JHA, xxxiii (2002)

COPERNICUS AND THE ORIGIN OF HIS HELIOCENTRIC SYSTEM

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The introduction of a heliocentric system by Copernicus (d. 1543) is often considered to be a major blow to the traditional cosmology of his time and an epoch-making event in the history of science. But what was the question for which heliocentrism was the answer? For astronomers in the late Middle Ages cosmic distances were based on Ptolemy's nesting hypothesis that was originally described in his *Planetary hypotheses* and transmitted to the Latin West through Arabic intermediaries. Copernicus specifically rejected this hypothesis in *De revolutionibus*, i.10, although he might have expressed himself more clearly. It will be my goal here to understand the reasons why Copernicus rejected this tradition of cosmic distances and the geocentric system in which it was embedded.

First, it is important to distinguish astronomical issues, such as the use of the equant, from cosmological issues, such as the location of the centre of planetary motion and the order of the planets in space. Ptolemy had motion on a planet's deferent move uniformly about the equant point, a point other than the centre of the deferent, in violation of the principle of uniform circular motion stated in *Almagest*, ix.2 (see Figure 1). Indeed, at the beginning of the *Commentariolus* Copernicus argued that

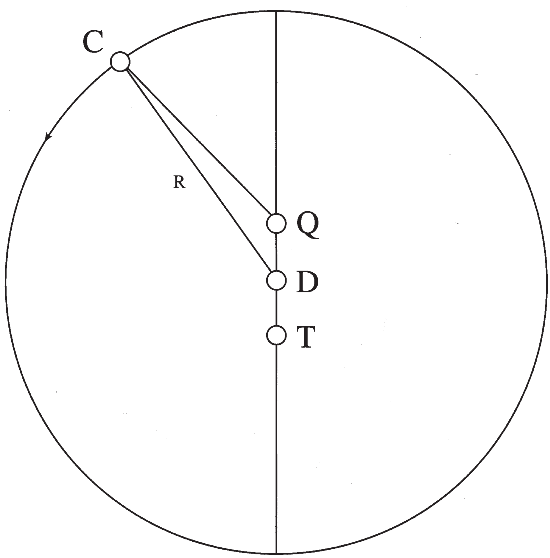

FIG. 1. An equant model: T is the Earth, D is the centre of the deferent circle whose radius is R, and Q is the centre of uniform motion for C that lies on the deferent.

0021-8286/02/3303-0219/$2.50

a planetary model with an equant is flawed. But we now know that Muslim astronomers, beginning in the thirteenth century, were able to produce many models that resolved the problem while maintaining a geocentric framework.[1] In other words, the equant was an astronomical problem whose solution did not impinge on cosmological issues. In the *Commentariolus*, Copernicus's earliest treatise on planetary theory (probably written shortly before 1514), he says nothing about his motivation with respect to cosmological issues, although he may allude to it (see below: Comment [1]). On the other hand, Copernicus gives a detailed account of his motivation for constructing a new cosmology in *De revolutionibus*, i.10, and it reveals much of his original thinking on the issue, although this passage was certainly revised (possibly more than once) between his initial insight and the final draft.

I propose a new account of Copernicus's initial acceptance of the heliocentric hypothesis that depends primarily on a simple computation of the sidereal periods of Venus and Mercury (i.e., their heliocentric periods) motivated by his reading of Aristotle with the commentary of Averroes (twelfth century A.D.), Vitruvius (first century B.C.), and Martianus Capella (early fifth century A.D.), among others. All the sources cited here were available before 1514, the approximate date of Copernicus's first draft of his heliocentric system. It is important to recognize that no new astronomical data were required; all that was needed could be found in the *Almagest*. Let me outline Copernicus's reasoning before presenting the evidence in the texts of Copernicus.

The key principle for Copernicus is that the periods of the planets are longer as their orbs are farther from the centre of motion. This principle was stated by Vitruvius: the periods of the planets are longer as their distance from the centre of motion, the Earth, increases. Copernicus was aware that this principle works well enough in a geocentric system for Saturn, Jupiter, and Mars. But it fails for the Sun, Venus, and Mercury whose periods are all one year. In the *Almagest*, ix.1, Ptolemy discussed the order of the planets from the Earth, and concluded that there was no available evidence to decide the question. Hence, he argued, one should simply accept the order that appears most plausible, putting the Sun in the middle with three planets above it and three planets (including the Moon) below it. In a later work, the *Planetary hypotheses*, Ptolemy reconsidered the question and concluded that the nesting hypothesis, according to which the greatest distance of one planet is equal to the least distance of the planet above it, allowed him to fix the order and the distances of the planets from the Earth.[2] Copernicus did not abandon the distance–period relationship stated by Vitruvius; rather, he rejected Ptolemy's argument for the order of the planets from the Earth based on the nesting hypothesis because it violated the distance–period relationship for the Sun, Venus, and Mercury. In *De revolutionibus*, i.10, Copernicus indicated that, having rejected geocentric systems (in all the varieties known to him), the choice is either to find a different centre of motion, or to accept that there is no principle governing the order of the planetary orbs and no reason why the orb of Saturn should be in the highest position rather than Jupiter or any other planet.

