phase 7": A Physical Explanation

1. Kepler now had a cinematic model of the Mars orbit accurate to within observational accuracy, give or take a little, but he still had no physical basis supporting the claim that the model gives the true motion, nor for that matter much of any basis for insisting that the true path is exactly an ellipse rather than something closely approximating it
    a. Still no physical reason why the orbit might be an ellipse instead of a circle
    b. Given that the area rule only approximates the inverse distance rule, no physical reason for it

c. And questionable whether to settle on the ellipse as exact if going to infer underlying physics from the trajectory

2. From the outset had singled out the true sun because, as a physical body and not an empty point in space, it can govern speeds: velocity varies inversely with distance from it
   a. That raises a question: why is sun not at center of the trajectory
   b. That question had led Kepler to posit a reciprocating motion of the planet along an epicycle of radius e to yield the eccentricity in classic Apollonian style
   c. Had then devised an ad hoc physics to account for that motion, a physics that had later led to his egg-shaped oval (see Chapter 39)
3. With diametral distance rule in hand, replaces the epicycle and its physics with a distance that contracts from aphelion to perihelion and then expands
   a. He thinks such a sinusoidal variation the sort of thing that occurs in nature
   b. Physics proposed now postulates magnetic fibers in each planet, with a north-south polarity typical of magnetic action, as shown in figure in Appendix, as taken from Chapter 57
4. General idea: when at aphelion fibers oriented neutrally, so that their interaction with the Sun results in no net increase or decrease of distance from Sun
   a. As Mars moves away from aphelion, one pole of its magnetic fibers nearer the sun, resulting in a net magnetic attraction toward it
   b. Effect vanishes at perihelion, where again magnetic action becomes neutral
   c. As Mars moves away from perihelion, the other pole of its magnetic fibers nearer the sun, resulting in a net magnetic repulsion away from it
   d. Both the ellipse and its eccentricity physically dictated by the strength of the interaction of its magnetic fibers with the sun
5. Struggles to get the precise diametral distance rule from this physical action
   a. E.g., why should the eccentric anomaly -- an angle defined with respect to the center of the circle -- be the variable governing the distance
   b. And why should the effect bring Mars closer along lines perpendicular to the line of apsides rather than along the radii of the circle
   c. And (in Part V) how are the fibers dictating the angle of inclination of the orbit
6. Still, comes away from this with three conclusions that complete the "war on Mars"
   a. The Mars-sun distances in the elliptical orbit exhibit a variation that is physically reasonable -- this because of the new distance rule
   b. There is a basic relationship between his original velocity rule and the area rule, once the velocity in the original rule is interpreted as the velocity (component) normal to the r-vector
   c. That it was this component that matters was consistent with Kepler's claim of a magnetic vortex from a rotating sun drives the motion, for the vortex should be normal to the radius vectors

d. The discovery that the $1/r$ distance rule can be reconciled with the area rule by having v be the component of velocity perpendicular to the radius vector is nowhere stated clearly in *Astronomia Nova* or quite anywhere else by Kepler, but only subsequently

e. The orbit is an exact ellipse (or, as he adds in a letter to Fabricius, differs insensibly from such an ellipse), for "here the consequences derived from physical principles come into agreement with the results of observation and the vicarious hypothesis." (Wilson, p. 21)

7. Upshot: ellipse and diametral distance rule hold as perturbations of a circular motion produced by a second physical action superposed on the basic action of the Sun, with the second action varying in strength from planet to planet

IV. Kepler's Original Justification for the Two "Laws"

A. The Context of Discovery versus the Context of Justification

1. Now want to turn to the question, what exactly did Kepler's evidence show about the orbit of Mars?

a. Need to be careful here because the evidence for a scientific claim typically changes over time, sometimes quite rapidly

b. Want to determine the best evidential argument as of 1609 for the following claim: the orbit of Mars is an ellipse (with minor axis 0.429 percent shorter than major), along which Mars sweeps out equal areas in equal times vis-a-vis the Sun; furthermore, the plane of this ellipse, which passes through the Sun, is tilted 1 deg 50 min relative to the plane of the Sun-Earth orbit

c. Then want to decide what his best evidential argument in 1609 actually shows about this claim

