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Ptolemy's Use of His Predecessors' Data

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When Ptolemy published his *Almagest* or his *Geography*, all earlier scientific treatments of those fields began to vanish, replaced by his comprehensive and systematic works. Yet there has always been skepticism concerning Ptolemy's abilities as a scientist and doubts about his integrity as a reporter. Anything new in Ptolemy has been attributed to his predecessors—easy to do, since their works have not survived. Tycho Brahe assumed that Ptolemy's catalog of stars was simply copied from Hipparchus' catalog with corrections for the intervening 260 years' worth of precession. J. L. Dreyer repeated this statement, and it became dogma. Delambre, the greatest of the nineteenth-century historians of astronomy, was consistently hostile to and distrustful of Ptolemy's works. For him, Ptolemy was an inferior and clumsy observer, an imprecise and inaccurate reporter of his own and his predecessors' observations, and a plagiarizer and a falsifier of observations.[1] Such criticisms have continued in the twentieth century, even reaching the American popular press with the publication of R. Newton's *The Crime of Claudius Ptolemy*, which contends that Ptolemy "based all his astronomical work upon fraud."[2]

These accusations of incompetence, dishonesty, and plagiarism have not been confirmed by detailed investigations of Ptolemy's individual works. Studies by von Mzik, Vogt, Neugebauer, Lejeune, and Britton (all cited below under the proper topic) have justified Ptolemy's standing as one of the great figures of science. The purpose of this paper is to contribute to the evaluation of Ptolemy's work by showing in what way he used the data inherited from his predecessors and in the discussion to show to what extent Ptolemy's scientific

[1] Brahe's comments in *Tychonis Brahe Dani Opera Omnia* II 151. Delambre said: "The fraud is obvious" with reference to Ptolemy's observations of the equinoxes: Delambre 1817: 110. For Dreyer's statement, see below n. 36. The opposite opinion, namely that Ptolemy was a researcher of the highest originality who left all his predecessors far behind, is also held: Swerdlow 1992: 181. A comprehensive review of the opinions concerning Ptolemy's originality in Grasshoff 1990: 23-84.

[2] Newton 1977: 365. This book excited comment in *Time*, the *New York Times*, and *Scientific American*, among others. Newton's thesis is supported by Hartner 1977; it was rebutted by Swerdlow 1978. Similar criticism of Ptolemy, for his geography, in Photinos 1960: 131ff.: "Ptolemy is an egotistical liar who passed off Marinos' work as his own."

work was original and to what extent it was derived from the ancient scientific consensus. I will use the *Optics*, the *Geography*, the *Phaseis*, and the fixed star catalog of the *Almagest* as data. This paper does not deal with Ptolemy's innovations—if such they were—in mathematics, i.e., the spherical trigonometry of the *Almagest* or the projection system of the *Geography*.

To anticipate the results: in each field of study, Ptolemy inherited a specific conceptual framework into which all data were fitted. In astronomy this framework included a geocentric universe with seven astronomical bodies moving with regular motions; the data are the velocities and directions of these motions. In geography the framework included a spherical earth with "our part" of it embracing one-half of the northern hemisphere. In astrology existing theory held that all celestial bodies influence the earth's environment just as the sun does, only in a less obvious way. In his researches Ptolemy attempted to verify and to add to the existing data by experimentation, by new investigations and observations, and by the application of mathematical procedures. He then presented this revised and augmented set of data in tabular, numerical form (optics, astronomy) or in numerically determined sets (geography). When he (re)organized these data and presented the information in an appropriate format, he did not redo observations which seemed correct or revise the original conceptual framework in which the data had originally been collected. This conservatism distinguishes Ptolemy from Copernicus. The latter, using the same type of data (with additional Arab observations), did attempt to revise the accepted truths of cosmology and thus effected a revolution in science. Ptolemy did not.

In each of the scientific fields in which he worked, Ptolemy claims to have based his researches on the work of one predecessor whose theoretical framework he adopted and whose data he revised. In optics, which I discuss first and which I use as a paradigm for his behavior as a researcher, he followed Euclid; in geography, Marinus of Tyre; in astronomy, Hipparchus. Where his predecessor's works survive—as they do in optics—Ptolemy's contributions can be fairly assessed. Where these works do not survive—in geography and astronomy—accusations of incompetence and plagiarism have arisen.

OPTICS

Ptolemy's work in optics can easily be compared with that of his predecessor, Euclid, primarily because Euclid's treatise survives.[3] In a series of articles,

[3] The total includes Euclid, *Optics*, *Opticorum rescensio Theonis*, and *Catoptrica* (on mirrors, a production of late antiquity), all in Euclid, *Opera*; Damianus, *Schrift über Optik*; Heron of

Albert Lejeune compared Euclid's and Ptolemy's treatises and outlined the advances made by Ptolemy in the science of optics and some of the peculiarities of his procedures.

In the *Optics*, as in his other systematic works, Ptolemy presented his work as a revision and a synthesis of existing knowledge, not as a revolution; he incorporated in this synthesis his own contributions, without putting a great stress on them.[4] An example of his procedures can be seen in his discussion of the phenomena of vision. In ancient theory, vision is produced by the interaction of visual rays emanating from the eye and the light rays in the environment. (This is the usual picture; other theories were current among the Epicureans and Stoics.) The visual ray is considered very much like an invisible hand reaching out, in a straight line, towards an object and sensing the object's shape and distance from the subject's eye.[5] Because of this conception, the phenomena of vision can be treated as a series of geometrical problems involving straight lines and their reflections. For Euclid, as for Aristotle, optics was simply a subdivision of geometry.[6] His *Optics* consisted of preliminary definitions, followed by fifty-eight theorems which are geometrically demonstrated:

"Let it be assumed

1. That the rectilinear rays proceeding from the eye diverge indefinitely [=visual rays];

2. That the figure contained by a set of visual rays is a cone of which the vertex is at the eye and the base at the surface of the objects seen [=the cone of vision];

Alexandria, *Opera*, vol. II: *Die Katoptrik*; Ptolemy, *L'optique de Claude Ptolémée* (Ptolemy 1989). The last work is a Latin translation of an Arabic translation of the lost Greek original. A French translation by Lejeune is included. All references to the *Optics* are to the book and section number in this edition. Partly due to the dreadful state of the text, Ptolemy's authorship has been questioned. See the preface to Ptolemy 1989 for a reaction to Knorr's suggestion that Sosigenes really wrote it. Burton 1945 translates Euclid's *Optics* into English. Aristotle, Galen, and many others refer to visual phenomena frequently. Our interest here is with the professional "opticians."

4 Lejeune 1948: 173ff. Van der Waerden in *RE* XXIII.2 1794-5.

5 Hipparchus: "The rays are like the palms of the hands," Aetius IV 13.8-12; Lejeune 1948: 22. The subject is aware of the length of the visual ray and hence can perceive depth: *Optics* II 26; Lejeune 1948: 87-88.

6 Optics as a branch of geometry: *Physics* 194a9-10, Simplicius, *In Aris. Physicorum Comm.* 294.26-7. Aristotle's *Meteorology* III 5 contains a geometrical proof of the proposition that a rainbow can never be a circle or an arc of a circle greater than a semi-circle (*Met.* 375b17-377a27). His *de Sensu* III shows that colors are the result of ratios (439b25-440a6). Both of these passages use purely geometrical terminology. Aristotle was, however, interested in phenomena (particularly color) that were ignored by Euclid. See Düring 1966: 393 and Lejeune 1948: 174.

3. That those things are seen upon which visual rays fall, and those things are not seen upon which visual rays do not fall . . ."

(Euclid *Optics* VII 2.2-9).

These rays, moving by definition in a straight line, furnished him with all the elements necessary for constructing his theory of perception, which he set forth in a series of propositions, just as in the *Elements*. Neither light, color, nor sensation played a part in his optics.

Likewise in Euclid's *Catoptrics*, the law of reflection (Hypothesis 3: the angle of the reflected ray is equal to the angle of the incident ray) is proven by the use of similar triangles in a purely geometrical fashion, with no appeal to experiment or to sensation, and no measurement in degrees or any use of numerical values (Euclid *Opera* VII 286.4-9).