Implicitly, Copernicus rejects the second choice as absurd. At this point he calls attention to a text by Martianus Capella in which Venus and Mercury are said to go around the Sun. This account also differed from Ptolemy's ordering, and suggested that the distance–period relationship might work if a centre of motion other than the Earth were chosen. To be sure, Martianus Capella did not present a full heliocentric system, for the Sun and the outer planets still revolved around the Earth.

It is my contention that, with these arguments in mind, Copernicus made several related assumptions, all of which appear in the *Commentariolus*:[3] (1) the Sun is at rest at the centre, and the Earth moves around it; (2) the Sun is the centre of motion for all six planets (the 'five' plus the Earth); and (3) the Moon is not a planet; rather, it is a 'fellow traveller' with the Earth around the Sun. The suggestion to make all six planets move around the Sun in order to maintain a modified form of the distance–period relationship depended on finding the periods of the planets around the Sun, rather than around the Earth. The order of the periods for Saturn, Jupiter, and Mars was not in doubt, and so it only seemed necessary to demonstrate that the heliocentric periods of Venus and Mercury were less than a year, and that the period of Mercury was less than the period of Venus. It was this calculation of the periods for Venus and Mercury that, I believe, initially convinced Copernicus that he was right to construct a heliocentric system and that this system had the properties of harmony (*harmonia*) and commensurability (*symmetria*) that he emphasized in *De revolutionibus*, i.10. That is, the clinching argument for his initial acceptance of the heliocentric system was that the heliocentric period of Venus was less than a year; Copernicus gives this period as "in the ninth month" in the *Commentariolus*, although he should have computed 225 days (see below: Comment [6]). Nevertheless, the miscalculation did not affect his argument. There were also a number of consequences of the heliocentric system that made it attractive, notably, it gave a coherent account of retrograde motions (and the ordering of their durations for different planets). Indeed, at the end of *De revolutionibus*, i.10, Copernicus claimed that the motion of the Earth provided a causal account of retrograde motion (*Quae omnia ex eadem causa procedunt, quae in telluris est motu*).[4] But consequences of a system are different from the initial motives for constructing it.

To construct a heliocentric system in any detail, Copernicus needed to transform Ptolemy's geocentric models (modified to resolve the equant problem) to heliocentric models. But, in my view, this was done only after he made an initial commitment to a heliocentric system. For this purpose he depended on two propositions in Regiomontanus's *Epitome of the Almagest*, as Swerdlow has argued persuasively.[5] Regiomontanus's propositions, in the first instance, would transform geocentric models for the outer planets into a Tychonic system with these planets going around the Sun while the Sun goes around the Earth; whereas for the inner planets it would transform geocentric models to heliocentric models (see Figures 4(a)–(d), below); hence, these propositions do not imply a heliocentric system, as acknowledged by Swerdlow and Neugebauer.[6] They argued that Copernicus decided on a heliocentric system to avoid the intersection of the orbs of Mars and the Sun in the Tychonic arrangement, a problem that bothered Tycho Brahe later on and that was only resolved by the recognition that there are no solid material orbs in the heavens.[7] But there is no evidence that Copernicus was concerned with this intersection of orbs, and I think it unnecessary to ascribe such a view to him. In any event, a Tychonic system would not satisfy the distance–period relationship, for the ordering of the planets (including the Sun) in it is not dependent on the order of their periods. Of course, Copernicus argued explicitly against the Ptolemaic system as violating the distance–period relationship; I conclude that the only system known to him that did satisfy this relationship was the heliocentric system that he advocated.

