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

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

A. The "Copernican Revolution" -- 100 Years

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

b. And a new generation of astronomers were coming of age to whom Ptolemaic theory was something from another era

2. Four figures were chiefly responsible for producing a complete transformation of the discipline of astronomy ("from the ground up" in accord with Tycho's goal)
   a. Copernicus -- by opening the way to a reconsideration
   b. Tycho -- by providing quality data and underscoring the need for a complete reconstruction
   c. Kepler -- by effecting the reform of mathematical astronomy
   d. Galileo -- by introducing and marshalling telescopic evidence
   e. But a host of individuals picking up where these four had left off
3. The academic discipline of mathematical astronomy had been transformed from a recondite branch of mathematics to the most advanced discipline of the new "science"
   a. Still a demanding mathematical discipline, but now also a part of natural philosophy -- i.e. physics -- in a way it had never been before
   b. And in the minds of the educated public, an extremely exciting field drawing talented young people into it
4. Equally, the discipline had become multi-dimensional, and not just mathematical, partly through the advent of serious programs in observational astronomy, but even more so from the excitement of total new discoveries through the telescope
   a. People with no interest or talent in mathematical astronomy were nevertheless becoming involved through the telescope
   b. Whole programs of selenography, open to any amateurs who could lay their hands on or construct a telescope
5. And empirical answers seemed to be waiting in the wings for those clever enough or persistent enough to find how to extract them from observations
   a. At least 3 new sources of empirical evidence
      (1) Telescope, extending and correcting naked eye observation
      (2) Using discrepancies from Kepler's predictions to refine Kepler's theory and then reassess its exactitude
      (3) Look to conjectured underlying physics for basis to choose between alternative hypotheses, as illustrated, each in their own way, by Kepler and Galileo
   b. Contrast with Copernicus, who had to offer almost exclusively "aesthetic" arguments: Galileo falls back on this kind of argument only when has to, and then reluctantly

B. Major Open Questions: Evidential Problems

1. The most fundamental question that had not yet been resolved, though one that could be worked around, was the question of which of the three systems
   a. The telescope had pretty well ended the last vestiges of Ptolemaic thought among serious investigators, but there were still plenty of proponents of the Tychonic (and variations of it -- Riccioli's *New Almagest* in 1651)

b. And no one had found a totally compelling solution to the problem of observational equivalence, unless you were prepared to buy Kepler's physics (or his aesthetical arguments)
c. But less sense of crisis over this among younger astronomers, despite Galileo's trial, for so many questions could be pursued without addressing the dispute over the Tychonic versus the Copernican system!
d. (Like current situation in quantum mechanics, where advances can be made without having to worry over issues about foundations)

2. The questions about the status of Kepler's "laws" discussed last time also remained open -- are they nomological, what is their range, are they exact, essentially exact, or only approximate, if not exact, are they idealizations, and do they hold in the mean
   a. Horrocks the one person attacking these questions directly at the time, and his surviving results did not emerge publicly until after 1660 and fully in print until the early 1670s
   b. Others working more along paths paralleling Kepler's, but was going to take a long time to be in a position to compare with him and reach assessments
   c. And, of course, the moon raised some more forceful questions about the status of the "laws"
3. Questions of scale -- i.e. of actual distances and sizes, in terms of earth units -- were beginning to be attacked empirically, but with major disagreements about the horizontal solar parallax
   a. Questions about relative distances were considered largely resolved through the conclusion that Mercury, Venus, Mars, Jupiter, and Saturn orbit the sun, with distances in astronomical units then from retrograde loops and from triangulation
   b. Telescope could go only so far at the time toward distances in terms of earth-radii, and beyond that inferences had to be drawn, especially about solar parallax, from such things as discrepancies in Kepler's predictions
   c. But increasingly the questions were being viewed as empirical ones, and the answers looked increasingly surprising, goading people to continued pursuit
4. Questions about the "perfectibility" of astronomy, initially given force by Kepler's remarks concerning the moon and outer planets, were being given serious empirical attention by a few
   a. Horrocks and his midland friends at the time, but their concerns would be heard by all in the 1660's and after
   b. Galileo, if not expressing doubts, making gestures suggesting that the time had not yet come to address this worry
   c. And here too the inability to bring the moon within observational accuracy raised questions
   d. In a sense, question of perfectibility had an a priori philosophical answer in ancient astronomy, yet with no concern for demonstrating that that answer was plausible
5. Finally, questions we have been ignoring almost entirely about the nature and trajectories of comets
   a. What are comets, what trajectories do they follow in space, are they governed by the same physical processes as the planets are etc.