2. Here doing something a little controversial, for I am implicitly invoking Reichenbach's distinction between the context of discovery and the context of justification

a. I.e. separating the steps leading to discovery from the steps justifying the conclusion

b. Former, of course, need not be rational or logical at all

c. But latter, on the view that the two are distinct, must be rational and logical for justification

d. To put the point differently, justification will in general require a rational reconstruction of the discovery process, eliminating elements of irrationality and leaving just an evidential argument

3. Kuhn, in particular, has attacked this distinction as one of the primary ways in which philosophers distort science and its history

a. He argues that acceptance of a new result within the scientific community is often influenced by aspects of the process of discovery that are not amenable to rational reconstruction

b. These arguments are a central part of his attack on the idea that (rational) evidential considerations drive science

4. Kepler's *Astronomia Nova* would appear to be fertile ground for Kuhn, if only because the book itself argues for its conclusions about Mars by "recounting" the process by which they were arrived at

a. In truth, Voelkel has shown that Kepler himself engaged in some (presumably) rational reconstruction of the discovery process in *Astronomia Nova*

b. Voelkel himself calls the shifts from the actual discovery process rhetorical steps

c. But still the argument is presented in the spirit that anyone who will follow him along the presented steps of the discovery process ought to reach the same conclusions that he did

d. And, of course, with the advantage of hindsight we know that much of the physical reasoning Kepler invoked along the way will not stand up under scrutiny

5. So, in isolating Kepler's evidential arguments and subjecting them to a critique, we will be able to examine Kuhn's claim that the distinction between the context of discovery and the context of justification yields a distorted picture of science

   a. Did the evidential arguments provide those at the time with compelling reasons for accepting Kepler's conclusions about Mars?

   b. If not, then is this indicative that science is less rational than philosophers would have it be?

6. In addressing these questions, need to keep three distinctions in mind:

   a. Kepler’s conclusions holding ***exactly***, versus holding “***essentially exactly***” (i.e. would hold exactly save for some external perturbing factors) versus ***merely approximately*** (i.e. not precluding alternatives to them equally, if not more, supported by the evidence)

   b. Between assessing the specific form of Kepler’s conclusions, with their particular values for all orbital parameters, and assessing his generic conclusions -- e.g. Mars describes *an* ellipse

   c. Between Kepler’s conclusions holding and their being (provisionally) ***taken*** to hold for purposes of ongoing research

B. The Evidential Argument for the Latitudes of Mars

1. Not going to go into detail here on argument for true sun and bisected eccentricity of earth-sun orbit

   a. True sun: *experimentum crucis* on three systems, plus triangulated distance confirmation and support from solution for latitudes

   b. Bisection: idealization of an approximate result, supported by large reduction in worst discrepancies with observation

2. The claim about the latitudes of Mars really consists of four separate claims

   a. The trajectory of Mars lies in a single plane

   b. That plane passes through the true sun

   c. That plane is inclined at a constant angle with respect to the plane defined by the earth and sun

   d. The angle of inclination (in final theory) is 1 deg 50 min 30 sec

3. The evidence for the claim about the specific value of inclination turns on sets of privileged observations, like the ones in Wilson's Figure 4

   a. But the reasoning from the observations to the value is thoroughly "theory-dependent": e.g. not only does the interpretation of the observations presuppose the other claims forming the account of latitudes, but also the position of the line of nodes and the claim that the angle MES is 90 deg -- a claim that depends on the account of longitudes

b. The other privileged observations also presuppose the other claims, but they do not rely on entirely the same aspects of the other parts of the account of Mars

c. Furthermore, the different observations, with their different theory-dependencies, yield almost the same values (within observational accuracy) thus indicating that measurements are not radically begging the question -- i.e. the measured inclination is robust

4. Furthermore, the overall account of the latitudes yields reasonably good agreement between predicted and observed latitudes

a. Discrepancies extraordinarily small compared to all earlier accounts, though still a little larger than desired -- i.e. not strictly within observational accuracy

b. Discrepancies are perhaps attributable to refraction and parallax effects

c. And the discrepancies exhibit no systematic pattern, especially none of the sort requiring either a second inclination or varying inclination of the sort proposed by Ptolemy and Copernicus

d. In other words, the discrepancies are more likely than not a consequence of imprecision in measurement