The main passage in which Copernicus indicates the motivation for heliocentrism occurs in *De revolutionibus*, i.10 (numbers in square brackets refer to the comments, below):

> We see the ancient philosophers were willing to take the sequence of the wandering stars as being in accordance with the size of their revolutions,[1] assuming the principle that if objects are carried along at equal speed, those which are further away seem to move more slowly, as Euclid proves in his *Optics*.[2] Hence they consider that the Moon goes round in the smallest circle. They make Saturn the highest, because it goes round in the largest circuit in the greatest time; Jupiter under it, and after that Mars.... On the other hand those who place Venus and Mercury below the Sun point out in defence of their argument the extent of the space which they find between the Sun and the Moon.[3] For they discovered that the greatest distance of the Moon from the Earth was sixty-four and a sixth units taking the radius of the Earth as one unit, and was one eighteenth of the smallest separation of the Sun from the Earth which was 1160 units. [The space between the Sun and the Moon is filled by the orbs of Venus and Mercury.] ... But what reason can be produced by those who put Venus below the Sun, and Mercury after it, or put them in some other order apart from each other, for not similarly placing their circuits (*circuitus*) apart from each other, and away from the Sun, even if the argument from their speed or slowness does not prove the order wrong? Then it must be either that the Earth is not the centre to which the order of the stars and spheres is referred, or else that there is no system in the order, and no reason is apparent why the upper position should be given to Saturn rather than to Jupiter or any other planet. Consequently I think we should certainly not despise the argument which was well known to Martianus Capella,[4] who wrote the Encyclopedia, and certain other Latin writers.[5] For they believe that Venus and Mercury revolve round the Sun which is in the middle of them, and they think that is the reason why they do not diverge further from it than the curvature of the spheres allows, because they do not go round the Earth, like the rest, but have their spheres turned the other way.... The first and highest of all is the sphere of the fixed stars, which contains itself and all things, and is therefore motionless.... There follows Saturn, the first of the wandering stars,

FIG. 2. N. Copernicus, *De revolutionibus*, Cracow, Jagiellonian Library, MS 10,000, f. 9v.

which completes its circuit in thirty years. After it comes Jupiter which moves in a twelve-year-long revolution. Next is Mars, which goes round biennially. Annual revolution holds the fourth place in which as we have said is contained the Earth along with the lunar sphere which is like an epicycle. In the fifth place Venus returns every nine months. Lastly Mercury holds the sixth place, making a circuit in the space of eighty days.[6] In the Middle of all is the seat of the Sun (see Figures 2 and 3).[7][8]

Comments

[1] Copernicus does not name these philosophers, and the clearest statement of this relationship in Antiquity is given in Vitruvius's *De architectura*, ix.1.14 (quoted below: see Comment [6]). But Copernicus probably had in mind a passage in Aristotle's *De caelo*, ii.10, for it was interpreted by Averroes as being equivalent to this relationship, and this tradition of interpretation goes back at least to Simplicius. Aristotle says:

> Let there be a study of their ordering — the way in which each [body] moves in that some are prior and others posterior — and how they are related to one another

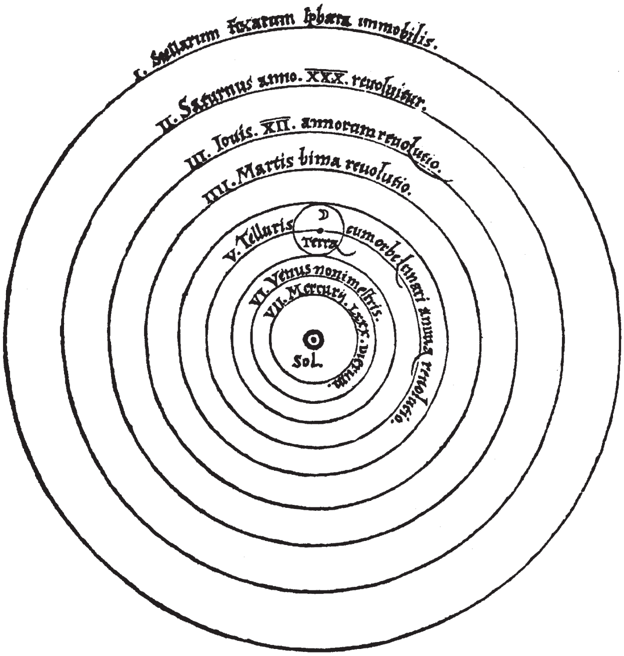

FIG. 3. N. Copernicus, *De revolutionibus* (Nuremberg, 1543), f. 9v.

