b. Would a comet knocking a planet out of its orbit constitute a counterexample to them?

5. As we have already seen to some extent, Kepler was perfectly aware of questions like these (though not in our jargon for them) and he devoted a great deal of effort toward addressing them

   a. He, and others following him, wanted these questions to be resolved empirically, and not "philosophically" or through "final causes"

   b. And he, and those following him, became acutely aware of the methodological problems in bringing empirical evidence to bear on them

   c. How can such questions be addressed empirically? -- perhaps the most basic issue of this course

III. An Examination of the Evidence for Kepler's "Laws"

A. The Precise Statement of Kepler's Generalizations

1. Goal, then, is to assess the evidence bearing on Kepler's "laws" at the time of his death in the light of these distinctions and complications

   a. With particular emphasis on how he chose to attack the methodological problems arising with the further questions

   b. Best start with concerns about the precise statement of the three generalizations

2. Kepler took the generalizations to apply to the six planets, with some vagueness about their application to "secondary" planets

   a. He expressly remarks that the 3/2 power rule extends to the satellites (his word) of Jupiter, and he applies the other two generalizations to the moon to obtain first approximations

   b. But he is clearly aware that the moon violates his first two generalizations, and therefore knows some sort of qualification is needed in stating them for it

   c. Also, his physical account is geared fundamentally to the sun, so that not entirely clear whether appropriate to include, without further qualifications, bodies not orbiting the sun

3. Kepler does not as such address "ceteris paribus" conditions, but it is clear that he intends that the "laws" be taken to hold, at least to a very high level of approximation, so long as the planets remain undisturbed by physical processes not now at work!

   a. Whatever the physical processes now at work might be, so long as nothing extrinsic to them enters, then generalizations apply

   b. Generalizations viewed as sustained by distinct physical processes, not by the active hand of God, spirits, or minds of any sort!

4. In the *Epitome* he expressly views the first two generalizations as "real world" replacements for an ideal

   a. If the planets themselves were not magnetically sensitive and had started in the plane of the ecliptic, then perfect concentric, uniform circular motion in the plane of the ecliptic

   b. The first two generalizations thus capturing a "second-order" departure from this ideal

5. At the same time he intimates in both the *Epitome* and the *Rudolphine Tables* that the first two laws

themselves are idealizations that would hold precisely were it not for interactions among the planets (primary and secondary)

a. The correlation of the lunar inequalities with sun-moon-earth positions the primary basis for this statement

b. He also allowed (from *Astronomia Nova* on) for slow rotations of lines of apsides and nodes (not so slow in the case of the moon) as another respect in which the "laws" were idealizations

c. And he foresaw the need for long-term data to specify any other variations in orbital elements, attributing any such variations to planetary interactions

6. In sum, a fair amount of uncertainty and vagueness in the statement of at least the first two generalizations, though with comparatively precise versions once restricted to the six planets

B. The Evidence in 1630 for the Ellipse and Area "Laws"

1. As of 1630, the primary evidence for the first two rules was that, taken together along with specific values of the requisite orbital elements, they yielded predictions between one and two orders of magnitude better than anything before, broaching on observational accuracy

a. I.e. accuracy to a level where just as reasonable to question observations or orbital element values as the rules when faced with any discrepancy between prediction and observation!

(1) Both a "resting point" and an impass

(2) Sciences often reach this stage for a while

b. No "deductions" of area rule or ellipse in the case of the other planets; instead, assumed them and determined elements (Venus in 1614; Mercury in 1609, 1614-15, and 1616; Jupiter in 1616, and earlier; and Saturn in 1616 -- Field, p. 191)

2. He, and every other qualified astronomer, was aware that this success left open the possibility that some other trajectories and/or motion rules might achieve a comparable level of success

a. Open in part because of imprecisions in the observations themselves, including recognized possibility of systematic errors -- e.g. from wrong parallax and refraction corrections, or imprecisely measured obliquity of the ecliptic (the reference axis for longitude, latitude)

b. But open also in part because the two rules and the values of the orbital elements could not be independently assessed, thus creating more of a chance for an alternative

c. Underlining this openness was a recognition by all that, given the observational inaccuracies, there was really no separate empirical evidence for the two rules from earth, Venus, Jupiter, and Saturn; Venus could even be done with uniform motion on an eccentric circle

