d. The pattern of variation in timing and width of retrograde motions then requires the center of the deferent to be located midway between the earth and that point: bisection of eccentricity

e. Specifically, given Ptolemy's method of deriving the ratio of the deferent and epicycle radii, do not given consistent values of ratio from one retrograde loop to the next unless the center is located (very nearly) midway between the two points

f. This implies that, of the total change in the apparent angular speed from minimum to maximum, half is only merely apparent and half is real

5. Not only a "model", but complete computational procedure for taking preferred observations to determine the elements and for then calculating geocentric longitudes
   a. Calculationally tractable; even more so with tables
   b. Model helps indicate which observations to use to determine elements
6. Mercury the only planet that posed a special problem for Ptolemy, requiring a feature beyond the basic epicycle-eccenter-equant model
   a. Not clear what data led Ptolemy to augment the model for Mercury
   b. One thing that makes Mercury different is that its (elliptical) orbit has a large eccentricity (0.2 versus 0.09 for Mars, 0.007 for Venus, and all others less than 0.06) -- i.e. Mercury orbit most elliptical (though even then its minor axis is only 2 percent shorter than its major axis)
   c. Another thing: Mercury difficult to observe, because of short time during which it can be observed and atmospheric refraction
   d. Ptolemy could easily have been misled by data; note, though, that he let data dictate the model, and his ultimate model has a trajectory approximating an ellipse
7. Ptolemy's solution for Mercury: a moving center for deferent, somewhat akin to way his first newly discovered anomaly of moon handled
   a. Motion on the two smaller circles constrained so as to counterbalance one another
   b. The only oddity in an otherwise uniform account of the longitudes of the five planets
   c. But even this less glaring than it may at first seem, for Mercury nearest the moon and hence not so odd that its motion involves features of the moon's

G. The Achievement of Ptolemaic Astronomy

1. Achieved what he set out to: a complete, computationally tractable account of the motion of the sun, moon, and five planets, covering all principal irregularities to a high degree of approximation
   a. First successful account in history
   b. No real improvement on its accuracy until the first decade of the 17th century, with Kepler
2. Focused on oppositions, stationary points, patterns of retrograde loops, maximum elongations, principal anomalies etc., where it had extraordinary success
   a. Complete prediction of latitude and longitude for all time, past and future, including (incorrect) effects of precession of the equinoxes

   b. But this primarily to the end of an account of the main regular irregularities in the motion, including the regular anomalies or inequalities, marked by various salient locations like stationary points, oppositions and conjunctions, and eclipses
3. Not 100 percent successful, for account of moon yields clearly wrong claim about how close it comes to the earth
   a. Latitudes of planets also not especially successful: errors of 2 deg or more common (four times the width of the moon)
   b. Errors well above the naked eye observation level in longitudes too: as much as 8 widths of the moon, and often more than two widths
   c. Also, Mercury did require a somewhat different treatment from the other four planets
4. Still, level of accuracy impressively high, as shown in the figure for some retrograde loops of Mars
   a. Not a great deal of interest in individual observations, and hence in discrepancies of sort shown in figure, so long as basic patterns of retrograde loops correct (as they visibly are)
   b. Ptolemy himself calls attention to the possibility of improving orbital elements with better future observations, but no one appears to have done much to that end in the next 14 centuries
   c. I.e. no one seems to have gathered the body of data needed to refine Ptolemy's orbital parameters
   d. This step would have had to be taken before anyone could realize that his overall model of planetary motion could not achieve accuracy beyond a certain level
   e. I.e. the sort of realization he himself achieved in the case of the basic theory of the Moon
5. Achievement maybe best captured by Neugebauer, who divides the entire history of astronomy into three parts, separated by Ptolemy's *Almagest* and Newton's *Principia*
   a. Of comparable importance in history of science to Newton's *Principia*, for mathematical tractability and quantitative accuracy the standard ever afterwards in astronomy
   b. Though stretching, not absurd to change Neugebauer's view about the history of astronomy to one about the history of science
   c. Really did reduce a set of very complicated motions down to a quite simple theoretical model -- at least quite simple compared to the level of complications in the apparent motions themselves
   d. This is one of the fundamental things we have demanded of mathematical "theories" of empirical phenomena ever since
   e. But then, even beyond that, have the values of the parameters of the model determined from observations by measurements mediated by the model, with the demand that these measurements be robust