Ptolemy's approach to the study of visual phenomena was different: he constructed a protractor-like instrument graduated in degrees, equipped with an eyepiece, a mirror, and an object on which to sight (Ptolemy *Optics* III 8-10); he determined what an observer would actually see when sighting on objects placed in varying configurations at varying distances from the eye; he performed demonstrations showing the real nature of monocular and binocular vision and revised the theory of the visual cone; he investigated colors, the nature of light, and the similarities between the visual ray and the light ray. By means of these demonstrations, Ptolemy enlarged the scope of this science, treating it in our terms as a branch of physics and transforming Euclid's geometrical postulates into "laws" of physics.

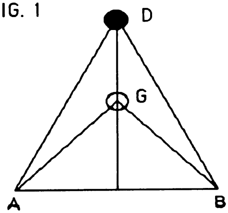
As an illustration, consider his experiments with binocular vision, experiments which study the subjective sensation of vision without discarding the older geometrical paradigm. A review of these experiments, which the reader can easily duplicate using two pencils of different colors, illustrates Ptolemy's conservatism (he maintains Euclid's geometrical tradition) combined with innovation (he experiments and seeks a physiological explanation for the experimental results).[7]

[7] This discussion owes much to Lejeune 1948: 132-141. The geometrical figures are in Ptolemy's text; the accompanying sketches representing what the observer sees are in Lejeune 1948 and Lejeune 1957.

Experiment One

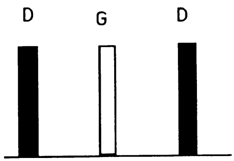
"The base of a pyramid is AB. B is at the right eye, A at the left. On a straight line perpendicular to AB at its midpoint are two upright cylinders, G and D. To these are produced from the base angles the straight lines GA, GB, DA, DB. We fix our vision on G, which is closer." (*Optics* II 33) G is white, D black, as in Figure 1.

FIG. 1



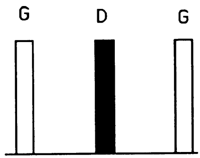
AG and BG are the center axes of the two cones of vision, one from each eye. Fixing our gaze on G, we see two D's; fixing our gaze on D, we see two G's, as in Figures 2a and b (II 34-5).

FIG. 2a



Gaze fixed on G

Fig. 2b



Gaze fixed on D

Explanation: If the gaze is fixed on G (the white cylinder), D is hit by a ray which is to the *left* of the axis of the cone of vision of the *left* eye (i.e. the line AD). D is also hit by a ray which is to the *right* of the axis of the cone of vision of the *right* eye (the line BD). Therefore the left eye receives the impression of a black cylinder on the left, and the right eye the impression of a black cylinder on the right. Hence two black cylinders are seen. On the other hand, if the gaze is fixed on D (the black cylinder), then G is hit by a ray which is to the *right* of the axis of the cone of vision of the *left* eye (the line AG). D is also hit by a ray to the *left* of the axis of the cone of vision of the *right* eye (the line BG). Therefore the left eye receives the impression of a white cylinder on the right, and the right eye receives the impression of a white cylinder on the left. Hence two white cylinders are seen (II 34-5).

This experiment describes an individual's perceptions and the reasons for them. Ptolemy then performs several closely related experiments.

Experiment Two

The same experimental setup as in experiment 1, but the gaze (the two lines AG and BD) is fixed on a distant point (Figure 3). Each cylinder produces two images on either side of its true position (Figure 4).

FIG.3

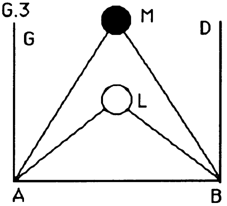
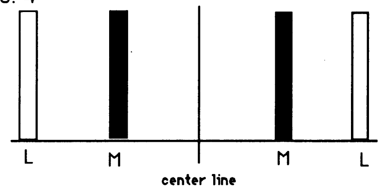


FIG. 4

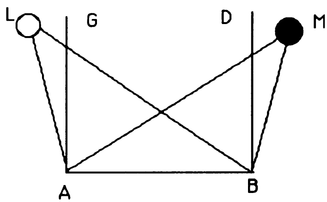


Explanation: Each cylinder is hit by a ray of each eye's cone of vision (as in the previous experiment). The *left* eye's (A's) ray is to the *right* of the axis of the cone (AL, AM); the *right* eye's (B's) ray is to the *left* (BL, BM). In addition, AL is more to the right than AM; hence L appears farther from the center line, its real position. A similar argument applies to BL, BM, and M.

Experiment Three

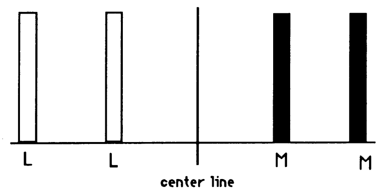
The cylinders are placed farther apart than the distance between the eyes, and the gaze is fixed on a distant point (Figure 5).

FIG. 5



Again four cylinders are seen, but in a different arrangement (Figure 6; II 42).

FIG. 6



Several similar experiments follow in the same vein.

It is clear from the figures and from the general procedure that Ptolemy kept Euclid's conceptual framework for describing visual phenomena: vision results from the action of visual rays; visible objects all appear in one plane—depth of field is ignored; simple figures suffice to explain the propositions, which are easily repeated without special equipment. All of this can be said of Euclid. However, Ptolemy went beyond Euclid in that he carried out an experiment to determine what the observer sees under varying circumstances in the course of the experiment. Ptolemy was concerned with the subjective side of perception, not just with perception as an abstract set of propositions. He was also trying to determine the conditions necessary for accurate perception of an object's true location and to accumulate a coherent body of data which would be applicable to the real world. In this, one can see the astronomer's concerns coming to the fore.[8]

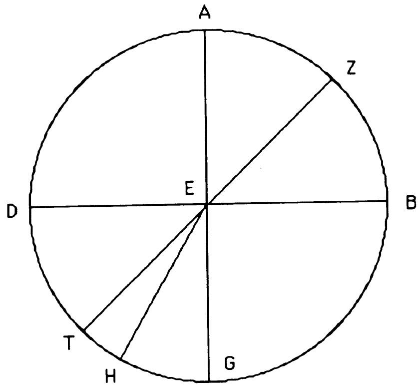
The same concerns can be seen in his determination of the refractive index (*Optics* V). There he reported experiments whose goal was the determination of the angles of refraction for the visual ray as it passes from one medium to another.[9] As in his researches into binocular vision, Ptolemy set up experiments, here using an instrument to determine the amount of refraction which occurs at varying angles and at the surface where different transparent media (air, water, glass) meet (*Optics* V 2-3).

To study the boundary between water and air, he made a disk which could be immersed in water (Figure 7). Two diameters intersect at E; each quadrant is graduated into 90°. A fixed sighting point (*magnitudo valde parva*–a peg; V 8) is put at E, a moveable sighting point at Z. The disk is then immersed in water to the line DB. Now the tip of another sighting rod is moved along the quadrant DG until it appears directly in line with ZE (appearing as if it is at T) and its position is marked. Its true position when pulled from the water is discovered to be H. When the angles AEZ and GEH are measured, AEZ is always greater than GEH. The visual ray is bent (*frangitur*) towards H by an amount dependant on the angle AEZ (V 9).

[8] A related series of experiments on binocular vision are reported in *Optics* III 26-45. They study various complicating factors; Lejeune 1948: 147-65.

[9] *HAMA* 894-96 and Smith 1982. See also van der Waerden in *RE* XXIII.2 1794; Schramm 1964: 74-85; Crombie 1963. An English translation of *Optics* V 1-35 (not in order) in Cohen and Drabkin 1948: 271-83.