3. Kepler had more responses to this open possibility than just saying, "Okay, you come up with something at least as good"; in defense of the ellipse:

a. In the case of Mars, triangulations show that an oval, and the variation of distance (with eccentric anomaly) in the case of the ellipse is physically reasonable -- $1 + e * \cos E$

b. In the case of Mars, assuming the area rule, an empirical argument specifically to ellipse, and possibility of other curves (e.g. the via buccosa, that is, the locus of points where the diametral distance intersects a radius drawn from the center) meeting the same conditions undercut by above physical argument

4. And in defense of the area rule:
   a. In the case of Mars, determines a specific answer to question of trajectory (i.e. at least an answer meeting the physical requirement)
   b. Concluded to be physically correct at apsides, and elsewhere equivalent to the physically sensible inverse distance rule (once recognized that the velocity in question is that normal to r, i.e. the velocity component driving the planet in its orbit); proof of equivalence with original inverse distance rule in *Epitome* (p. 143) inadequate, for it does not handle adjacent triangles
   c. Finally, alternatives to it, in particular the equant, objectionable (*Epitome*, V, p. 145)
      (1) Loss of accuracy unless equant point has irregular movement
      (2) No physical account of equant, in contrast to Kepler's physical account of area rule
5. All of this said, still some complicating concerns as of 1630
   a. Predictions not altogether within observational accuracy -- e.g. within 2 or even 4 min of arc
   b. Lunar theory fits only by treating higher order inequalities as second-order perturbations on basic rules, and even then doubts about whether have an adequate predictive account of moon
   c. Signs that orbital elements of Saturn and Jupiter (he says Mars too) may vary over time

C. The Evidence in 1630 for the 3/2 Power "Law"

1. In a very different sort of position with the 3/2 power "law" since evidence for it comes by means of an empirical generalization from cases
   a. An inductive generalization, with residual discrepancies to begin with
   b. Moreover, a generalization not from data, but one involving inferred values of an orbital element (mean distance)
   c. Unclear that Kepler himself put as much stock in this “law,” although he did offer a physical explanation -- something he did not do for other velocity comparisons (the other harmonies)
2. The physical explanation of the third law, more glaringly than those of the first two, entails further consequences, viz. about planet densities, that are lacking independent evidence
   a. I.e. in some respects a more ad hoc explanation
   b. Though also more open to contrary evidence (from telescopic determinations of planet sizes)
3. No argument against some other relationship holding instead, given the small discrepancies; and the relatively small number of cases makes this a distinct worry
   a. Mere numerical happenstance (of the sort that subsequently arose with Titius-Bode law)
   b. But, level of agreement a counter to this, as is the proposed extension to the satellites of Jupiter, provided future data remove the discrepancies; (does the physical explanation hold there too?)

4. Since the physical explanation built off the numbers, it yields no argument that the "law" holds exactly, or would hold exactly were it not for secondary effects
   a. Evidence that it may well hold exactly from the level of agreement achieved, with one element (mean distances) subject to variations from observational inaccuracies
   b. But lots of room for its being inexact, especially with physical argument, for even a small departure in density-distance relations would undermine its exactitude
5. One interesting thing to notice here is that the level of agreement in the case of the 3/2 power rule is high enough to give reasons to take it to be exact and use it to correct the inferred mean distances
   a. Periods can be determined more precisely from observations than mean distances can be
   b. Maybe should just take rule to be exact, and use it to obtain better values of this orbital element, in the process narrowing the range of uncertainty in one respect
   c. Can do so non-arbitrarily, for new elements should yield even better predictions than old did
   d. In fact, Kepler's values for mean distances are off by 0.25 percent for Mercury, 0.11 for Venus, 0.01 for Mars, 0.05 for Jupiter, and 0.38 for Saturn (versus values for 1600 implied by Simon Newcomb's tables)