> in their distances on the basis of [works] on astronomy, since it is discussed [there] sufficiently. It happens that the motions of each are in proportion to their distances (*kata logon ... tois apostêmasi*) in that some [motions] are faster and some slower. That is to say, since it is supposed that the outermost revolution of the heavens is simple and fastest, and that the [motions] of the others are slower and more numerous — for each moves in a direction opposite to the heavens along its own circle — it is actually reasonable that the [body] nearest the simple and primary revolution goes through its own circle in the longest time, and that the one that is farthest away in the least time; whereas of the others the nearer always [goes through its own circle] in more time and the farther in less time. The reason is that the one that is nearest [the outermost revolution] is dominated [by it] most of all and the one that is farthest [is dominated] least of all on account of its distance; whereas the intermediate [bodies] are actually in the proportion of their distances, just as the astronomers in fact prove.[9]

A difficulty with appealing to this passage is that if the periods are strictly proportional to the distances measured from the outermost sphere, they are not proportional to their distances from the Earth: If *P* is a planet's period, *d* its distance from the outermost sphere, and *D* the distance from the Earth to the outermost sphere then, where d is proportional to P, the distance from the Earth to a planet, $D - d$, is not proportional to P.

The text of Aristotle's *De caelo* in Latin translation appears in *Aristotelis opera cum Averrois commentariis*, which was printed many times in the fifteenth and sixteenth centuries. This edition consists of a Latin translation of the Greek text by William of Moerbeke (thirteenth century) together with a Latin translation by Michael Scot (thirteenth century) of the Arabic version of Aristotle's text by Ibn al-Biṭrīq (ninth century) that was included by Averroes in his long commentary, and Scot's Latin translation of Averroes's long commentary on Ibn al-Biṭrīq's version of Aristotle's text. In the translation of the Arabic version of *De caelo*, ii.10, the Latin has "according to its distance" (*secundum suam remotionem*) instead of "in proportion to their distances" (*secundum rationem ... elongationibus* [ed. 1562: *ipsis spatijs*]) that appeared in the immediately preceding translation of *De caelo*, ii.10, by William of Moerbeke.[10] This is not a typographical or copyist's error, for Moerbeke is following the Greek text whereas Scot is faithful to the Arabic version quoted by Averroes. Moreover, in his long commentary, Averroes argued against the strict proportionality that appears in the Greek text of *De caelo*, ii.10. As Endress characterized the view of Averroes, "Aristotle's statement on the connection between the planet's velocity and its distance from the first heaven does not imply a mathematical, proportional ratio".[11] The doctrines of Averroes were very much at the centre of philosophical discussion when Copernicus was a student in Italy (1496–1503).[12] In particular, Achillini (d. 1512), one of the most celebrated philosophers in Italy at the time, published in Bologna an Averroist attack on Ptolemy while Copernicus was a student there; Achillini discussed *De caelo*, ii.10, as well as Averroes's comment on it and, in this context, he also cites Averroes's Comment 44 on Aristotle's *Metaphysics* XII which includes the following:[13]

> It is also evident that the rank of these movers relative to the first mover must follow the order of the spheres in space because their precedence in position and magnitude determines their hierarchy in nobility. But with regard to their velocity of motion, we find them in the opposite situation, I mean the closest to the Earth is the fastest.[14]

Simplicius (sixth century) had already ignored the strict proportionality, and took Aristotle to provide an order for the planetary distances (according to their periods) that can be measured either from the outermost sphere or from the Earth:

> It turns out, he [Aristotle] says, that the motions are in proportion to their distances because [planets] that are nearer the Earth, like the Moon, move faster whereas those that are farther move more slowly in the proportion of their distances. Now then, this [claim], which was appropriately introduced, justifiably raised a problem for the account of the ordering, that is, of the distances, namely, why the [planets] circling near the Earth move faster and the [planets] that are higher and come closer to the fixed [sphere] move more slowly, just as the [star] of Saturn

> which returns in position after 30 years [moves more slowly] than the Moon which makes a revolution in a month....[15]

The same principle in a heliocentric context appears in the section on the order of the spheres in Copernicus's *Commentariolus*: "One [planet] exceeds another in rapidity of revolution in the same order in which they traverse the larger or smaller perimeters of [their] circles."[16] A parallel passage occurs elsewhere in the *Commentariolus*:

> But the sphere of Saturn completes a revolution in the 30th year, the sphere of Jupiter in the 12th, and the sphere of Mars in the 23rd [MSS: 29th; corrected by Swerdlow] month, just as if the size of the spheres slowed down these revolutions.[17]

Swerdlow comments: "This could indicate that after finding the heliocentric theory gave the order and distances of the planets with certainty, Copernicus attempted to find some precise correspondence between distance and period, but failing to accomplish this, fell back on the possibility that the sheer massiveness of the spheres retarded the planetary motions. There is no mention of this theory in *De revolutionibus*...."[18] I suggest that "size" here does not refer to bulk, but to the circumference of the orb, and that Copernicus was alluding to the distance–period relationship according to which the farther a planet is from the centre of motion, the longer is its period.