FIG. 7



A view along the perpendicular AE will exhibit no bending, and the ray will hit G. Ptolemy took sightings for varying angles, with results as expressed in the following table (V 11).[10]

Refraction at the air/water boundary

AEZ = ANGLE OF INCIDENCE	GEH = ANGLE OF REFRACTION	[DIFFERENCE	SIN I:SIN R]
10°	8°	[___	1.248]
20°	15 1/2°	[7 1/2°	1.270]
30°	22 1/2°	[7°	1.308]
40°	29°	[6 1/2°	1.369]
50°	35°	[6°	1.336]
60°	40 1/2°	[5 1/2°	1.333]
70°	45 1/2°	[5°	1.329]
80°	50°	[4 1/2°	1.286]

This table, which would have been beyond Euclid, is itself a sign of Ptolemy's innovative approach.[11] The astronomer was familiar with tables, particularly

10 The two columns on the right are not in Ptolemy. They are found in Cohen and Drabkin 1948: 278, and in *HAMA* 894-96.

11 Schramm 1964: 73 emphasizes the importance in the development of science of the use of numbers rather than pure geometrical construction, the use of mathematical tables to illustrate functions, and Ptolemy's experimentation to verify hypotheses. Such experimentation was uncommon: the oft reported story of Pythagoras and the blacksmith's hammers, the point of which is that a weight twice as heavy makes a tone twice as high in pitch, a factoid reported by several authors throughout antiquity, though refutable by the simplest experiment, proves the rarity of

those based on constant differences. For example, Ptolemy's table of chords (*Alm.* I 11, col. 3) contains a column with increments in the chord lengths of 1/60° (=1') to facilitate linear interpolation; the earlier Babylonian lunar motion tables are computed using arithmetic progressions with constant differences.[12]

In addition to Ptolemy's use of tables, it is also clear that he applied a mathematical adjustment to his data. The figures in the 'difference' column decrease at a constant 1/2°, and therefore must be approximations: "Cumque fuerit circumferentia AZ decem partium . . . erit circumferentia GH octo partium *ad prope*" (V 11). Ptolemy corrected the observed results—always subject to error, as any hapless chemistry lab student can testify—to correspond with a set formula, which may in fact have been derived from a first reading of the data. In this example Ptolemy's formula is only roughly correct: the true formula states that the ratio of the *sines* of the angles of incidence to the *sines* of the angles of refraction (i.e. the sine of AEZ to the sine of GEH) is a constant, not the ratio of the angles themselves. Smith has pointed out that Ptolemy expected to find a linear relationship between the angle of incidence and the angle of refraction, and that this apparently reasonable expectation led him into error. It can, however, be seen from column four above that Ptolemy's figures have approximately their correct values: the refractive index of air/water is 1.33, and Ptolemy's values group around this value—not bad for naked-eye observation. One might doubt that his original series of observations gave results as neat as his final table would indicate.[13]

In applying this adjustment to his data, Ptolemy was again following astronomical practice. The Babylonians had calculated planetary motion by means of step functions which assigned different velocities to the planets at different points of the ecliptic. Such mathematical operations are derived from first readings of the data, but go far beyond these readings in the number of

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such experimentation. See Cherniss' note on Plutarch's *De animae procreatione* 1021A (in the Loeb edition of the *Moralia* XIII,1).

12 Explanations and examples in Neugebauer 1969: 110-115, *HAMA* 375-39; for the importance of tables for the development of mathematical physics, see Schramm 1964: 71ff. Ptolemy's methods derive ultimately from the Babylonians, but the transmission is unclear. See Jones 1990 and Jones 1991 *passim*.

13 Lejeune 1946: 24ff. Ptolemy is asserting that the law of refraction is deducible from his observations and experiments. One might suspect that the experiment provides supporting evidence for the (presupposed) law. In defense of Ptolemy, I might cite Karl Popper's contention that it is impossible, indeed inadvisable, to observe first and only later to form a hypothesis (the schoolbook definition of the scientific method). See Guthrie 1981: 6.110 for an anthology of quotations on this point.

"decimal" places entered on each line of the table and in the regularity of the function's steps.[14]

Ptolemy carried out similar experiments for the boundary of glass and air, then glass and water, with some modification of the apparatus: he added a semicircle of glass to the bottom half of the disk illustrated above and sighted through that glass. He then proceeded to find the angle of refraction for the glass/air (V 14-18) and the glass/water (V 19-21) boundary as he did for the water/air boundary. He also discussed refraction at the air/aether boundary and its problems for astronomy (V 23-30; compare *Alm.* IX 2; H 2,210), but dismissed the possibility of actually determining the values.

This survey of one section of the *Optics* has shown three principles according to which Ptolemy presented his research to his audience: 1) he maintained the conceptual framework (visual rays, cone of vision) of his predecessor Euclid; 2) he conducted experiments to demonstrate certain optical principles and to study the aspects of vision which could not be treated by means of his predecessor's strictly geometrical approach; 3) he expressed his results in numerical, tabular form, smoothing the data reported in the tables to correspond to a set formula. This smoothing may have been the result either of an adjustment of the experimental results or of a selection of "good" values from a large number of experimental results.[15] These same principles, adapted to a different field of study, can also be seen in his *Geography*.

GEOGRAPHY

First of all, a description of this text itself. The *Geography* is not a qualitative description of the earth, but rather a description of the technical problems of mapping the points on a sphere onto a plane surface (Book I), a list of the map-coordinates of cities and places (Books II-VII), and a description of the resulting regional maps (Book VIII). "Geography is a representation of the

[14] For details see Neugebauer 1969: 97-119, *HAMA* 375-79. The precision of the Babylonian tables is not amazing accuracy, but simply a refusal to round off and hence destroy the periodicity of the function. I must point out that we do not know the steps between the Babylonians and Ptolemy, but there certainly were steps: see note 30.

[15] Many of these same points could be made about Ptolemy's work in music/harmonics, in which he reports experimental results on which a mathematical theory is based. See Lejeune 1957: 338-9 and Düring 1930 (the Greek text of Ptolemy's *Harmonics*), and Düring 1934 (a German translation with notes). A music treatise, the *Sectio canonis*, was also attributed to Euclid in antiquity.

known part of the earth through geometrical means" (*Geo.* I 1).[16] The goal of his labors was a series of tables listing accurate, *numerical* coordinates of cities and other places on the earth in such a way that a map could be constructed from these tables alone, without the geographer's being at the mercy of his copyists (I 19). Even in the *Almagest* this goal was foreseen: it only remains "to determine the coordinates in latitude and longitude of the cities... We shall *list* for each of the cities its distance in degrees from the equator...and the distance in degrees of [its] meridian from the meridian through Alexandria..." (*Alm.* II 13; trans. Toomer, emphasis mine). *Geography* II-VII enlarges this plan to cover coastlines, rivers, harbors, and all other prominent features of the landscape with the final product being tables such as the following (from *Geo.* II 2.1-2):

The Position of Ireland, a British Island

The northern coast of Ireland is situated on the arctic (lit: Hyperborean) ocean; its description is as follows:

The Northern Cape	11° [longitude]	61° [latitude]
Cape Vennicnius	12 5/6°	61 1/3°
The mouth of the Vidua River	13°	61°
The mouth of the Argita River	14 1/2°	61 1/2°
Cape Robogdius	16 1/3°	61 1/2°

and so on to cover the entire world in unprecedented detail. These tables certainly make up one of Ptolemy's chief claims to be a researcher of unparalleled diligence. The tabular style of presentation is parallel to the style of the *Optics* and the *Almagest*.

In his optical researches, Ptolemy had inherited definitions and principles from Euclid, not numerical data. In geography on the other hand, as in astronomy, his predecessors had accumulated numerical data concerning distances and positions of cities or of stars. Ptolemy found, however, that his

[16] διὰ γραμμῶν. "Geometrical *means*," not *pictures*: as mentioned below, Ptolemy's real goal is to make a series of tables listing the coordinates of places on the earth. Whether Ptolemy himself supplied the maps now accompanying the *Geography* is disputed. See Polaschek 1959: 17-18. Significantly, διὰ τῶν γραμμῶν often means "by precise means" rather than "by numerical approximations." See Luckey 1927. In Plato and Aristotle, the word διάγραμμα means both a geometrical figure and the proof of a proposition. For a discussion of the meaning here see von Mzik 1938: 13 n. 2. This work, a translation of *Geography* I 1-II 1 with explanatory appendices by Friedrich Hopfner, is indispensible for understanding Ptolemy's *Geography*. An English translation with commentary by L. Berggren and A. Jones is promised. Ptolemy is cited from the text of Nobbe. References are to the book, chapter, and section number of this edition. Full-sized facsimiles of the maps in several mss. can be found in Ptolemy 1932. Selections from the *Geography* (including I 1-5) are translated into English in Cohen and Drabkin 1948: 162-181. The English translation of the entire work by Stevenson is unreliable.

predecessors' data varied in quality. In an astronomical treatise, the data could be checked by direct observation of the given star's position; in geography, the criteria for evaluating observations had to be developed anew.