D. Evidence that the "Laws" are Laws: Kepler's Approach

1. Turn now to the evidence that the three "laws" are nomological, and not just some sort of numerical or epochal accident
   a. The fact that the rules are known to apply to so few objects, and then only over a quite limited period of time, underscores the worry here
   b. And Kepler complicates matters by claims that threaten to rule out some counterfactuals -- e.g. the regular solid argument suggests that there could only have been 6 planets, and they had to be situated much as they are, thus barring counterfactual talk of other planets in other positions
2. Kepler did not have much in the way of a model for running evidential arguments to show that generalizations are nomological (or exact)
   a. Mathematical proofs could be used to argue that things had been established in accord with a design -- Neoplatonism
   b. Appeals to reason, in the manner of Aristotle, had clearly failed in astronomy
   c. Kepler was one of the first to try to devise empirical arguments for concluding that observed regularities are (what we now call) nomological
3. Kepler did have some "internal" evidence that his generalizations were not mere artifacts
   a. The level of precision to which they hold, and the way they interlock with one another, tieing parameters to one another; still notice here that a stance is being adopted on the discrepancies that exceeded observational accuracy: they do not amount to counter-evidence
   b. Also, their ability to explain, e.g. Ptolemy's successes, gave grounds for thinking that the planetary system had not changed that much for a long time

c. (Kepler does invoke Ptolemy's successes as evidence for his trajectories, which he takes to be a refinement built off of Ptolemy's first-approximation)

4. But Kepler's preferred strategy for showing that "laws" are nomological, as he makes clear time and again, is to argue that they are manifestations of underlying physical processes and mechanisms

   a. His insistence that any regularity be physically plausible is intended as a safeguard against accidental truth -- this is his way of dealing with the risk of being misled by e.g. numerical agreement, and not just his way of justifying the Copernican system over the Tychonic

   b. His criticisms of his predecessors accepting regularities merely because they work reasonably well -- e.g. comments on the equant in *Epitome*, V, p. 145

   c. His decision in the *Epitome* to present the physics first and then derive the geometric astronomy from it

5. Note here his curious practice of insulating his "efficient" causation arguments from his "final" causation ones

   a. He may feel he has an explanation of why there are 6 planets and why the velocity ratios are as they are, but he rarely permits such explanations to intrude on his physical ones

   b. The "laws" hold not because God chose for them to, but because mechanisms governing planetary motion, once set in place by God, entail that they do

E. Kepler's Approach to the Underlying Physics

1. The trouble Kepler faced, of course, is that he had almost no physics to turn to in forming arguments that the "laws" are manifestations of underlying physics

   a. Only some empirical results of "experiments" and observations on earth, plus analogic reasoning from them

   b. In particular, magnetism, and diminution of driving "force" of a vortex

   c. Simple fact is that Kepler was working in the early stages of the development of the science of motion, and as all scientists have had to do in this situation, he had to try to pull himself up by the bootstraps

2. That is, Kepler turned the situation inside out: he assumed, at least provisionally, that the observed regularities are manifestations of underlying physics, and he then used them to draw conclusions about the physics

   a. If unable to come up with a physics that would yield the observed regularities, then nomological thrown into question

   b. Equally, the more Rube-Goldbergish the physics, the more the worries about nomologicality

3. Kepler should not be criticized for trying to do this, for it is a time-honored procedure that is still being followed today -- e.g. the genesis of the big-bang theory

   a. He is perfectly open about the need for conjecture in physics -- see p. 48 of the Introduction to *Astronomia Nova*

   b. Conjecture constrained by limited knowledge of physical processes on earth and by the need to conform with tentatively accepted, highly accurate astronomical regularities
4. Of course the danger here is circular reasoning, void of content: Kepler is assuming that the regularities are nomological in order to use them to draw conclusions about the underlying physical processes, and he is then using these conclusions as grounds for arguing that the regularities are nomological
   a. On his view, can't get anywhere without conjectures about physics
   b. Problem then is to make sure the conjectures are not question-begging
   c. Strategy sure to leave a large promissory note outstanding
5. He tried to counteract this danger by minimizing the number of basic physical assumptions and by insisting that the regularities then be strictly (and exactly) derivable from the physics
   a. I.e. exactly derivable under appropriate ideal conditions, such as no interaction with third bodies
   b. Exactitude, at least under ideal conditions, a key constraint here; reasoning loses much of its force if regularities hold only very roughly!