In his defence of Tycho Brahe, Kepler (d. 1630) included detailed comments on Copernicus's argument in *De revolutionibus*, i.10, and referred to a number of ancient writers not mentioned explicitly by Copernicus, but he did not cite this passage in Aristotle (see below: Comment [5]). Elsewhere, however, Kepler treated the passage in *De caelo* as equivalent to an ordering principle such that the planetary periods increase with distance from the centre of motion (apparently not taking "in proportion" strictly), for in his *Mysterium cosmographicum* (1596), chap. 20, we find the following:

> First everyone wants each planet to proceed with a slower motion the further its distance from the centre. For nothing is more reasonable, witness Aristotle, *De caelo*, Book II, Chapter 10, than that "the motions of each should be in proportion to the distances". ... In Copernicus such a ratio is apparent at first sight. For of the six moving orbs (*orbium*), the narrower always revolves faster.[19]

Hence, I think it likely that Copernicus took the distance–period relationship from Aristotle as interpreted by his commentators.

[2] Copernicus alludes to the assumption that if the linear speeds of the planets are the same (see below: Comment [6]), then the planet farthest from the centre of motion would appear to have the longest period. This follows from Euclid's *Optics*,[20] but is inappropriate for Copernicus's own system in which the distances are determined from the transformation of Ptolemy models such that for an outer planet the radius

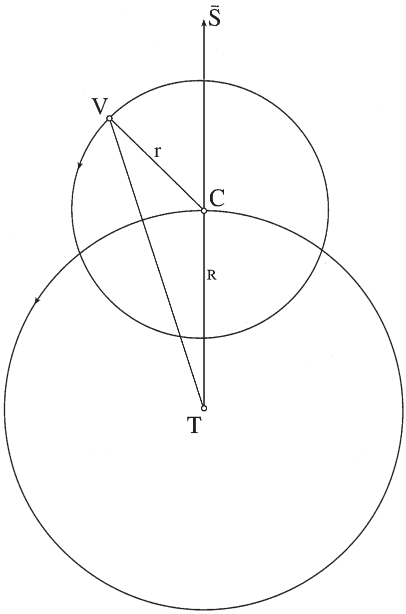

FIG. 4(a). A geocentric model for an inner planet.

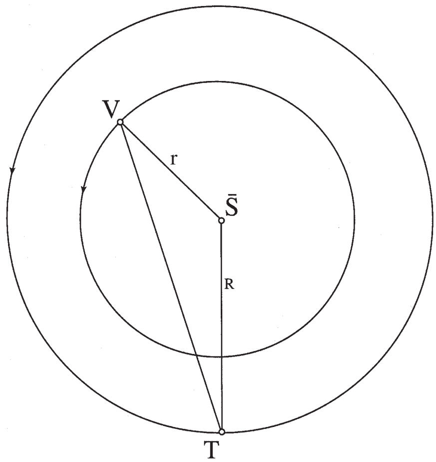

FIG. 4(b). A heliocentric model for an inner planet.

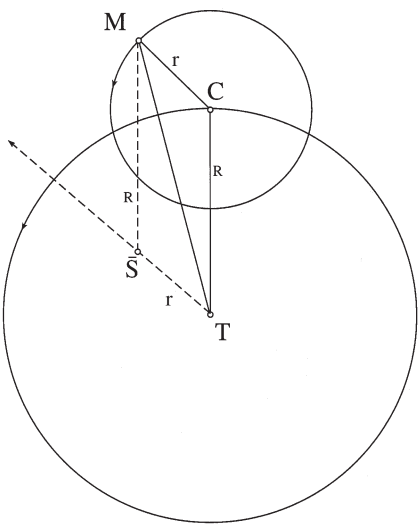

FIG. 4(c). A geocentric model for an outer planet.

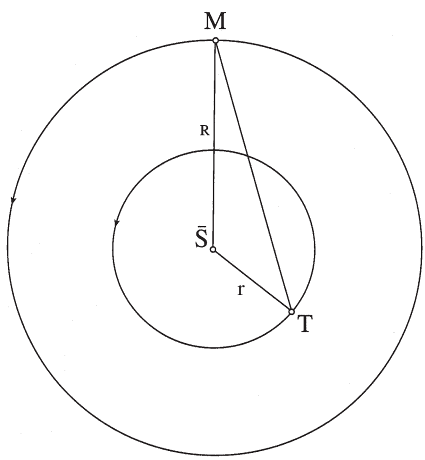

FIG. 4(d). A heliocentric model for an outer planet.

of the epicycle corresponds to the radius of the Earth's orb, and for an inner planet the radius of the deferent corresponds to the radius of the Earth's orb (see Figures 4(a)–(d)). To illustrate these models we make the simplifying assumptions that the orbs of the planets have no eccentricity and that their motions all take place in the same plane.