Of course Ptolemy, given the information at his disposal, could not determine exact distance from travel times and astronomical observations, but he tried to do so, and if he had succeeded, the tables of the *Geography* would be as accurate as the refraction tables of the *Optics* or the astronomical tables of the *Almagest*. Ptolemy did have some astronomically derived data: Hipparchus' observation of the elevation of the Pole star at a few cities (*Geo.* I 4); Heron's attempt to establish the straight-line distance from Alexandria to Rome;[17] the observations of "corresponding places" (ἀντικειμένων τόπων, places lying on the same meridian); the one known observation of a lunar eclipse visible in two different places (Arbela on the Tigris River and Carthage in N. Africa); and finally the detailed data reported by Marinus of Tyre, Ptolemy's immediate predecessor in geography (*Geo.* I 6ff.).[18] In practice however, the sources from which he received most of his information reported no astronomical observations, much less instrument readings. As a result, Ptolemy needed criteria which could be applied to his data in order to judge their veracity or to bring them into agreement with known facts. His long discussion (*Geo.* I 7-14) of the limits of the inhabited world (οἰκουμένη = the northern hemisphere of Eurasia) provides a glimpse into his criteria. In brief, he undertakes a common-sense evaluation of the reports on the basis of what he "knows" about the dimensions of the inhabited world, the difficulties and delays in travelling, and political and biological realities. The role of each criterion will be clear in the sequel.

As in his earlier works, he conveniently assumes that the E-W dimension of the known world is 180°. The dimensions cited in his earlier works are all 180° E-W and 90° N-S.[19] In the *Almagest* he believed the earth to be divided into four quarters (εἰς τέσσαρα . . . τεταρτημόρια, *Alm.* II 1; H 1, 87-88) by the equator and a meridian circle through the poles. Ptolemy's part of the world lies in one of the northern quarters, i.e. in a quarter bounded on the south by the equator, on the north by the North Pole, and on the east and west by a meridian circle, hence a distance of 180°. There is no more than 12 hours' difference in time (one hour = 15°) between any two points in the known world, since the reported times of lunar eclipses never differ by more than 12

[17] *HAMA* 847-8. This may not have been known to Ptolemy.

[18] For Marinus' date (a generation or two before Ptolemy), see von Mzik 1938: 24-26.

[19] For these maps see Boll 1894: 194ff., a ground-breaking study on Ptolemy in general. Cf. Riley 1988. This world picture is the common inheritance of Greco-Roman scholarship.

hours local time (*Alm.* II 1).[20] In the *Tetrabiblos*, he (probably) referred to this passage of the *Almagest*: "The region inhabited by us is in one of the northern quarters" (ἐν ἑνὶ τῶν βορείων τεταρτημορίων, *Tetr.* II 2.2), and this quarter is said to be bounded on the south by the equator.

A review of the chapters (*Geo.* I 7-14) in which he fixed the boundaries of the inhabited world will make his procedures clear. The northernmost point is at latitude 63°N (Thule),[21] the southernmost at latitude 16 $^{5}/_{12}$°S (Aigisymba and Cape Prason). It extends east to west 180° or 12 hours, from the Isles of the Blessed (Azores/Canaries/Madeira?) to China (*Geo.* I 10-11). These were the limits of his map. Within these boundaries he attempted to fit the geographical data which he inherited from his predecessors, particularly Marinus of Tyre, matching the astronomical data which he possessed to the fixed points on his map.[22]

He estimated the difference between the reported journeys and the true distances ("true" means distances which fit between latitude 63°N and 16 $^{5}/_{16}$°S and within 180° of longitude) using various common-sense methods, correcting unreasonable reports on the basis of geographic, ethnographic, or biologic probability, when astronomical data are lacking, as they usually were. Marinus had reported three-month journeys from Garama (in Libya) to Ethiopia, or four-month journeys from Garama to Aigisymba ("where the rhinoceroses mate") in Ethiopia.[23] Employing these reported times, Marinus had then assigned to Aigisymba a position 24,680 stades south of the equator (500 stades = 1° of latitude; 24,680 stades would bring the traveler to approximately 49°S latitude). Marinus had also reported a journey from Ptolemais in Troglodytia to Cape Prason, also a part of Ethiopia, of 27,800 stades (56°S). According to Ptolemy, such distances would put Ethiopia in the cold zone of the southern hemisphere (ἐπὶ τὴν κατεψυγμένην ζώνην τῆς ἀντοικουμένης, I 8.1) around

[20] This statement would imply that he had records of the same lunar eclipse from Western Europe and from China—most unlikely. As mentioned above, only *one* such simultaneous observation is mentioned, that of 20 Sept. 331 BC at Arbela and Carthage, only three hours apart (*Geo.* I 4.2; discussion in von Mzik 1938: 21).

[21] Pytheas of Massilia (ca. 330 BC), although distrusted by later geographers, fixed Thule (63°N) as the northern limit for all subsequent work. Dilke 1985: 29-30.

[22] von Mzik 1938: 22 n. 1; *HAMA* 938.

[23] Aigisymba is in the central regions of Africa; Prason (mentioned below) is on the coast of Africa. They are on the same latitude. The relationship between them may be seen on the maps included with the facsimile edition: Ptolemy 1932. See Tabula XV from Urb. Gr. 82 (ff. 87-88) or Tabula XLII from Vatic. lat. 5698 (ff. 27v-28r). Sina (China) and Kattigara (the "outpost of the Sinae" mentioned below) are on the same longitude; approximately 180° E: Urb. Gr. 82 (ff. 107-108); Vatic. lat. 5698 (ff. 47v-48r). The identification with existing locations, even if possible, is unimportant here.

latitude 50°-55°S, impossible for rhinoceroses. In addition, the Garamantes are themselves Ethiopian and have ties with the Ethiopian king. It would be laughable for a king to be so far away (and in just the N-S direction!) from his subjects. This report must be a tall-tale or simply mistaken (I 8.6-7).

In addition, since there should be correspondences of climate, race, and animal life between corresponding zones of the northern and southern hemispheres, and since the black Ethiopians resemble most closely the people of southern Egypt, the Ethiopians must live as close to the equator to the south as the Egyptians do to the north. They must therefore live at or north of the Tropic of Capricorn (I 9.9-I 10). Therefore all the reported distances must be halved to bring them close to 23 ½°, the Tropic of Capricorn—as Marinus had already done, without giving reasonable justification (I 8.3-4).

Marinus had also reported sea journeys between Aromata (the Horn of Africa) and Rhapta (somewhere on the east coast of Africa). Diogenes had been blown for 25 days south to the sources of the Nile at Cape Rhapta. Theophilus had sailed from Rhapta north to Aromata in 20 days (I 9.1). Dioscoros had then gone from Rhapta south to Prason, "many days journey" (I 9.4; Marinus takes a day's sail as 1000 stades). Ptolemy comments that these figures too would put Ethiopia (on whose coast Prason lies) and the "rhinoceros' mating place" in the cold zone of the southern hemisphere (I 9.4), and so he reduces the figures by half.

The result of this adjustment is to reduce the extension of the known world south of the equator. As mentioned above, the geometrically convenient maps of the *Almagest* and the *Tetrabiblos* stopped at the equator, but of course one cannot gainsay the facts. However, Ptolemy adjusted the reports in such a way that the southern limit of the known world was put at approximately the same distance south of the equator as Meroe in Egypt is north of it. The latitude of Meroe defines klima 1; therefore, in the inhabited world we have one matching klima south of the equator (for a definition of *klima,* see note 46). This symmetry certainly did not discourage Ptolemy from believing that his figures were correct. In this entire section Ptolemy used no astronomical data, simply ethnographic and biologic probabilities, to bring Marinus' data in line with the "truth."