5. Ultimately, a simplicity argument can also be invoked here, though with caution

a. Reasonable agreement with observation from a model that is physically simple -- i.e. that places almost no demands on an account of underlying physics

b. Furthermore, orbital inclination at least tied to a physical object, the sun

c. In the absence of a pattern in the discrepancies from observation, no grounds for further complications (as of 1609)

6. The evidential argument for the account of latitudes clearly does not close the door completely to alternative accounts, but it places a burden of proof on anyone who is going to offer such an account

a. Must agree at least as well with observation

b. To the extent that less simple physically, must include some grounds for thinking that physically plausible

c. And should provide an explanation for the success -- i.e. the enormous level of improvement -- achieved by Kepler's account

C. The Evidential Argument for the Ellipse

1. Strictly speaking, the claim here concerns only the relationship between angular position, say vis-a-vis the Sun, and distance: form an ellipse

a. No claim that sun at focus (a term Kepler coined), though eccentricity in terms of sun, perihelion, aphelion etc.

b. No claim about time at which planet at each position, only about the locus of points

2. Triangulation off of observations gives compelling evidence that an oval of some sort, narrower than circle at quadrants and symmetric about line of apsides through true sun

a. Theory dependent -- vicarious theory and (upgraded) solar theory

b. Sensitive to observational error and to errors in these theories

c. But sensitivity analysis showed that oval conclusion supported regardless of these errors -- i.e. the conclusion is robust

3. An argument that, given area rule, must be an ellipse, 429/100,000 narrower at quadrant

a. For must be midway between circle of Phase 4 and auxiliary ellipse of Phase 5 since discrepancies at octants in these are equal and opposite in sign, while discrepancies at apsides and quadrants negligible

b. And distance-angle relationship of ellipse physically plausible since distance variation of a sort that is physically plausible on two counts

(1) Sinusoidal variation of a natural sort

(2) (normal v) varies as 1/r -- something that a continuous physical mechanism might yield

c. And finally the "diametral" distance rule together with accurate heliocentric longitudes yields roughly this ellipse, and with area rule taken as exact, this ellipse precisely

4. Three key premises in this argument, each open to contention

a. Octant error exactly equal and opposite -- an idealization, consistent with observational error, but without separate justification except via the distance rule argument

b. Vicarious theory yields heliocentric longitudes (vs. time) within observational accuracy -- confirmed by 8 "observations" in opposition

c. Area rule -- without it, no argument to ellipse rather than oval, for "midway" argument turns on considering three orbits satisfying the area rule, and so does distance rule argument

5. A further argument: ellipse plus area rule together yield good predictions of observations from earth

a. Enormous improvement, but still with some predictions apparently lying outside observational accuracy

b. Enough discrepancy to allow for possibility of some other oval, though admittedly no pattern to discrepancies to provide clear evidence of it

6. Upshot: the argument that an oval compelling, but the argument that an ellipse, and hence the argument for the specific ellipse, rests on a collection of assumptions, including most notably the area rule

a. Nevertheless, the ellipse was accepted long before the area rule was

b. As above, this is in part an indication that nobody bothered with Kepler's reasoning in *Astronomia Nova*

D. The Evidential Argument for the Area Rule

1. Area rule makes a claim about motion that cannot be "tested" independently of a trajectory

a. I.e. to define area, need trajectory as well as distance

b. Hence, so long as the trajectory is entirely unspecified, no possible way to bring “direct” evidence to bear on area rule