H. Shortcomings of Ptolemaic Astronomy
1. Concern here is with shortcomings that were detectable at the time, not ones that became evident after Newton and the advent of modern celestial mechanics, or even after 1600
   a. Will examine Ptolemaic science from a modern perspective in Part IV below

b. Concern here is to identify shortcomings that in fact led to further research over the next centuries, or that might well have done so

2. Two empirical shortcomings were expressly noted over the course of the next 10 or so centuries:
   a. The observationally unacceptable excessive variation in the distance from the earth to the moon
   b. The too slow rate of the precession of the equinoxes, leading to the date of the vernal equinox gradually slipping earlier and earlier
3. Two further shortcomings that might be regarded as "philosophical" insofar as they involve violations of Aristotle were also expressly noted
   a. The non-uniformity of the motion on the deferent circle, losing the perfection of circular motion and violating the requirement that the motion be compounded out of uniform motion on circles
   b. The earth is at the center of the stars, but the centers of the deferents do not coincide either with one another or with the earth, nor with the center of the sun's orbit
   c. Both of these might also be regarded as obstacles to realizing the required motions physically, even in a mechanical model of the system (of which there were many attempts)
   d. (Also unclear how tilting account of latitudes could be physically or circularly realized)
4. Other shortcomings were not expressly noted over those centuries, but were likely recognized
   a. Discrepancies between calculated and observed longitudes and latitudes greater than 2 deg, that is, four apparent widths of the moon
   b. No solution for the distances, absolute or even relative, of planets and sun from earth; even in his later *Planetary Hypotheses* Ptolemy could only determine the minimum size required to fit everything inside of the sphere of the stars without having the spheres intersect
   c. Each planetary orbit independent of all other planetary orbits, so not really a planetary system: only tie is via relation of each to the mean sun
   d. The seemingly ad hoc character of having the motions of each of the five planets tied to that of the mean sun even though they were otherwise independent of one another
   e. The latter three, all of which were emphasized by Copernicus, can again be regarded as largely "philosophical," while the first is empirical
5. Given these shortcomings, one might well ask why more than a millennium passed before thoroughly worked out alternatives to the Ptolemaic system emerged
   a. Part of the reason was the difficulty of developing an alternative as good as Ptolemaic theory was in predicting salient phenomena
   b. In other words, the *Almagest* set a standard of excellence that any serious alternative had to match, and this proved far more demanding than we might now think
   c. Another part of the reason was a failure to appreciate that the discrepancies in planetary longitudes and latitudes might be telling them something important to the orbital theory
   d. But this may be a failure only from a far more modern standpoint

IV. Some Philosophic Issues

A. Introduction: Ptolemy as Bad Science?

1. In short, Ptolemaic astronomy is one of the greatest achievements in intellectual history -- so great that it rather overwhelmed everyone for over 1000 years
   a. Criticisms, revisions for sun and moon, various difficulties emerging over time such as with precession of equinox
   b. But no real alternative proposed until Copernicus, and no substantial revision to Ptolemaic orbital theory until Kepler
2. Yet Ptolemaic astronomy the standard example of "bad" science over the last 350 years
   a. Bad science, inferior science, pseudo-science, or non-science
   b. I.e. the example to contrast with modern science, the sort of thing the scientific revolution came to replace: science rejected as fundamentally wrong in certain key respects, something we want to claim is not true of any well-established modern science
3. The view of Ptolemaic science as bad science, which derives in no small part from Galileo's invective against it (as we shaill see later), is not so wide-spread today
   a. Historical research, most notably by Neugebauer and his protegé Swerdlow, as well as Toomer, has done much to reclaim the status of Ptolemy in the history of science
   b. But notice that that merely underscores the real question here: ***if Ptolemaic science was not such bad science by modern standards, then what is it about our current science that assures us that large parts of it are not going to be rejected as fundamentally wrong -- and even ridiculed -- in the future in just the manner that happened with Ptolemaic science?***
   c. Some sociologists of science, notably Bruno Latour, insist that nothing assures us of this
4. At least since mid-century (Koyré and Kuhn), historians of science have regarded it as inappropriate to judge the "science" of any other time by our current standards
   a. Let each period define 'science' and set methodological standards for itself, and then judge work in the period on the basis of this definition and these standards
   b. The alternative is to impose our definition and our standards without recognizing that they may turn out to have been just as parochial as theirs were
5. Nevertheless, in some sense modern science seems superior to Ptolemy, and much of this course -- in the philosophy of science -- is devoted to trying to spell out this sense
   a. So must ultimately face the issue, how, if at all, is Ptolemaic astronomy epistemically inferior, if only in an effort to better understand our conception of science today
   b. Begin to face the issue now by asking, what was the worst feature of Ptolemaic astronomy?
6. I will be violating Koyré's and Kuhn's dictum in this way throughout the course, judging the science we review not merely from the standards of the time, but also from contemporary standards -- always in an effort to understand the latter better, not to demean the former