Having established the principle that reported distances are to be halved, he applies the same principle to the E-W dimensions of the known world. Marinus had reported the journey from Hierapolis on the Euphrates in Syria to the "Stone Tower," on the western boundary of China, to be 26,280 stades, and the journey from the Stone Tower to Sera, the capital of China, to be 36,200 stades, a seven-month journey, for a total of 62,480 stades, or 156 ⅕°. Add to this figure the 72° from the Isles of the Blessed to Hierapolis, and the total E-W dimension of the known world becomes 228 1/5°. (At this latitude, 1° of longitude equals 400 stades, *Geo.* I 11.2.). Applying the same rule of thumb here as he did for the N-S distance in Africa, the distance from Garama to Aigisymba (both in Ethiopia) or from Aromata to Prason (both on the coast of Ethiopia), Ptolemy reduces the reported travelling time/distance across China (36,200) by one-half, and it becomes 18,100 stades, or 45 1/2° (I 12.2), which is, perhaps accidentally, close to the true figure. The figure of 26,280 for Hierapolis to the Stone Tower, not unknown territory, is adjusted downward to account for a caravan's deviations from a straight course, and it becomes 24,000 stades, or 60°, for a total of 105 1/4° distance from Hierapolis to Sera. Now the grand total from the Isles of the Blessed to Hierapolis (72°) and then from Hierapolis to Sera (105 1/4°) is 177 1/4°, close enough to 180° to be comfortable. In the next chapter (I.14) the reported distance by sea from India to Kattigara (an "outpost of the Sinae" on the same longitude as Sera) is also reduced by applying the same principle to bring the E/W dimension again close to 180°.

Ptolemy, of course, had resources other than common-sense. He corrected older reports using more recent reports and mentioned the necessity of "attending to the latest reports coming to us" (I 5.2). He cited "present day investigators" (τοῖς νῦν ἱστορουμένοις, I 17.2) when correcting Marinus' reports on Arabia; he quoted "all who have sailed these regions" (= Arabian Sea; I 17.3-4); he had learned about East Africa from "those who have travelled from Arabia Felix to Aromata, Azania, Rhapton, and all Barbaria" (I 17.6). Indeed he made an effort to gain new information to clarify what was unclear in Marinus (I 19): he searched out some special source for the detailed description he gave of the east coast of Africa (I 17.6-12); he consulted Roman sources, Tacitus for Germany and centuriation (= survey) maps for Italy.[24] He had, however, no resources to send out an expedition, and he could rely for the most part on dubious reports from constitutionally mendacious merchants.[25] It is sobering to read the measures he is forced to take, the conjectures, approximations, and guesses he is forced to make, in order to construct a believable map.

To sum up: in the *Geography*, as in the *Optics*, Ptolemy seems to have the framework in which earlier researchers had worked, in this case the traditional world map covering a quadrant of the northern hemisphere. However, he

[24] Dilke 1985: 77 (Tacitus), 85 (maps of Italy).
[25] Mendacious merchants in *Geo.* I 11.7-8.

"adjusted" their reports in light of his deductions about the dimensions of the known world, and he put the data in numerical form, viz. in latitude and longitude coordinates. Since Marinus' *Geography* has not survived, we cannot establish how much Ptolemy changed his figures. I suspect that Ptolemy's detailed critique (*Geo.* I 15-17) comprises the total number of changes that Ptolemy made to Marinus' data and that Ptolemy kept Marinus' basic framework, simply making it more accurate and more suitable for his projection system.[26] Again Ptolemy demonstrated his talents for the reporting and organizing of data.

ALMAGEST[27]

Unlike the situation in optics and perhaps geography, where numerical precision was a new idea, astronomy had been mathematized long before Ptolemy's time. The Babylonians had found very precise numerical parameters of the solar, lunar, and planetary periods. Hipparchus in the second century BC had already developed tables of trigonometric chords and tables of solar motion.[28] It was indeed the astronomer's predisposition for numerical calculation which enabled Ptolemy to construct the refraction tables of the *Optics*.[29] Ptolemy could not hope to improve astronomical precision by orders of magnitude, as he could perhaps hope to do in other fields. Nevertheless, he took on the task of defining astronomical terms precisely and of giving exact numerical and geometrical form to celestial motions, encompassing them all in one unified theory, all the parts of which follow in an "ineluctable logical sequence"—if indeed "pedagogical" is not a better term, for it must be remembered that the *Almagest* describes the construction of the tables in such a way that the student can see the logical progression; it does not give the process by which these tables were actually derived.[30]

[26] Similar conclusion in Dilke 1985: 73.

[27] References to the *Almagest* are to the Book and Chapter number followed by the volume and page number in Heiberg's edition of Ptolemy 1898, 1903 (= H); Ptolemy 1984 is the standard English translation by Toomer; Britton 1992 is the best work to date on Ptolemy's observations and their errors; see also Britton 1969.

[28] Hipparchus' chord tables were relatively primitive, based on units of 15° (*HAMA* 299); see Toomer 1973. His solar tables are cited in Vettius Valens IX 11; further discussion below.

[29] Schramm 1964: 87. Pedersen 1974 treats Ptolemy's use of tables for expressing functions of one, two, or three variables. His methods derived somehow from the Babylonians; Jones 1991 *passim*.

[30] Quote from Jones 1991: 445. For the pedagogy, see Britton 1992. An appreciation of this fact would have forestalled the accusations that Ptolemy has deceived his readers—as in Newton's writings and in Hartner 1980. By coincidence, a Babylonian tablet listing one of Ptolemy's lunar eclipses survives, and this tablet contains at least one other report, which was

I shall outline here his innovations in a specific section of the *Almagest*, the fixed star catalog. With reference to this catalog, as with the rest of his astronomical work, the "truth-loving" Hipparchus, Ptolemy's great predecessor in astronomy, has been given the credit for most—if not all—of Ptolemy's achievements. Much of the work on Ptolemy's star catalog has dealt with its errors and its originality. My aim is to show how Ptolemy rearranged and reorganized Hipparchus' data, even if we assume—unjustifiably—that he copied the underlying numbers *in toto*. His originality will then lie in the presentation, not in the figures. First a review of Hipparchus' own fixed star catalog.[31]

Details of Hipparchus' work must be deduced from his sole surviving work, the commentary of Aratus' and Eudoxus' *Phainomena* and from the fragments of his star catalog quoted in the *Almagest*.[32] His work was, of course, a great improvement on the purely pictorial "coordinates" of his predecessors Aratus and Eudoxus, whose reports are in a non-numerical format:

> Eudoxus: "Behind the Great Bear is the Bearkeeper [= Boötes]... and under his feet is Virgo."
> Aratus: "Behind the Bears circles the Bearkeeper, like a

perhaps at the astronomer's disposal (Published in Kugler 1907: 70-1; the date is 16 July 523 BC). Contrast Ptolemy with Kepler, who recounted in painful detail the successive steps in his reasoning. Ptolemy's outline of the derivation of the table of chords is also pedagogic. According to Theon 1943: 451, Hipparchus and Menelaus had already investigated chords; see Pedersen 1974: 56-65. Furthermore, Ptolemy assumes that his readers can perform trigonometric calculations and passes over in silence the procedure for such calculations, not to mention the procedures for more ordinary multiplication, division, and square root extraction. In the same way, he assumes his readers are familiar with "spherics," the standard circles and coordinates of the celestial sphere: the equator, meridians, colures, etc. The trigonometry of *Alm.* I 9-11 cannot have been new.

[31] On the pre-Ptolemaic (= Hipparchus') star catalogs see Grasshoff 1990: 174ff. The standard edition of Ptolemy's catalog is Peters and Knobel 1915, a critical text and identification of P's stars using modern nomenclature.

[32] Hipparchus 1894, hereafter *In Arat. Comm.* This work is in two parts: a narrative attack on Aratus and Eudoxus for their inaccuracy (2-182) and a list of constellations as seen from latitude 36°N with their chief stars, their culminations, time of rising, and so on (183-270). Maeyama 1984 showed that this part contains H.'s most accurate and latest (ca. 130 BC) observations. Ptolemy, whose catalog has the epoch date 137 AD, dated Hipparchus' catalog "about 260 years previous" (*Alm.* VII 1; H 2,8). According to Pliny (*NH* 2.95), he was prompted to make this list by the nova of 134 BC, in order to discover if the fixed stars really are fixed. Hipparchus' catalog is discussed in *HAMA* 277-91; Pedersen 1974: 255-57; Maeyama 1984; Nadel & Brunet 1984, 1989. Its remains are found in later astrological literature: *Liber Hermetis* (ed. Gundel 1936) chapter 25, and in various chapters in Vettius Valens and Hephaistion.