2. To a large extent the evidential arguments for it in *Astronomia Nova,* where it is never stated as clearly as it subsequently came to be, are arguments countering objections to it
    a. A calculationally superior approximation to a physically plausible rule (inverse distance rule) that holds exactly at apsides for planets in Ptolemaic, Copernican, and Tychonic theory (once solar theory suitably refined and correct relation between area rule and 1/r rule made clear)
    b. Yields a physically reasonable invariance around orbit (component of v perpendicular to radius vector SM varies as 1/SM) -- which Kepler made somewhat clear only later
    c. Level of approximation to the other rule within observational accuracy for case of earth-sun
    d. (Though this other rule does not yield as unequivocal an answer about Mars trajectory in the way it does)
3. Together with ellipse, area rule yields reasonably good predictions of observations from earth
    a. But, as remarked above, not strictly within observational accuracy
    b. Still, accurate enough to put burden of proof on anyone who is going to offer an alternative to these two
4. There are two other arguments in support of the area rule, both beginning, "If you accept it, then ...."
    a. "... with a slight idealization of some numbers it will determine an unequivocal answer to the question of the trajectory"
    b. "... once distance and velocity properly understood, can be reconciled with inverse distance rule and allows for a physically plausible answer to why an ellipse rather than an eccentric circle" -- viz. superposition of two independent effects
5. Upshot: the least evidence for the area rule, for it was introduced as a mere convenient approximation to begin with, and most of the evidence accruing to it derived from its yielding the ellipse
    a. Danger of a question-begging line of argument here: ellipse presupposes area rule, and area rule justified because it yields ellipse
    b. Still, a clear burden of proof: any alternative to area rule must, together with trajectory, yield at least as good overall agreement with observations and not be far more physically implausible
    c. And ellipse and diametral distance rule, taken as exact, entail area rule

E. Some Standard Objections to the Arguments

1. Issue: what do the evidential arguments really show -- i.e. what conclusion is warranted
    a. Newton later remarks that Kepler only guessed that the orbit was an ellipse, while he proved it
    b. Newton almost certainly was not familiar with the argument as laid out in *Astronomia Nova*
    c. Unclear whether much of anyone other than Kepler understood the argument in *Astronomia Nova*, for that argument supplanted by other arguments within a few years, so that few ever worked their way through the original argument
2. One obvious response to the evidential argument is that Newton is correct, for Kepler pulls the area rule out of the air with no supporting physical evidence

a. Idealization of "data" in the crucial argument is bad enough

b. But, granting it, all that the evidential argument really shows is that, if the area rule is correct, then the orbit is the ellipse Kepler says it is

c. And once idealization of the "data" is taken into consideration, all that the argument really shows is that, if the area rule is correct, then the orbit differs from an ellipse imperceptibly

3. The obvious reply to this argument: but the area rule works!

   a. Kepler's orbit for Mars yields predictions enormously better than any earlier accounts -- enormously more accurate (virtually within observational limits) and enormously simpler

   b. The area rule leads to a single definite answer, namely the ellipse, arrived at in two ways, with the second yielding an argument for physical plausibility

   c. Thus the area rule does just what we want it to: puts us in a position where data more or less forces a single answer on us, and that answer stands up when checked in other ways!

4. But this reply will not be enough, for someone arguing as above will respond:

   a. The second point, about yielding a definite answer, is question-begging, for the issue is whether an ellipse, and once we allow that it is not an ellipse, then the area rule no longer "works" -- indeed, the area rule is then in trouble

   b. The first point at most shows that the true orbit approximates Kepler's, for errors above observational limits are still present

   c. Thus the evidential argument at most shows that orbit an oval approximating an ellipse that conforms to high approximation to the area rule, but other possibilities remain open

5. Kuhn would jump into such an exchange at this juncture to point out that Kepler's efforts on Mars are a wonderful example of the way in which science overreaches the available evidence

   a. Kepler is being persuaded by the combination of a purely conjectural physics and the extra-ordinary way in which his numbers happen to come together

   b. Any others are being persuaded just because of the order of magnitude improvement (after 14 centuries); they are not pausing to realize how many other possibilities remain open

6. The issue is whether it was appropriate, as of 1609, for Kepler or anyone else to accept his conclusions about Mars on the basis of the evidential arguments presented in *Astronomia Nova*

   a. One option is to accept the conclusions and proceed with them

   b. The other is to consider the conclusions one more competing alternative on planetary trajectories, and leave the issue of the "true" trajectory open

   c. In other words, what if anything did Kepler's arguments settle?