In Figure 4(a), we represent a geocentric model for an inner planet; T is the Earth, V is the planet, and S̄ is the direction to the mean Sun. The directions of motion on the deferent circle about T and on the epicycle about C are indicated by arrows. The radius of the epicycle is *r*, and the radius of the deferent is *R*. The transformation to a heliocentric model is shown in Figure 4(b). To do so, we identify C in Figure 4(a) with S̄, i.e., the mean Sun is no longer a direction but a point at the centre of the epicycle, and the planet moves in a circle about it. We then interchange the roles of S̄ and T such that both V and T move in circles about S̄. Note that *r* is now the radius of the orb of an inner planet, and *R* is the radius of the Earth's orb; the ratio *r*/*R* is unaffected by the transformation. For the geocentric model of an outer planet, see Figure 4(c). The planet, M, moves on an epicycle whose centre is C and whose radius is *r*, and C moves on the deferent circle whose radius is *R* about the Earth at T; the directions of motion on the circles are indicated by arrows. In this case the direction to the mean Sun is indicated by a dashed line from T parallel to the direction from C to M. To transform this geocentric model into a heliocentric model, we introduce a point S̄, in the direction of the mean Sun, at a distance *r* from T, and then we complete the parallelogram, TS̄MC. If we fix T and let S̄ move about T and M about S̄, we have a Tychonic (geo-heliocentric) model, i.e., the planets move about the Sun and the Sun moves about the Earth. But if we fix S̄ and let both T and M move about it, we have a heliocentric model, as in Figure 4(d). Note that in the heliocentric model *R* is the radius of the orb of an outer planet, and *r* is the radius of the Earth's orb; the ratio *R*/*r* is unaffected by the transformations.

Neugebauer compared the planetary distances from the mean Sun (the centre of the Earth's orb for Copernicus), based on the parameters in Ptolemy and Copernicus, respectively, using the radius of the Earth's (or Sun's) orb as the unit. Neugebauer's results show that, with these assumptions, the distances computed with Ptolemy's parameters and those of Copernicus agree very closely, and do not differ greatly from the modern values.[21] With these values for the mean distances of the planets from the mean Sun, the circumferences of their paths around the Sun may easily be computed, and the circumference divided by the period yields *v*, the linear speed of a planet. In units of the radius of the Earth's orb, *u*, the mean distance of Saturn from the centre of the Earth's orb is 9.175*u* and its period is about 30 years, whereas the mean distance of Jupiter from the centre of the Earth's orb is 5.219*u* and its period is about 12 years.[22] Thus, for Saturn

$$v\ (\text{Saturn}) = 9.175u \cdot 2 \cdot \pi/30\text{y} = 1.92u/\text{y},$$

and for Jupiter

$$v\ (\text{Jupiter}) = 5.219u \cdot 2 \cdot \pi/12\text{y} = 2.73u/\text{y},$$

i.e., the linear speed of Jupiter is greater than that of Saturn. We now know from Kepler's third law that a planet's period is proportional to the 3/2 power of its mean distance from the Sun. But even without knowledge of Kepler's third law, it is clear that equal linear motion cannot be ascribed to the planets in the Copernican system. There is no evidence that Copernicus ever computed values for the linear speeds of the planets, and there was no precedent for such a computation in the works of Ptolemy.

[3] Copernicus described Ptolemy's nesting hypothesis only for the space between the Moon and the Sun because the issue he addressed concerned the order of the inner planets with respect to the Sun. The maximum distance to the Moon is given here as 64;10 t.r. [terrestrial radii] as in the *Almagest* (and elsewhere), and the minimum distance of the Sun is given as 1160 t.r. as in Proclus's *Hypotyposis*.[23] Copernicus gave a correct account of Ptolemy's cosmic dimensions, and rejected them because Ptolemy's distances do not conform to the distance–period relationship. One should also note that Copernicus ascribed to Plato the view that the Sun's orb was closer to the Earth than those of Mercury and Venus. For Copernicus, this order is incompatible with the nesting hypothesis, for it leaves much empty space between the orb of the Moon and the orb of the Sun (given the range of values for the distances from the Earth of the Moon and the Sun that were current among astronomers in the Ptolemaic tradition). Similarly, Copernicus dismissed the view of Alpetragius (al-Biṭrūjī: *c.* 1200) who placed the orb of Venus above the Sun and that of Mercury below it.[24] To be sure, Copernicus did not call attention, here or elsewhere, to the gaps between the planetary orbs that are a consequence of his heliocentric system.[25]