> herdsman...under the feet of Boötes you may glimpse Virgo."
> (quoted by Hipparchus, *In Arat. Comm.* 10.5-21)

In contrast, Hipparchus listed 374 stars (in 42 constellations), with 881 bits of numerical data for these stars: some of them are coordinates of a primitive type; others are such that they can be transformed into coordinates by trigonometric calculations. An example illustrates the originally crude state of his trigonometry and his coordinate system:

> Assume that the southernmost star in the left foot of Boötes [= υ Bootis] is setting on the horizon. This star then lies 27 degrees north of the equator (degrees 360 of which are in the circle through the poles). Then the arc above the horizon of the circle drawn through the aforementioned star, parallel to the equator, is 15 segments minus 1/20th of a segment (segments 24 of which make up an entire circle).
> (*In Arat. Comm.* 148.25-150.3)

Hipparchus in this early report uses at the same time both the 360° norm and 15° segments (usually called "steps," βάθμοι); $14^{19}/_{20}$ of these segments are slightly less than 224 1/2°, which is the length of the arc which passes through υ Bootis, lies parallel to the equator, and is above the horizon. Hipparchus' chord (= trigonometric) tables were based on these units of 15°.[33] His predecessor Aristarchus (ca. 280 BC) had expressed arcs in a similarly awkward way: "When the moon appears to us to be halved, its distance from the sun is a quadrant minus 1/30th of a quadrant" [i.e. 90° - 3° = 87°]. "The moon subtends 1/15th of a zodiacal sign" [i.e. 2°].[34] By the time Hipparchus wrote the second part of *In Arat. Comm.* (186-end), he had regularized his reports with standard degree measure. An example:

> Boötes rises with [the arc of the ecliptic] extending from the beginning of Virgo to the 27th degree of Virgo. While it is rising, the part of the zodiac from the middle of the 27th degree of Taurus to the 27th degree of Gemini is culminating. The first star to rise in Boötes is the one in the head; the last [to rise] is the one in the right foot. When Boötes is beginning to rise, the following stars culminate: the [one in] the left shoulder of Orion and the [one in] the left foot. (These are one-half cubit to the west of the meridian.) As it is completing its rising, the bright star

[33] *HAMA* 299. Toomer 1973 shows that Hipparchus, using the Pythagorean theorem, could have compiled a table of chords for arcs incrementing by 7 1/2° internals. For other measurements, Hipparchus also used a cubit equalling 2 1/2° (πῆχυς, *In Arat. Comm.* 254.11; 272.1), half-cubits (ἡμιπήχιον, 186.11, 190.8), zodiacal signs (ζῴδια, 98.22), and degrees themselves (μοῖραι, 82.24). Terminology was still flexible. His minimum degree-measurement was 1/5°—perhaps his instrument was so graduated. See Vogt 1925: 21 and Britton 1967: 19.

[34] These are Hypotheses 4 and 6 in Aristarchus 1913.

> on the haunch of the Dog is culminating. Boötes in its entirety rises in very nearly two equinoctial hours. (*In Arat. Comm.* 186.1-15)

Throughout the second part of *In Arat. Comm.* Hipparchus gave the degree of the ecliptic corresponding to each of the four phenomena which interested him: the beginning and end of a sign's rising, and the beginning and end of a sign's setting.[35]

Correlating this information, Vogt (1925) reconstructed Hipparchus' star coordinates—or rather the coordinates Hipparchus would have used if he had reported them in the same format as Ptolemy did two centuries later. (Using simple trigonometry one can convert Hipparchus' reports to the later ecliptic coordinates; in the example just quoted the value for the ecliptic longitude of the star in the head of Boötes, β Bootis, is Virgo 23° and the star in the right foot, ζ Bootis, is Libra 2°.) Vogt used these reconstructed coordinates to compare Hipparchus' coordinates with those in Ptolemy's star catalog. It had been widely assumed that Ptolemy simply copied Hipparchus, merely correcting for the precession of the intervening 260 years (= 2° 40' according to Ptolemy's value for precession).[36] Vogt showed that the *average* difference between Hipparchus' and Ptolemy's longitudes is close to 2° 40', but that there is no *constant* difference, which would be the case if Ptolemy had simply added a constant to Hipparchus' figures. Therefore, according to Vogt, Ptolemy's catalog was an independent creation: Ptolemy must have redone all of the "truth-loving" Hipparchus' observations.

[35] Vogt 1925: 18-19. I emphasize the primitive nature of Hipparchus' star coordinates. Even Dilke in his excellent *Greek and Roman Maps* gives evidence for the widespread overevaluation of Hipparchus' achievements: Hipparchus..."list[ed] the exact latitude and longitude for eight hundred stars" (145). Seventy-five years ago Vogt showed that he had not done so.

[36] "The great work of Ptolemy also contains a catalogue of stars, which however is nothing but the catalogue of Hipparchus brought down to his own time..." Dreyer 1953: 202. Dreyer was simply repeating the standard view since Delambre, not to mention Tycho Brahe. Recently this thesis has been most vigorously defended by Newton 1974, 1977, 1983, where he suggests methods by which Ptolemy could have fabricated the basis of his star tables, acting under the assumption that Ptolemy's results are too good and fit the underlying theory too closely to be either accurate or true; Newton's methods are bizarre (see particularly Newton 1983: 28-29). While it is true that Ptolemy may have adjusted raw data to fit his hypotheses, as I have pointed out above, I can see no reason for wholesale fabrication requiring complex mathematical methods to succeed—methods perhaps not even available to Ptolemy, and certainly not in the trigonometric form used by Newton. Evans 1987 and Grasshoff 1990 review Newton's arguments in detail. *Precession* is the motion of the fixed stars relative to the vernal equinox. Ptolemy assumed a value of 1° per century, hence 2° 40' in 260 years. Swerdlow 1992 rejects *any* dependence of Ptolemy on Hipparchus, but Grasshoff's study does demonstrate some correlation, although limited. For the reason mentioned in the text, a total recalculation by Ptolemy does not make sense.

When phrased this way, Vogt's conclusion seems doubtful—why should Ptolemy discard observations made by the founder of Greek astronomy?—and indeed, his conclusions have been modified by Grasshoff (1990), who showed that most of Ptolemy's data has some statistical correlation with Hipparchus' data. The distribution of errors in the two sets of data (Hipparchus' catalog and Ptolemy's) are too similar to be entirely independent, although the steps between Hipparchus and Ptolemy are not clear. Did Hipparchus make a catalog other than *In Arat. Comm.*? Who converted the coordinates? and so on. But in any event, whatever the steps between Hipparchus and Ptolemy, Hipparchus had not reported a complete set of data, had not reported the data in tabular form, and had not used the reporting format adopted by Ptolemy and hence by later medieval astronomers.[37] Ptolemy enlarged Hipparchus' catalog from perhaps 850 to 1022 stars, including all stars of the first through sixth magnitude,[38] used a standardized coordinate system with ecliptic longitudes and latitudes, and presented the data in tables. Ptolemy employed the 360° norm for all angle measurements, calculating a trigonometric table in steps of 1/2°, the first such table surviving, by the use of which the calculations found throughout the *Almagest* were facilitated (*Alm.* I 11; H 1, 48-63). He retained the grouping of stars into pictorially visualized constellations—a necessity, since the naming of individual stars (with a few exceptions) was not practiced in antiquity. His presentation is as follows:

Boötes

Star no.	Identification	Longitude	Latitude	Magnitude
1	The most westerly of the 3 in the left arm	Virgo 2 1/3°	58 2/3° N	5
2	The middle, the southernmost of the 3	Virgo 4 1/6°	58 1/3° N	5
3	The most easterly of the 3	Virgo 5 1/3°	60 1/6° N	5
6	The star in the head	Virgo 26 2/3°	53 5/6°N	4

37 In Ptolemy stars are located by the latitude N/S of the ecliptic (the path of the sun) and by longitude along the ecliptic. The ecliptic's 0° of longitude is Aries 1°, the vernal equinox. In modern astronomy stars are located by the declination, the latitude N/S of the equator, and by right ascension, measured along the equator, but expressed in hours and minutes, not degrees (15° = one hour).