F. Illustrate Via the "Physics" for Keplerian Motion

1. Kepler's basic physical model separates two aspects of planetary motion, attributing each to a different mechanism
   a. The basic motion of planets revolving around the Sun (and satellites around their principals)
   b. The "libration" in the distance from the planet to the Sun that causes a non-circular trajectory
2. Planets revolve around the Sun because of a magnetic or magnetic-like vortex given off by the rotating sun
   a. Rotation of sun postulated before Galileo observed it
   b. Strength of the vortex -- i.e. the push of the vortex -- diminishes with distance
   c. Different planets have different periods because of their "inertias" (Kepler invents the term) -- their differing tendencies to resist motion, either initial or continuing, altogether
3. Planets have a non-circular trajectory (which lies outside the plane of the ecliptic) and hence variable velocity because they contain magnetic fibers themselves that cause them to be attracted to and repelled from the Sun
   a. Magnetic fibers (ideally) always pointed in the same direction -- perpendicular to the line of apsides, so that at perihelion and aphelion, no attraction or repulsion
   b. Orientation in one half of orbit, vis-a-vis the Sun, then attractive, and in the other half repulsive
   c. Attraction reaches a maximum when pointed directly to the Sun
4. From these two together can derive elliptical orbit and area rule exactly with minimal additional assumptions
   a. Impetus from spinning Sun always drives planet in direction normal to radius vector -- the impetus that would yield a perfect (circumscribed) circle if planets were magnetically neutral

b. The attraction and repulsion, occurring along the line of the radius vector, yield the relation, SM=$r(1+e*\cos E)$, that is, the diametral distance rule

c. But the area rule is tantamount to the delay per equal arc varying directly, and hence the velocity varying inversely, with distance (see *Epitome*, p. 143), and the ellipse then results from SM radius vectors being laid out properly (p. 133ff)

d. The obliquity of the orbital plane also from the magnetic fibers

5. This physical account of ellipse and area rule end up entailing a lesser status for the 3/2 power rule

   a. The 3/2 power rule is no longer strictly nomological as it stands, for it reflects a choice by God of planet densities making it hold

   b. But it is nomological when re-expressed as a relation between period, mean distance, and density

G. The Empirical Limitations of Kepler's Physics

1. I have been more sketchy in describing Kepler's physics than it merits in large part because (i) it does not work and (ii) it itself had relatively little influence

   a. Stephenson's book lays the physics out in far more detail, bringing out the logical integrity of his physical reasoning

   b. The physics is wrong because he has the elementary physics of motion wrong, but the reasoning is neither mystical nor crazy

2. Having said this, however, we should pause to be clear about the evidential shortcomings of the physical reasoning -- shortcomings that can be detected without having to know the right answer!

   a. The basic problem is that the evidential arguments never close the loop -- i.e. the physics never entails much of anything in the astronomical realm that was not built into it in the first place!

   b. I.e. the physics remains ad hoc, with little or no independent evidence for it -- something that was quite clear at the time

3. In truth, this is an exaggeration, for Kepler tries to get the inequalities of the motion of the moon out of the very same physics

   a. By using the magnetic properties of the bodies needed to account for their "two-body" motion, but now with a "three-body" interaction

   b. Likely the part of the *Epitome* of which he was most proud

   c. Did not assign it because difficult, and ultimately again ad hoc, for he was unable to get the inequalities out "for free," much less to within observational accuracy

4. Kepler did see ways in which "the loop" might be closed -- i.e. ways in which his reasoning from the assumed nomologicality of astronomical regularities to an underlying physics back to the nomologicality of the regularities might not beg questions

   a. First, by getting several regularities which are astronomically independent of one another out of the same physics -- the area rule and the ellipse together, in particular (cf. pp. 143ff)

b. Second, by having the very same physics then cover systematic discrepancies from the initial regularities