[4] The reference is to Martianus Capella, *The marriage of Philology and Mercury*, viii, 857:

> *Tria item ex his cum Sole Lunaque orbem Terrae circumeunt, Venus vero et Mercurius non ambiunt Terram....* Three of these planets [i.e., Saturn, Jupiter, and Mars], together with the Sun and the Moon, go around the globe of the Earth, but Venus and Mercury do not go around the Earth.[26]

[5] There is some dispute about the identities of "certain Latin writers". One of them is surely Vitruvius, for in his *De architectura*, ix.1.6, he says:

> *Mercuri autem et Veneris stellae circa solis radios uti per centrum eum itineribus coronantes regressus retrorsus et retardationes faciunt....* The stars of Mercury and Venus, making their paths in the form of a crown around the rays of the Sun as around a centre, perform back and forth motions, and retardations.[27]

But in explicating Copernicus's "certain other Latin writers" Kepler includes Pliny and Macrobius, in addition to Vitruvius.[28] Pliny is cited in this context by Rheticus in his *Narratio prima*,[29] but not Macrobius. As Eastwood comments: "For Kepler, the question is not, 'Where did Copernicus get the idea?', but rather, 'Where did the idea originate?'."[30] Kepler saw a chain of ancient authorities who supported heliocentrism, and used this argument in his defence of Tycho Brahe against Ursus.[31]

[6] The computations for Venus and Mercury are straightforward (and adequate results do not depend on very precise parameters). To compute the sidereal periods of Venus and Mercury we consider the Earth as moving instead of the Sun.

1. The synodic period of Venus is about 584 days.[32]

> In 584 days the Sun (Earth) moves $584^{d} \cdot 0;59,8^{\circ/d} \approx 575;30^{\circ}$. *Ex hypothesi*, Venus is closer than the Earth to the Sun and faster than the Earth; hence it makes a complete revolution plus 575;30°. So $(575;30^{\circ} + 360^{\circ})/584^{d} \approx 1;36^{\circ/d}$, and $360^{\circ}/1;36^{\circ/d} = 225$ days.

This is the correct sidereal period, to the nearest day, for Venus;[33] Copernicus should have computed $7\frac{1}{2}$ months, but in the *Commentariolus* he has "in the ninth month" and in *De revolutionibus*, i.10, he has 9 months.[34]

2. The synodic period of Mercury is about 116 days.[35]

> In 116 days the Sun (Earth) moves $116^{d} \cdot 0;59,8^{\circ/d} \approx 114;20^{\circ}$. Then, by the same reasoning as above, $(114;20^{\circ} + 360^{\circ})/116 \approx 4;5^{\circ/d}$, and $360^{\circ}/4;5^{\circ/d} \approx 88$ days.

This is the correct sidereal period for Mercury to the nearest day;[36] in the *Commentariolus* Copernicus has 88 days but in *De revolutionibus*, i.10, he has 80 days.[37]

I cannot account for Copernicus's mistakes in arithmetic which are found in his earliest and latest works, but all he needed was to find that the ordering of the planetary periods around the Sun conformed to the distance–period relationship.

Vitruvius (*De architectura*, ix.1.14) had already transformed the measuring of planetary distances: whereas in Aristotle, the distance of a planet is taken with respect to the outermost sphere, in Vitruvius it is taken from the centre of motion, namely, the Earth. Note also that Copernicus, as Vitruvius, considered the planets to have equal linear speeds (see above: Comment [2]). Vitruvius writes (*De architectura*, ix.1.14–15):

> The star Jupiter traversing its path (*circinationem*) between those of Mars and Saturn, flies along a course greater than that of Mars and less than that of Saturn. So, too, with the remaining stars, the farther distance they are from the limits of heaven and the nearer they keep their path to Earth, the faster they seem to go, because each one of them, in traversing a smaller circle, more frequently passes underneath one which is higher up, and then overtakes it. In the same way, if seven ants were to be placed on a potter's wheel, and as many channels were to be made around the centre of the wheel, growing in size from the smallest to the outermost, and the ants were forced to make a circuit in these channels, then, as the wheel was spun in the opposite direction, it would be no less necessary for these ants to make their way against the rotation of the wheel, and the