38 He missed about 700 stars classified as fifth and sixth magnitude today; see the table in Pedersen 1974: 259.

And so on for 1022 stars (*Alm.* VII 5-VIII 1; H 2, 36-169. This passage is at H 2,48).

Along with Ptolemy's acceptance of his predecessor's data came the acceptance of his conceptual framework. For example, Hipparchus had worked in astrology and was perhaps the founder of the art among the Greeks—certainly Pliny thought so (*Hist. Nat.* 2.95). Ptolemy likewise worked in astrology, in fact systematizing the art.[39] Little or nothing can be said about Hipparchus' views on physics or cosmology, but a consensus on these topics had developed by Ptolemy's time, and Ptolemy simply adopted this consensus as his own. Ptolemy included a description of the universe in the first chapters of the *Almagest:* the earth is spherical and stationary, located in the center of a spherical universe; the stars, eternal and incorruptible entities, move with eternal unvarying circular motions.

Ptolemy cast these assertions in the form of propositions to be proven and does give ingenious proofs, but in fact none of them was controversial: of his arguments for the central location of a stationary earth, one depends on the Aristotelian doctrine that heavy objects have their natural place at the center of the earth (*Alm.* I 7; H 2,22-23); the other contends that if the earth moved, the intervals between the stars would vary, contrary to observation (*Alm.* I 5; H 1,17-19). The latter contention could be refuted by the option which he himself employed in the next chapter, that the earth has the ratio of a point to the heavens (*Alm.* I 6; H 1,20). Clearly Ptolemy is reporting these accepted notions simply as a preface to his real mathematical work. The commentators to the *Almagest* can cite only pre-Socratic philosophers and Epicurus, a well-known philistine, for any of the beliefs attacked in *Almagest* I 3-7.[40] As hardly needs to be pointed out in this forum, the "Ptolemaic" universe illustrated in so many history books is not Ptolemy's creation, but simply the common ancient world–picture. Ptolemy's contributions were his precise definitions and his mathematical and geometrical descriptions (including his use of mechanical models and experimental apparatus).

Almagest I 1 mentions a way of subdividing philosophy: philosophy can be divided into "practical" and "theoretical" disciplines. In turn, the theoretical can be further divided into theology, mathematics, and physics.[41] Questions of

[39] Hipparchus' astrological geography is mentioned in Hephaistion, *Apotelesmatica* I 1 (pp. 4.14; 22.2). A treatise on the astrological influences of the 12 signs is attributed to him (*CCAG* 8.3, 61).

[40] Heraclides of Pontos and Aristarchus of Samos had adopted the theory of a rotating earth, but they found no followers. For this view of *Alm.* I 3-7 see Owen's commentary in Crombie 1963: 95-97.

[41] Discussion in Pedersen 1974: 26ff.

the shape and size of the universe, as well as the hot or cold, dry or moist, nature of the stars fall under physics (*Alm* I 1; H 1,5). The *Almagest,* on the other hand, is a treatise on mathematics, dealing with "objects" and truths which are eternally the same: these objects are the stars and the truths are their motions (I 1; H 6). One might say that the *Almagest* describes the mathematics of the stars, the *Tetrabiblos* their physics. The *Optics*, in which his goal was to study the eternal truths about rays moving in mathematically straight lines, would also be a mathematical treatise.[42]

The Phaseis

The *Phaseis* is perhaps best viewed as the transitional work between Ptolemy's astronomy and his astrology. Here too Ptolemy used familiar procedures: he accepted traditional data along with the traditional belief—the data are the *phases* (the dates of the first or last appearance of the fixed stars in the morning or evening sky) and the belief is that these phases influence the weather. He systematically calculated the phases of important bright stars and he gave specific numerical positions in degrees at definite dates for these phases.[43] In the *Phaseis* he cites as his predecessors Dositheus, Philip, Callippus, Euctemon, Meton, Conon, Metrodorus, Eudoxus, Caesar, Democritus, and Hipparchus, as well as an ill-defined group called the "Egyptians." For what data does Ptolemy cite these quite different astronomers?[44] Ptolemy is citing them, not for their study of celestial motions, but for their observations of the weather and of the stars' phases: he has "recorded these weather indications (ἐπισημασίας) and set them down according to the Egyptians..." (*Op. Min.* 66.23-67.1). They had recorded that star *X* appeared (or disappeared) on *Y* date accompanied by *Z* weather.

As mentioned, these dates, or phases, were believed to be indicative of the weather. In particular, the first appearance of Sirius in the morning sky in

42 Aristotle classified astronomy as part of physics (*Physics* II 2 194a) and as part of mathematics (*Metaphysics* XII 8 1073b), indicating an ambiguity which continued to the middle ages, when astronomy, optics, music/harmonics, all providing mathematical descriptions of the material world, are called *scientiae mediae:* Th. Aquinas, *In Libr. Boethii de Trinitate*, quaes. 5a3, quoted in Pedersen 1974: 30.

43 The *Phaseis* is edited in Cl. Ptolemaei, *Opera Astronomica Minora* 1-67 (hereafter *Op. Min.*). Vogt 1920 laid the foundation for all later work on the *Phaseis*. Vogt found Ptolemy's *arcus visionis* for each star for each phase and determined that Ptolemy had calculated values for klima 2, then applied these values to the other klimata. See *HAMA* 926-931. Vogt 1920: 51 described the *Phaseis* as a transition between astronomy and astrology.

44 Hipparchus was certainly a scientific astronomer; Conon, on the other hand, was highly regarded by Archimedes as a mathematician, but as an astronomer is known primarily because of the constellation named by him after Queen Berenice; "Egyptians" is a term generally used to refer to astrologers as a class.

early July coincided with the rising of the Nile, and perhaps gave the impetus to the other phase correlations. In any event the influence of the stars' (and the moon's) phases on the weather is assumed in ancient astrology.

> It is well to carry on the investigation of weather indications (and indeed of all such forecasting) with a clear idea first of all of the cause of such things. We must not have everything depend on one [factor] alone, because some of the compilers of these weather indications [i.e. those listed in the *Phaseis*] have observed in one region, others in another region, and they have not [all] met with the same environmental conditions—either because of the peculiarities of their region or because one phase does not always occur on the same day. Therefore, as much as possible, we must take into account the other causative factors, and we must particularly examine the planetary transits as found in the almanacs, so that we may make the date of the weather indications accord with the date of the nearest quarter moon, and (most particularly) with the dates of the new and full moons, in addition to the date of the sun's entry into [certain] signs around [the time of] the phase. [We must also examine] the nature and qualities of the planet which is best configured [with the phase]: Venus adds heat to the prevailing conditions, Saturn cold, Jupiter moisture, Mars dryness, Mercury motion and wind. The stars of opposite nature will be included and will bring opposing influences.
> (*Op. Min.* 11.15-12.12).[45]

Ptolemy accepted the data associating a phase with certain weather:

> Tybi 1 [= 27 December]: in the klima where the longest day is 14 hours, Sirius rises in the evening; in the klima where the longest day is 15 hours, Procyon rises in the evening.[46] According to Eudoxus, the weather is changeable (ἐπισημαίνει); according to Democritus, there are moderate storms.
>
> Tybi 2: in the klima where the longest day is 13 1/2 hours, the star α Geminorum sets in the morning sky. According to Dositheus, there are storms... (*Op. Min.* 32.1-6)

and so on throughout the year.

[45] Similar sentiments in *Tetrabiblos* I 2.5; the antiquity of this belief is indicated by the Babylonian tablet quoted by Toomer at *Almagest* V 14: "The north wind blew." Kepler made a life-long study in an attempt to correlate the stars with the weather; Kepler 1979.