B. Issue: What Claim is Ptolemaic Theory Making?

1. First, however, should pause to consider more carefully what sort of claim the Ptolemaic system should be interpreted as making
   a. Have used the word 'account' to avoid words like 'explain' and 'predict' -- words couching distinctions within contemporary philosophy of science that may have been irrelevant to Ptolemy
   b. Issue: given our more sophisticated views about the different ways in which his account might be interpreted, how is it best interpreted?
2. It is definitely not a mere recapitulation of existing data, or a curve-fit of some sort on old data
   a. Definitely meant to project beyond all existing data
   b. Takes the regularities it addresses themselves to be projectable -- as occurring repeatedly indefinitely into the past and into the future
3. Though it yields longitudes and latitudes versus time, seems primarily an account of -- a theory about -- various regularities noted in the past, and not about individually observed longitudes and latitudes
   a. Distinguish between data (or observations) and phenomena, where latter are the regularities exhibited within the data
   b. Ptolemy seems to have been aiming at giving an account of these phenomena, including some new ones he discovered as a consequence of his account
4. Not a mere recapitulation of the phenomena it accounts for either, for these phenomena exhibit far more "degrees of freedom" -- far more distinct, seemingly independent variations -- than Ptolemy's account has elements
   a. In particular, six independent elements, to account for a much larger number of variations in retrograde motion
   b. In some sense a reduction of a complicated range of phenomena to a comparatively simple base
   c. Furthermore, generalizations: same basic model, with exception of minor addition in case of Mercury, covers all planets
5. Thus at the very least making a strong claim: whatever the true motions are, they are reducible to a simple basic account at least to a sufficient approximation to "save the phenomena" of interest
   a. An account whose elements can be determined from a handful of observations
   b. And that is computationally tractable both in derivation and application, allowing a set of questions pertaining to observable locations over time to receive computed answers
   c. Thus a mathematical theory in the modern sense -- a complete question-answering system of the same general sort that we now learn in physics and other such fields
6. This in contrast to claiming that describing the precise motions of the planet or giving an account of the physical mechanisms underlying their motions
   a. Phenomena either result from a motion involving compounds of circles with eccenters and equants, or are as if they result from such a motion

b. Thus, at the very least, a starting point for pursuing the precise motions and the physical mechanisms underlying them

C. Issue: Is It Bad Because It Is Too Complicated?

1. Most common criticism of Ptolemaic astronomy today is that the system was inordinately complicated -- so complicated that no one in their right mind should have taken the system seriously

   a. "Epicycles on epicycles" -- a claim that in fact is basically false, though it does appear to have a historical source in a remark made in the 13th century by King Alphonso of Spain

   b. As you will see by the end of the course, orbital descriptions are not less complicated today, because in fact the orbital motion really is quite complicated

2. Still the classic complaint that Ptolemaic astronomy is too complicated can be put into a forceful form -- e.g. it is too complicated in the sense that his cinematic models involve too many ad hoc elements, making then too Rube Goldbergish

   a. Obvious reply: but captures an extraordinary range of phenomena -- primary regularities and secondary and tertiary anomalies -- within a model involving only a handful of parameters, with the same basic model generalizing across several planets

   b. What more can we legitimately ask for? (Indeed, has modern science done more than this?)

   c. This is not to deny the arbitrary features of the model, and differences from one planet to another

      (1) Sun and moon different from the others and from each other

      (2) Inner planets tied to (mean) sun and hence different

      (3) Outer planets tied to (mean) sun in a different, seemingly arbitrary way

      (4) Mercury requires exceptional feature, and Moon requires two

   d. But Ptolemaic astronomer can reply not just that the data force those features on us, but -- more importantly -- that his mathematical representation served to reveal these secondary regularities, which otherwise might have seemed to have no pattern to them!