5. Kepler succeeded only partially in the first respect, and even less in the second

   a. But he had no way of knowing that in the long run converging evidence would not develop for some version of his physics

   b. And in this regard he is to be criticized no more than others who have offered conjectural theories that did not pan out even though they were carefully crafted from observed regularities

   c. Science really is difficult, especially in the early stages of theory construction

IV. Kepler's Methodological Legacy: Some Final Remarks

A. Kepler's Conception of "Scientific" Astronomy

1. In one respect Kepler was the culmination of a 2000 year tradition of mathematical astronomy, stretching back through Ptolemy and Apollonius; but in another respect, he was the initiator of a quite new science of astronomy

   a. Physical astronomy, in contrast to just mathematical astronomy -- a branch of "physics", not of mathematics, as it had been for centuries

   b. Needed because of the crisis posed by the three systems -- i.e. because it seemed hopeless to settle the dispute among the three systems unless astronomy became a branch of "physics"

2. One way in which this shows up is in Kepler's attention to the specific physical trajectory of planets, in contrast to that of his predecessors on the geometric constituents needed to synthesize a trajectory that gives an account of the salient phenomena

   a. The actual trajectory is a physical fact, the geometric constituents are part of geometry, and different geometric constituents may yield the same net result

   b. The issue is whether that net result is correct, to at least a very high level of precision

3. It also shows up in the insistence not merely that claims about the trajectory allow for a physical -- mechanical -- explanation, but also that astronomical regularities be derivable from physics

   a. Kepler akin to Darwin in a way: he (ultimately) exorcized the need for "mind" in astronomy, insisting that all regularities be purely mechanical

   b. Note the passages in the *Epitome* that argue this point; he keeps pointing out that Copernican astronomy allows an end to a certain kind of nonphysical explanation

4. He further puts forward a conception of how to go about marshalling evidence in physical astronomy, namely by using astronomical regularities to infer some physics, then deriving the regularities from the physics

   a. Multiple, astronomically independent regularities and "laws" from the same physics (as much as possible)

   b. Derivations to yield the exact "laws" under idealized assumptions, which in turn makes a tight relationship between the "laws" and observations more important (the tighter the better)

c. Finally, physics must cover any systematic deviations from the "laws" (with minimal additional apparatus)

5. Not just a new "science", but a new scientific methodology, placing much greater emphasis on theorizing, not merely as an end, but as part of the process of developing evidence
   a. Also greater emphasis on exactness, for one of the key ideas is to use systematic discrepancies between observation and theory as new evidence
   b. Discrepancies not being swept under the rug, but looked to as providing information about what is going on, with the corollary of attaching much greater importance to the data themselves being very precise
   c. In particular, discrepancies that can be characterized as ones that would disappear were it not for certain second-order effects
   d. Consequently, a science that proceeds via successive approximations, playing off two levels of theory against one another and against observations
6. Even while granting that Kepler was the culmination of a 2000 year tradition, I nevertheless want to insist that his efforts illustrate the early stages of theory construction
   a. Two tenets of that tradition, trajectories compounded from circles and equiangular motion about some point, had provided not just constraints in theorizing, but principles entering into evidential reasoning from observations
   b. Once those tenets were abandoned, theorizing ceased to be constrained, and novel principles were needed for reasoning from observations, while still granting and hence needing to explain the successes of the past
   c. In particular, Kepler's appeals to physics and his use of triangulation under the assumption that Mars orbits the sun replaced them
7. An historical parallel to the situation in which Kepler found himself occurred in the first decade of the 20th century when the constraint that *energy* is a continuous variable was dropped, and a couple of decades of effort was then needed to figure out how to constrain theorizing
   a. Initiated by Planck's law for black-body radiation, under Einstein's 1907 interpretation of that law, and Einstein's 1907 proposal for the specific heats of solids
   b. The first Solvay Conference of 1911 called to address the question of how to incorporate quanta into physics while still granting the successes of classical physics
   c. Fifteen years then before Heisenberg's matrix mechanics and Schrödinger's equation emerged

B. Some Residual Problems Facing Kepler in 1630

1. For all his achievements, Kepler could not help but be aware of certain difficulties in his account at the time he took sick and died in 1630
   a. He more than anyone would have been aware of these, though others saw them over the next 10-15 years

b. (Indeed, he calls attention to some of them explicitly in the *Rudolphine Tables* and implicitly in subsequent Ephemerides, though without challenging claims about underlying physics)