F. A Contrasting View of Scientific Evidence

1. Some sciences have much higher quality evidence than others do

   a. I.e. they are much more able to turn data into evidence

   b. Physics able to get much more compelling evidence from data than, say, political science is

2. *Prima facie,* the sciences that are more successful have a good deal more established theory with which to interpret and marshal data -- i.e. the more advanced the theory available in the background, the higher quality evidence that can be derived from data
   a. I am here saying only that this in fact appears to be the case
   b. Leaving open questions about whether it has to be the case, or even whether it truly is the case
3. The obvious problem then is to get the whole process off the ground
   a. If need theory to get quality evidence -- i.e. to turn data into evidence -- then how does one get reasonable quality empirical evidence for theories in the first place?
   b. The problem in the early stages of sciences -- in neuropsychology today, in physics in 1600
   c. A chicken-and-egg problem to which there are some standard answers
      (1) Get lucky: just happen onto a basically correct theory
      (2) Kuhn: overreach, but then learn to live with the residue of a totally arbitrary element in the theory, leading to subsequent scientific revolutions
4. On my view, the proper approach to this problem is to adopt working hypotheses instead of theories
   a. Working hypotheses: hypotheses that enter constitutively into evidential reasoning, yet at the time cannot be tested or verified in any non-question-begging way
   b. A good working hypothesis: one that (i) can be fruitful and (ii) can be accepted safely
      (1) I.e. one that yields higher quality evidence than can be achieved without it, leading to developments that will ultimately allow it -- the hypothesis itself -- to be empirically evaluated and, if need be, refined or discarded
      (2) One for which there are safeguards against its leading down a long, illusory garden path, so that when hypothesis finally brought into empirical scrutiny, will not lose everything predicated on it if forced to abandon or modify it
      (3) Note: issue of truth of the hypothesis not as such crucial
   c. The reasons for accepting such a working hypothesis will differ from the reasons for accepting conclusions evidentially predicated on it
5. Empirical evidence can be brought to bear on whether a proposed working hypothesis ought to be accepted
   a. Does it yield higher quality evidence than is attainable without it?
   b. If two competing working hypotheses both yielding higher quality evidence, then need empirical arguments supporting one over the other, or should pursue separate lines of research predicated on each, and let things come out in the wash -- just as Kepler did with area rule and 1/r rule
   c. If hypothesis does not -- or ceases to -- yield higher quality evidence, then it becomes suspect, for then reasons to worry about whether all is going to come out in the wash
   d. If someone has identified a possible way for the hypothesis to lead down a garden path -- e.g. some other hypothesis is true and it entails that the working hypothesis is systematically mis-

leading, giving only the illusion of quality evidence -- then must eliminate this risk, usually by showing that the alternative not true

G. A Defense of the Evidential Arguments for Mars

1. Claim: Kepler's evidential argument a paradigm of science at its best in the early stages of theory development
    a. A paradigm of how to evaluate and use working hypotheses
    b. A type of evidential argument that we will find again, much refined, in Newton's *Principia*
2. The area rule, in particular, is a classic example of a working hypothesis
    a. Evidence that it is true was beside the point -- indeed, no independent evidence for its truth possible at the time Kepler began using it
    b. Instead, he adduced evidence that it is plausible and that it is unlikely to lead down a garden path (given its relation to a physically plausible alternative to it, as well as to the equant)
3. Empirical evidence then emerged that it is a good working hypothesis, for on two counts it led to higher quality evidence
    a. With it, data can be marshaled to determine an unequivocal answer about the trajectory
        (1) In the process getting around difficulties with inaccuracies in the observations
        (2) And hence getting much more evidence out of the data than can get without it
    b. Leads to an order of magnitude improvement in predictive accuracy for Mars and earth orbits, thereby putting everyone in a position to use residual small discrepancies for further refinements
    c. Provides at least an initial basis for examining underlying physics, for constrains physics, but is not physically paradoxical or perplexing in a way that would shut the door to physical theorizing on the basis of it
4. I therefore claim that provisional acceptance of Kepler's Mars orbit was in fact warranted on the basis of his 1609 evidential argument
    a. Provisional because working hypothesis, now extended to include ellipse, must continue to yield higher quality evidence
    b. Provisional because of the possibility that some competing working hypothesis will prove equally effective
    c. Provisional because have much less evidence for its truth than expect will accrue to it in the future, if it is really true
5. In saying that Kepler and others ought to have accepted his conclusions about Mars on the basis of his evidential arguments, instead of remaining neutral and open-minded, I am saying that there were real advantages to doing so
    a. Could simply adopt area rule and ellipse for each of the other planets, bypassing the need to extract the orbit from the data; evidence would begin accruing to the first two "laws" if the results of doing so were satisfactory