3. There is a related classic complaint, perhaps better capturing the intent: Ptolemaic astronomy is too complicated in the sense that no physical mechanism seems to fit it, and on surface not very likely that one can be found

   a. The basic system of the crystalline spheres ceases to work -- i.e. can no longer build an actual running model -- once the complications are included

   b. Equant the major problem, for can't be handled by rotating spheres in any obvious way – a complaint raised in Islamic astronomy, as well as by Copernicus

   c. But inner epicycles for Mercury and Moon also a problem

4. A legitimate complaint, but as we shall see later in the course, less injurious than one might think, for a complaint that holds against many of the great successes in modern "good" science

   a. At the time Ptolemy had little empirical basis for making claims about the underlying physical mechanisms

b. Especially in the light of the empirical basis he had for the planetary theory, even with its many complications, claims about the underlying mechanisms had to be regarded as mere conjectures -- that is, as hypotheses in contrast to features dictated in significant part by observations

c. The most that can be said is that his planetary theory shed little light on the underlying physical processes; but this is true of lots of the greatest theories in science

5. In sum, the complaint that the complexity of Ptolemaic astronomy was by itself enough to raise serious doubts about it does not stand up well under scrutiny

a. This is not to say that complexity objections to scientific theories are never appropriate

b. Rather, the point is that such objections are legitimate only in special circumstances that we have not yet identified, beyond arguing that they did not so clearly hold in the case of Ptolemy, at least in the context of all other information available to him at the time

c. In particular, the bald fact of complexity is not even a serious prima facie objection to a scientific theory, for once you get past the classroom level you will find that many fields of contemporary physics are staggeringly complex -- e.g. contemporary wave-particle optics

D. Issue: Is It Bad Because It Is Simply False?

1. Of course, the preceding defense of Ptolemy begins to raise a worry, for we know that Ptolemaic astronomy is seriously false, and we don't want any false theories to count as good science

a. For, if they do, we may have to make allowances for the possibility that current theories satisfying the strictures of good science may turn out to be false too

b. Idea: false theories that are held for extended periods of time, as if the final word, must in some sense be bad science, for the whole point of methodological strictures is to preclude just that!

2. An obvious basis for saying that Ptolemaic science is inferior science is that it is false, for the planets do not in fact describe epicyclic motion, nor for that matter uniform angular motion with respect to some point in space

a. Indeed, Ptolemaic science is even worse than false, for it was in certain respects a dead-end, a garden-path, that had to be surmounted before scientific progress could be made

b. In particular, an impediment to gaining empirical access to the underlying physical processes

3. While there is surely some truth to this complaint, it does have the fault of presupposing that we must take Ptolemy as asserting without qualification that the planets really do describe epicyclic motion, with the Earth at the center

a. The *Almagest* opens with a brief argument against the motion of the Earth that is best read as making a prima facie case that the Earth is an appropriate reference point for all other motion

b. This at least opens the possibility of interpreting his theory as making a weaker claim: it is describing the motion of the celestial bodies relative to the Earth, taken as a reference point

4. If we adopt this slightly less extreme interpretation of Ptolemaic theory, then accusation of falsity has to be qualified too

a. For relative to Earth the planets do exhibit (as we shall see) at least something akin to the compound circular motion that he says
   (1) In the case of the outer planets, the epicycle represents the orbit of the Earth, while the deferent does so in the case of the inner planets
   (2) But in both cases a compound of two basically eccentric circular motions
b. Moreover, the other main claim -- that the variations in apparent motion are roughly half attributable to a real variation in motion, described by the equant, and half to an appearance arising from the observer being off-center -- also can be defended in retrospect