[46] In the *Phaseis* there are five klimata (= terrestrial latitude expressed in terms of the length of the longest day):

klima 1 - the longest day is 13 1/2 hours (southern Egypt)
klima 2 - the longest day is 14 hours (Alexandria)
klima 3 - the longest day is 14 1/2 hours (Rhodes)
klima 4 - the longest day is 15 hours (the Hellespont)
klima 5 - the longest day is 15 1/2 hours (Rome, Pontus) (*Op. Min.* 4.5-10).

He had no direct observations from klima 5.

Ptolemy characteristically felt the need for a precise definition of "phase." He reports the "usual, naive" meanings of the word: a phase can be "true" (ἀληθινόν) when the sun and the star in question are both exactly on the horizon, either rising or setting. For example if the sun and the star both rise exactly at the same moment, the star is said to be at "true morning rising." In such a case, the star would of course be invisible, its light blotted out by the sun's glare. A phase can be "visible/apparent" (φαινόμενον) when, for example, the star rises far enough ahead of the sun to just become visible in the early dawn. In such a case, the star is said to be at "visible/apparent morning rising" (*Op. Min.* 6.27-7.9). Ptolemy is satisfied with neither definition: the precise moment of a "true" phase is invisible because of the sun's glare; the sun's position at the "visible" phase is uncertain since it is below the horizon. As a result of these defects, neither type of phase can be precisely defined. Ptolemy then introduces his definition, temporally precise and at the same time determinable. He uses the *arcus visionis*, the minimum distance from the sun at which a star may become visible.[47] If this arc is found, and if the sun's position is known precisely, then the moment of the phase can be calculated at each latitude (*Op. Min.* 7.9-8.2). This definition is essentially the same as that of the "visible/apparent" phase just mentioned, but it is numerically determined in advance, not subject to the vagaries of observation on a particular day which may be cloudy, stormy, or clear. Characteristic of Ptolemy is his desire to fix as parameters certain events whose time and place can be precisely determined.

Ptolemy recognized that a particular star's brightness, its latitude (distance from the ecliptic), and the inclination of the ecliptic could all affect the date when the star would be far enough from the sun to become visible or near enough to vanish from view. So he determined by observation the actual date of the phases of his thirty stars in the klima of Egypt, calculated the distance between the star's position and the sun's at that date, then applied the same figure to the other four klimata (*Op. Min.* 4.4-20). Vogt recalculated Ptolemy's *arcus visionis* for each star, and his tables show that Ptolemy—whatever his actual procedure had been—had figured each star separately.[48] The result was the precise calendar of star appearances which fill more than fifty pages in our text of the *Phaseis* (*Op. Min.* 14.1-65.4).

Ptolemy, however, did not use all his predecessors' observations.

[47] More precisely, the perpendicular distance of the sun below the horizon at the moment when the star first becomes visible when rising or is visible for the last time when setting; Vogt 1920: 5. Naturally this distance is less for the bright stars.

[48] Tables in Vogt 1920: 54-65. Ptolemy's own procedure had been described in the lost Book I of the *Phaseis*. A fragment of Book I survives in Arabic: Morelon 1981.

> The reader must forgive me if I mention neither here nor in my detailed discussion of this topic [= the lost Book I of the *Phaseis*] some of the dim stars named by the ancient [astronomers]: the Arrow, the Pleiades, the Haedi, the Vendemiator, the Dolphin, etc. It is hard to distinguish and to note the first and last visibilities of such small stars. One must conjecture that my predecessors used guesswork rather than observation when dealing with the visibilities of these stars. (*Op. Min.* 12.13-23)

In other words, these stars are too dim to serve as marking points in a system which hopes to be precise. Only those phenomena which can be precisely dated are usable, and so he made a canonical list of the stars which can have phases worth noting, fifteen first and fifteen second magnitude stars, and he explicitly rejected the use of stars and constellations which had been important for earlier astronomers and astrologers.

It is clear that Ptolemy accepted at face value the belief that the phases of the stars are indicative of the weather and hence are important astronomical contributions to knowledge—otherwise why do all this work? But he also attempted to make precise the definition of a phase and to tabulate the actual position and date of each phase's occurrence. In this respect his procedure is not unlike that seen in the works discussed so far. It is also not unlike his procedure in the *Tetrabiblos*, where he unites the prevailing theories of Aristotelian physics—the fundamental influences of the four humors, heat/cold, wet/dry, from which each planet derives its influence—with the most traditional type of astrological forecasting.[49] He could juxtapose statements such as the following: "Venus...warms because of its proximity to the sun and humidifies (like the moon), absorbing, because of the intensity of its own light, the vapors arising from the moist environment of the earth" (*Tetrabiblos* I 4.6), a statement based on contemporary scientific thought; and "Venus attached to Mercury in honorable configurations makes men artistic, philosophical, academic, talented, poetic... In the opposite configurations Venus makes them pugnacious, inventive of evil, slanderers, unstable, malicious, deceivers..." (*Tetrabiblos* III 14.34-35), a passage which can be paralleled in the lesser astrologers. His acceptance of the data (the stars' chemical/physical nature) brought with it the acceptance of the rest of the astrological world view (the stars' influence on persons, cities, and nations).

[49] Ptolemy seems to have been the first to correlate the Aristotelian doctrine of the four elements or humors with the influence of each star and hence give "scientific" support for astrology. The earlier astrologers, Dorotheus and Manilius, and his contemporary, Vettius Valens, show no signs of attempting such a correlation, although they naturally mention the obvious effects of the sun's heat and light as evidence for the more subtle influence of the other stars. See Riley 1988.

Conclusion

Some criticism of Ptolemy's work may be justified: some of his reports are adjusted to fit a regular pattern (the refraction tables of the *Optics*); some seem to be corrected to suit an *a priori* model (the world boundaries of the *Geography*); the procedures he used to derive the models are not described in detail (generally true for the *Almagest*). His research procedures were not those of a twentieth-century scientist.

Nevertheless, Ptolemy's achievements justify his high standing in the history of science. At a minimum, we can say that he systematically preserved and augmented the data handed down by his predecessors. He restudied, revised, and mathematically tabulated these data using techniques first developed by the astronomers, and he thus improved one science with the techniques developed in another. Moreover, to his mathematics he added experiments and demonstrations, especially in the *Optics*, which dealt with visual phenomena obviously relevant to astronomy.

Perhaps more important, however, was Ptolemy's attempt to unite mathematics and physics in his astronomical studies. These two sciences, considered inseparable today, were clearly separated in antiquity. The physicist (ὁ φυσικός) studied the real nature of the stars, in the manner of Aristotle in *de Caelo:* he studied the essence, the quality, the generation and destruction of the stars. The mathematician (ὁ μαθηματικός), specifically the astronomer, studied the configurations, the distances, and the motions of the stars, endeavoring always to save the phenomena, regardless of the physical reality behind the phenomena—which physical reality may be unknowable under our present circumstances.[50] Ptolemy tried to determine not only the motion of the stars as mathematical points moving in mathematical circles within the ether—the job of the mathematician. He also tried to discover, in the *Tetrabiblos* and the *Planetary Hypotheses*, the real nature of the stars and their distances from the earth using the empirical data accumulated since Aristotle. As a physicist, he had a clear apprehension of the requirements of what we call the scientific method (not that Ptolemy knew this phrase): he made observations and he presented these observations in a framework of hypotheses. His type of presentation is particularly evident in the refraction tables in the *Optics*, where the hypothesis may well have preceded the observations. The fact that his conclusions were in error—an error shared by all his peers in antiquity—does not diminish the level of his achievement. Katsoff has pointed out that Ptolemy's

[50] All this is explicitly stated by Simplicius in his commentary on Aristotle's *Physics*: *In Aris. Physicorum Comm.* 291.23-292.26. See also Aristotle, *Physics* 193b23ff.

errors were due, not to defects in his use of observations and data, but to his acceptance of his contemporaries' Aristotelian "physics," which included what are certainly the simplest hypotheses for saving the phenomena: circular motion of the ether and a centrally located, stationary earth.[51] As mentioned above, Ptolemy's abilities did not extend to forming revolutionary hypotheses which might have created a new world-picture. His talents lay in reorganizing and updating existing areas of knowledge.

[51] Katsoff 1947: 21-2.

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