    b. Lots of literature, but save for Tycho's meticulous work, little progress in bringing such questions under empirical control
    c. Galileo's *Assayer* and its attack on Tycho's parallax determinations had, if anything, clouded matters all the more
6. In sum, the 100 years of astronomy following publication of *De Revolutionibus* had not so much answered questions as it had replaced the questions of 1542 with a whole host of entirely new questions; the questions of 1542 had come to look antiquated indeed:
    a. How inaccurate are the tables, and is corruption of Ptolemy's original work the source of the inaccuracies
    b. What is needed in the way of calendar reform (Gregorian calendar in Catholic world in 1582; Julian retained in England until 1752)
    c. What to make of the system being worked out by Copernicus (according to Rheticus)
7. There is something to be said for doing history of science as a history of questions -- when and how they arise, when they come to the forefront, and when they are resolved or discarded

C. The Changing Conception of the Science

1. Paralleling the change in questions is a changing conception of what those in astronomy think they are up to -- i.e. how they would have described the goals, standards, and methods of their discipline
    a. In particular, why the questions they were concerned with were important
    b. And what it would take to have conclusive answers to them or otherwise resolve them
    c. (Need for caution in describing this, for too easy to read things into the times that weren't there, something Drake seems often guilty of)
2. The old conception: to describe and explain the systematic deviations from uniform circular motion in the apparent motions, preferably showing that these appearances nevertheless result from compounds of uniform -- or at least equiangular -- circular motion
    a. A descriptive as well as explanatory task, with success dictated by being able to predict at least features of salient astronomical events in the future
    b. To some extent to confirm philosophic conceptions of what is happening in the heavens, as in Plato and Aristotle
    c. Also driven to some extent by astrology and the emphasis it places on salient astronomical events
3. One sign of a change of conception is the increased emphasis on exactitude, or perhaps more correctly the increased interest in every small discrepancy between observation and theory
    a. The new attitude: discrepancies raise the question, what are they telling us
    b. Continuity with the past mathematical tradition, but now viewing it in a different light
    c. Exactitude takes precedence over restriction to uniform circular motions
4. Another sign of change of conception is the preoccupation with physically true motions, distances, and sizes

a. Now accurate to describe their goal as determining these, and not just saving the main phenomena in a computationally tractable manner
b. A demand on answers that they recognize is not so easy to meet
c. This recognition and the concerns it raised, more than anything else, may be what makes astronomy as of 1642 look so much more like modern science than astronomy of 1542 does

5. Kepler out in front in his insistence that astronomy is a branch of physics, and the physically true motions are those dictated by the physical mechanisms governing the motions
   a. Notice that telescopic observations undercut the divide between the celestial and the sub-lunary realms by showing e.g. the moon like the earth and the sun and planets not ideal
   b. Appropriate then to expect physical processes to be the same on earth and in the heavens
   c. Kepler not alone here: Galileo's theory of tides represents an appeal to physical processes to settle the question of which system is right, and Galileo's attacks on Scholastic physics part and parcel of his attack on Ptolemaic theory
6. Still another sign of the changing conception is the clear preference for settling questions empirically rather than through an appeal to philosophy or mathematical elegance
   a. Increasing commitment to letting the empirical world be the ultimate arbiter in questions of astronomy
   b. The consequent worry, largely absent from astronomy 100 years earlier, was whether and how the empirical world could resolve some of the questions of concern

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