5. In other words, taken this way, Ptolemaic astronomy is, at least to a first approximation, true!
   a. What is more, these elements of truth proved historically important, for they were the basis of subsequent developments
   b. So, Ptolemaic astronomy was not even a dead-end or a garden-path in any simple way

E. Issue: Is It Bad Because It Is Too Inaccurate?

1. There is a more subtle version of the complaint that Ptolemaic astronomy is false
   a. There was sufficient evidence available at the time, or at least over the next centuries, to establish that Ptolemaic astronomy is false
   b. Namely discrepancies day in and day out between observed longitudes and those given by the theory, not to mention discrepancies in latitude as well
2. Ptolemaic astronomy is indeed not exact, for predicted longitudes, and latitudes too, wrong by much more than observational error (said by Ptolemy to be around 10 min of arc)
   a. As remarked above, errors in latitude of 2 deg common, and as figure for the retrograde loops of Mars shows, longitudes off by this much and more, even 4 deg every once and a while
   b. Diameter of the Moon is 30 min -- half a degree -- so that these discrepancies are clear to the naked eye
   c. Though, unlike the discrepancy owing to the mistaken rate of precession of the equinox, these errors are not cumulative
3. Reply: fair enough, but the only claim is that the theory holds to a sufficient approximation to yield a good account of the primary phenomena
   a. Furthermore, as Ptolemy himself illustrates in the case of the Moon, theory holds to a sufficient approximation to be a basis for continuing research in which future observations may yield better elements, or reveal further patterned anomalies
   b. Every theory always has its discrepancies, so the mere presence of discrepancies here is not grounds for an indictment
   c. The whole idea is to use theory to expose discrepancies so that they can in turn be learned from
   d. Ptolemy himself not only illustrates this, but invites just such future attention in the way he instructs the reader in using observations to fix the orbital parameters

4. Historically, however, this is not what happened; no one appears to have pursued the observational data needed to be in a position to describe the discrepancies in longitudes and latitudes systematically, much less to expose telling patterns in them
    a. Perhaps some started, but failed to see any pattern right away, and lacking an adequate base of data, abandoned the effort
    b. Or perhaps the view was that the discrepancies were not to be taken all that seriously -- e.g. they may involve observational errors, or they may be the consequences of ill-behaved secondary mechanisms that are beyond the scope of scientific investigation
    c. Or perhaps nobody even became concerned about the discrepancies, because, Ptolemy's own efforts in this direction notwithstanding, they lacked the modern concept of exact science on which every systematic discrepancy with observation is taken as raising a worry
5. Regardless, so far as I can see, the most serious fault of Ptolemaic astronomy, though less so of Ptolemy himself, is a failure to use it as a basis for further research, attempting to identify residual imperfections and characterize these as new phenomena requiring refinements of the theory
    a. Ptolemy showed the value of doing just this with his discovery and treatment of the second and third lunar anomalies
    b. But subsequent astronomers did not exploit Ptolemaic astronomy in this way
    c. If they had, they would have made a number of startling and useful discoveries, though the effort in doing so would have had to extend across a community over a substantial period of time
6. Maybe this is the primary lesson to learn from the "failures" of Ptolemaic astronomy: a community of demanding scientists is needed to subject theories to constant criticism -- repeatedly revisiting the evidence for their fundamental principles and presuppositions underlying them
    a. Not just the "greats" of the history of science who have made science what it is, but also the many lesser figures whose primary role has been one of critical assimilation
    b. Such a community would have at least begun developing a record of the inaccuracies of Ptolemaic theory, in the process raising questions
    c. The history of science might have been substantially different if such a community had been at work in the 1000 years following publication of the *Almagest*

<u>Select Sources</u>

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Credits for Appendix

Slide 2: Seeds (1988)

Slides 3, 14, 15: Evans (1998)

Slides 5-8: NASA.gov/multimedia/imagegallery

Slides 9, 23, 30: Neugebauer (1975)

Slides 16, 22, 25: Evans (1984)

Slide 21: www.faculty.umb.edu

Slides 26-28: Swerdlow, unpub lished