2. One concern was whether he had optimal values for the elements of the various orbits

a. He knew perfectly well that the calculated positions were not always within observational accuracy, though he was probably unsure how much of this should be attributed to faults in observation and how much to the elements

b. He openly questioned the solar parallax, and hence by implication openly questioned the corrected "data" he worked from in obtaining the values of the elements

c. The small residual discrepancies in the 3/2 power rule also raised questions (though less for him, given his physical account)

3. Another concern was the apparently slowly changing values of the elements of Saturn and Jupiter (and perhaps Mars)

a. By 1625 was confident that not just a data problem, but a real variation extending over a long time

b. Speculated that from planetary interactions, but no way of beginning to argue for this until the variations were characterized

4. Final concern was the Moon, for which he had managed to devise a better predictive account than anyone before him, but still had not come close to achieving observational accuracy

a. "The problem of the moon" -- just to give an astronomically accurate system for predicting its observed positions

b. Further inaccuracies had yet to be characterized systematically

c. This in turn raised questions about the adequacy of the physics invoked in support of the model

5. Finally, his physics was clearly ad hoc and largely conjectural, with a need for much more independent, converging evidence

a. His physics logically akin to Ptolemy's astronomy -- not as unified as one would like

b. With implications remaining to be tested -- e.g. density implications

6. A worry in the background that some others made increasingly explicit around the time of his death and after: can claims about underlying physics be anything more than mere conjectures?

a. Kepler's physics scarcely gave reasons for thinking that the underlying physics could be settled once and for all

b. Maybe best one should hope for is accurate prediction of phenomena

C. Issues Raised on His Conception by These Problems

1. These residual difficulties had to raise some fundamental questions in the mind of anyone with Kepler's conception of "scientific" astronomy

a. Questions that would presumably have preoccupied him had he not died at the age of 58

b. Questions that came to preoccupy others over the next 50 years

2. Do the three "laws" hold exactly -- or exactly were it not for certain second-order physical effects -- and if not, is this reason for worrying about the possibility of alternatives to them
   a. Maybe they just happen to approximate some "true laws" which, if discovered, would remove residual discrepancies and yield a better physics
   b. In particular, maybe some alternative would allow further lunar inequalities to be characterized
3. To put the point differently, the question, given his conception of science, is not whether the three "laws" hold to a very high degree of approximation -- for they do -- but whether they may nevertheless be systematically misleading
   a. Misleading with regard to whether deviations from them can be systematically characterized, and hence astronomy be "perfected"
   b. Misleading with regard to physical processes underlying the regularities "laws" are capturing
4. The interesting issue facing anyone who saw things in this way was whether it was appropriate to accept Keplerian theory, at least provisionally, or instead to look aggressively for alternatives to it
   a. One can always construct alternative hypotheses, at least up to a point
   b. Which promised the greater likelihood of long run success, to build on Keplerian theory or to hold it in abeyance and look for alternatives to it?
5. Kepler himself probably felt that he had reached somewhat of a dead-end -- i.e. had gotten as much out of Tycho's data as it was possible to get
   a. Needed at least further observations, made specifically in the light of his theory, or else still more accurate observations
   b. Perhaps explains why he had done almost nothing new in astronomy since 1625 at the time he died
   c. In effect, he had reached the same sort of point that Ptolemy had reached 15 centuries earlier: could see no way to extract further evidence from the data available at that time
6. Regardless, we can be confident that by the time he died Kepler had come to appreciate the magnitude of the problem of establishing physically correct trajectories for the planets, for he had come to recognize the challenge posed by the issues listed in the table at the end of the Appendix
   a. Residual systematic error in data
   b. Risk of garden-path from theory-mediated evidence
   c. Limitations of astronomical data in selecting among alternative trajectories at same level of accuracy
   d. Threat of circularity in appealing to physics to select trajectory and trajectory as evidence for physics
   e. Questions about what to make of residual discrepancies
   f. Projection, in time and to other orbiting bodies