Class 4: Kepler's Planetary System and the *Rudolphine Tables*

I. Kepler's Astronomical Work Following *Astronomia Nova*

A. The Orbital Innovations of *Astronomia Nova*

1. With *Astronomia Nova* Kepler introduced in sequence and developed evidence for five innovations in planetary theory that are still central to orbital astronomy (see list in Appendix)
   a. The true sun instead of the mean sun
   b. Bisection of eccentricity for the Earth-Sun orbit
   c. The area rule for determining location in time
   d. The elliptical trajectory
   e. The orbit on a plane through true Sun at constant inclination to the plane of the ecliptic
2. Of these five, only the area rule is not clearly formulated in *Astronomia Nova*, and Kepler never quite formulates it in the form, component of v perpendicular to r varies inversely with r
   a. Kepler was using an algorithm equivalent to it, but he did not come to state it as "equal areas in equal times" in non-circular orbits until after the book was published
   b. (Specifically, using equal areas in equal times as a measure of the sum of the arc distances in circle initially, then in circumscribed circle, not remarking that that amounts to the same as the fraction of the total area swept out in the inscribed ellipse)
   c. The first clear published statement of it is in the *Epitome*, where he apologizes for the earlier confusing formulation (V., 4., p. 143)
3. As Kepler fully realized, his orbital innovations can be incorporated directly into the Tychonic system, and even into the Ptolemaic system, to yield comparable accuracy on latitudes and longitudes
   a. More than a little perverse to incorporate them into the Ptolemaic insofar as triangulations that make no sense as evidential reasoning in that system were used to provide key evidence
   b. Nevertheless, because they could be incorporated into all three systems, such refinements in the orbits could not by themselves "prove" the Copernican system
4. This raises the question: what was so unique to Kepler's position that these innovations emerged for the first time here? I think the answer is a combination of five factors
   a. Tycho's data -- their scope, precision, and recognized bounds of observational precision
   b. Kepler's realization of the limitations of relying on acronychal data (yielding both an *experimentum crucis* for the mean vs. true sun and for developing evidence on the trajectory)
   c. A redefinition of the problem of planetary astronomy: find the true trajectory instead of using compounded circular motion to save the salient phenomena
   d. The idea of using theory-mediated triangulations to infer sun-planet or earth-sun distances (legitimated for the first time by Copernicus and carried over by Tycho)
   e. Tycho's theory of the sun, which provided (even before its revision to incorporate bisection of eccentricity) accurate heliocentric longitudes of earth and good earth-sun distances

5. Newton's remark that Kepler merely guessed the ellipse probably reflects his view that Kepler had simply hypothesized his orbital model and then found that it could be made to fit impressively with Tycho's data
    a. Newton was openly contemptuous of such "hypothetico-deductive" reasoning in science, complaining that too many different hypotheses could fit the same data and no empirically based choice could be made among them
    b. The general impression then and now was that this is what Kepler must have done (just as it is that this is what Ptolemy must have done)
    c. This impression stems from not having worked through *Astronomia Nova*
6. Finally, we should note that it is one thing to have evidence for Kepler's conclusions about the trajectory of Mars between 1580 and 1605 and quite another to have evidence for generalizations of these conclusions! -- the central theme of this class
    a. What does the evidence in *Astronomia Nova* say about Mars' orbit in the far past and future?
    b. And what does it say about the orbits of the other planets?
    c. Generalizations beyond Mars in the period covered by Tycho's data involve a huge further leap -- or, to use Nelson Goodman's technical term, a *projection* beyond Tycho's data
        (1) Kepler's claims about the orbit for those years involves a projection from Tycho's data to conclusions that reach well beyond these data
        (2) Still an enormous further projection to this orbit over other times and to the orbits of other planets

B. The Achievement of *Astronomia Nova*: Summary Remarks

1. *Astronomia Nova* did in a sense effect a total reconstruction of mathematical astronomy from the ground up, much as Tycho had hoped for and Kepler had intended
    a. Between one and two orders of magnitude improvement in the accuracy of predicting latitudes and longitudes of the planets over everything that had gone before
    b. Established a new standard for predictive astronomy, replacing a 1400 year old standard -- a new standard that was not itself replaced for the better part of 200 years (telescope notwithstanding)
2. Methodologically, the book also represented a breakthrough of sorts in the problem of turning data into evidence
    a. Showed how to exploit comparatively accurate observational data, with a reasonably well known level of precision, while at the same time making allowances for residual inaccuracies
    b. Turned an age-old question -- what trajectories do the planets actually follow? -- into a question which observations can answer, given some theoretical assumptions, like Tycho's solar theory
    c. That is, Kepler was able to put himself into a position in which a comparatively small range of inexact observations yielded a perhaps qualified, but still unequivocal answer to the question of trajectory (at least up to an appropriate level of approximation) for Mars