b. Could begin examining any small discrepancies outside observational accuracy for implications about (i) the need to refine orbital elements and (ii) the presence of second-order effects

(1) Looking for systematic discrepancies that would be informative

(2) If do not accept Kepler's conclusions, then still at square one, asking what the trajectories are, and hence not looking at higher order, small discrepancies

c. For example, apply area rule and ellipse to earth-sun orbit to see whether reduce or increase agreement with observation for either it or Mars, especially before turning to other planets

d. Provides promising evidential basis for conjecturing about underlying physics -- i.e. for developing a much richer, more complete theory -- not just by imposing some distinctive constraints, e.g. via ellipse rather than other oval and via area rule, but also because trajectory composable out of no more than two superposed physical mechanisms, with no need for additional special mechanisms

6. In fact, in 1609 and the decade following no one seems to have been especially convinced by all this but Kepler himself, for no one but Kepler adopted both the ellipse and the area rule, even as a working hypothesis

a. Surely no one in those years worked their way through *Astronomia Nova*, and, even if they had, Kepler's argument requires huge effort to extract it in above form and to appreciate how many cross-checks he provided along the way, plus of course access to Tycho's observations

b. Magini's 1614 tables came the nearest to following Kepler, for they incorporated all his innovations except the area rule; but that shortcoming is evident in their discrepancies versus those Kepler subsequently achieved in his *Rudolphine Tables*

c. Not to mention the enormous departure in the mathematics for determining Keplerian orbits and planet positions, at least compared with the old compound circles of Ptolemy and Copernicus

d. Historically then, in claiming that the argument in *Astronomia Nova* provides adequate grounds for (provisionally) accepting Kepler's first two rules, I am making a claim about the rationality of only Kepler himself

7. The moral I suggest you take away from Kepler's *Astronomia Nova* is that it falls very far short of establishing once and for all the truth about the orbit of Mars, yet it is nevertheless a model of evidential reasoning in science at its very best in the early stages of theory construction

a. This sounds paradoxical only if one is inclined to think that evidential reasoning in science at its best must establish truth once and for all

b. Asking evidential reasoning to do this in the early stages of theory construction, I submit, is asking for the impossible

c. And once Kepler became prepared to drop the Ptolemaic working hypothesis of at least equiangular, if not uniform, circular motion, he was in the early stages of theory construction even though he was part of a tradition that was a millennium and a half old

<u>Select Sources</u>

Kepler, Johannes, *Astronomia Nova*, Vol. 3, *Johannes Kepler Gesammelte Werke*, Max Caspar (ed.), C.H. Beck'sche Verlagsbuchhandlung, 1937.

--------, *New Astronomy*, tr. William H. Donahue, Cambridge University Press, 1992.

--------, *Apologia pro Tychone contras Ursum*, in N. Jardin, *The Birth of History and Philosophy of Science, Kepler's* ***A Defense of Tycho against Ursus*** *with essays on its provenance and significance*, Cambridge University Press, 1984.

--------, *Optics Paralipomena to Witelo & Optical Part of Astronomy*, tr. William H. Donahue, Green Lion Press, 2000.

Caspar, Max, *Kepler*, tr. and ed. C. Doris Hellman, Dover, 1993 (reprint of 1959 edition).

Jardine, N., *The Birth of History and Philosophy of Science: Kepler's* ***A defense of Tycho against Ursus****, with essays on its provenance and significance*, Cambridge University Press, 1984.

Wilson, Curtis, "How Did Kepler Discover His First Two Laws?," in *Astronomy from Kepler to Newton: Historical Studies*, Variorum Reprints, 1989; originally in *Scientific American*, vol. 226, 1972, pp. 93-106.

--------, "Kepler's Derivation of the Elliptical Path," in *ibid.*; originally in *Isis*, vol. 59, 1968, pp. 5-25.

Stephenson, Bruce, *Kepler's Physical Astronomy*, Springer-Verlag, 1987. (The best source for laying out the many aspects of Kepler's evidential reasoning throughout the course of *Astronomia Nova*)

Voelkel, James R., *The Composition of Kepler's* ***Astronomia nova***, Princeton University Press, 2001.

--------, *Johannes Kepler and the New Astronomy*, Oxford University Press, 1999.

Voelkel, James R. and Gingerich, Owen, "Giovanni Antonio Magini's "Keplerian" Tables of 1614 and Their Implications for the Reception of Keplerian Astronomy in the Seventeenth Century," *Journal for the History of Astronomy*, vol. 32, 2001, pp. 237-262.

Gingerich, Owen, "Johannes Kepler," in René Taton and Curtis Wilson (ed.), *Planetary Astronomy from the Renaissance to the Rise of Astrophysics, Part A: Tycho Brahe to Newton*, Cambridge University Press, 1992.

Smart, Robert, *An Account of the Astronomical Discoveries of Kepler*, London, 1804; reprint, University of Wisconsin Pres, 1963.

Beer, Arthur and Beer, Peter, *Kepler: Four Hundred Years*, vol. 18 in *Vistas in Astronomy*, Pergamon, 1975.

Gilbert, William, *De Magnete*, tr. P. Fleury Mottelay, Dover, 1958.

Whiteside, D. T., "Keplerian Planetary Eggs, Laid and Unlaid, 1600-1605," *Journal for the History of Astronomy*, vol. 5, 1974, pp. 1-21.

Neugebauer, Otto, *Astronomy and History: Select Essays*, Springer, 1983, especially the essay on Kepler.

Donahue, William, "Kepler's Fabricated Figures: Covering Up the Mess in the *New Astronomy*," *Journal for the History of Astronomy*, vol. 19, 1988, pp. 217-237.

--------, “Kepler’s First Thoughts on Oval Orbits: Text, Translation, and Commentary,” *Journal for the History of Astronomy*, vol. 24, 1993, pp. 71-100.

Martens, Rhonda, *Kepler’s Philosophy and the New Astronomy*, Princeton University Press, 2000.

Pafko, Wayne, “Visualizing Tycho Brahe’s Mars Data,” http://www.pafko.com/tycho/observe.html, 2000.

Wesley, Walter G., “The Accuracy of Tycho Brahe’s Instruments, *Journal for the History of Astronomy*, vol. 9, 1978, pp. 42-53.

Chapman, Allan, *Astronomical Instruments and Their Users: Tycho Brahe to William Lassell*, Variorum, 1996, especially Chapters 1-3.

Grafton, Anthony, *Michael Maestlin’s Account of Copernican Planetary Theory*, *Proceedings of the American Philosophical Society*, vol. 117, no. 6, *Symposium on Copernicus*, 1973, pp. 523-550. (This includes a translation with some commentary of Maestlin’s exceptionally clear account of Copernican orbits, “On the Dimensions of the Heavenly Circles and Spheres, according to the *Prutenic Tables*, after the Theory of Nicolaus Copernicus,” which appeared as an Appendix in Kepler’s *Mysterium Cosmographicum* of 1596.)

Moore, Patrick, *The Great Astronomical Revolution: 1534-1687 and the Space Age Epilogue*, Albion Publishing, 1994 (reprint of *Watchers of the Stars*, 1973).

Koestler, Arthur, *The Sleepwalkers: A History of Man’s Changing Vision of the Universe*, Penguin Books, 1964.

<u>Credits for Appendix</u>

Slide 1: Moore (1994)

Slides 3, 22, 36: Voelkel and Gingerich (2001)

Slides 6, 7, 9-15, 18-21, 23, 27-32, 34, 35: Kepler (1992)

Slides 8, 17, 18, 23, 32, 33: Kepler (1937)

Slide 16: Stephenson (1987)

Slides 24, 26: Wilson (1972)

Slide 25: Gingerich (1992)