> one whose channel was nearest the centre would have to finish his circuit more quickly, but the one that traversed the outermost circle of the wheel, even if it walked just as quickly, would complete its round much more slowly because of the circle's sheer size. In the same way these stars, striving against the course of the cosmos, complete their circuit (*circuitum*) as they journey on, but because of the rotation of the firmament they are carried back in redoublings because of the daily twirling of time.[38]

[7] The famous figure of the planetary orbs with their periods in *De revolutionibus,* i.10, may have been inspired by the image of ants moving in seven channels on a potter's wheel in Vitruvius, *De architectura*, ix.1. Copernicus may have been reluctant to cite it because of the general avoidance of analogies between celestial and terrestrial matters (following Aristotle).

The figure in the autograph manuscript (Figure 2), illustrates Copernicus's cosmology better than the figure in the *editio princeps* (Figure 3). In the printed edition a circle has been added for the Moon, and the captions for the fixed stars and the superior planets are one space too high.[39]

Conclusion

In sum, Copernicus's initial commitment to a heliocentric system was a response to an issue debated in the philosophical community at the time when he attended universities in Italy, *c.* 1500. Copernicus began by rejecting Ptolemy's nesting hypothesis and noting its incompatibility with the distance–period relationship that he took to be the proper basis for ordering the planetary orbs from their centre of motion. The order of the planetary periods around the Sun conforms to this relationship, but there is no way for it to work in a geocentric world.

Acknowledgements

I am most grateful to P. Barker, A. C. Bowen, J. Chabás, G. Endress, R. Glasner, and J. L. Mancha, for their assistance in interpreting passages in Greek and Latin, and for their comments on earlier drafts of this article.

REFERENCES

1. As Neugebauer demonstrated, Copernicus and his Muslim predecessors did not 'abandon' the equant; on the contrary, it was preserved and, with a secondary epicycle and uniform circular motions, very nearly the same results are produced as those that follow from Ptolemy's equant models: see O. Neugebauer, "On the planetary theory of Copernicus", *Vistas in astronomy*, x (1968), 89–103 (espec. pp. 92–96), reprinted in *idem*, *Astronomy and history: Selected essays* (New York and Berlin, 1983). See also N. M. Swerdlow, "The Commentariolus of Copernicus", *Proceedings of the American Philosophical Society*, cxvii (1973), 423–512 (espec. pp. 434–5); and N. M. Swerdlow and O. Neugebauer, *Mathematical astronomy in Copernicus's De revolutionibus* (New York and Berlin, 1984), 43–48, 294–5. For a comparison of Copernicus's planetary models with those of Ibn al-Shāṭir (d. 1375), see G. Saliba, "Arabic planetary theories after the eleventh century AD", in *Encyclopedia of the history of Arabic science*, ed. by R. Rashed (3 vols, London and

New York, 1996), i, 58–127 (espec. pp. 108–14).

2. See G. J. Toomer, *Ptolemy's Almagest* (New York and Berlin, 1984), 419–20; B. R. Goldstein, *The Arabic version of Ptolemy's* Planetary Hypotheses, *Transactions of the American Philosophical Society*, lvii/4 (1967); and A. Aaboe, *Episodes from the early history of astronomy* (New York and Berlin, 2001), 114–34. In the *Mysterium cosmographicum*, Kepler revived the nesting hypothesis in a heliocentric system such that the dimensions of the five regular solids fit the spaces between the six planets: see Johannes Kepler, *Mysterium cosmographicum* (Tübingen, 1596), chap. 14, translated by A. M. Duncan with introduction and commentary by E. J. Aiton (New York, 1981), 155–9; see also P. Barker and B. R. Goldstein, "Theological foundations of Kepler's astronomy", *Osiris*, xvi (2001), 88–113 (espec. pp. 99–103).

3. Swerdlow, *op. cit.* (ref. 1), 436. The *locus classicus* for the heliocentric theory in Antiquity is Archimedes's *Arenarius* (*Sandreckoner*) concerning Aristarchus: T. L. Heath, *The works of Archimedes* (Cambridge, 1897; reprinted New York, 1953), 221–2. But there is no evidence that Copernicus knew the passage and it was not published until after his death: *cf.* Nicholas Copernicus, *On the revolutions*, transl. and commentary by E. Rosen (Baltimore, 1992), 361. Copernicus mentioned Aristarchus in the autograph manuscript of *De revolutionibus*, but the passage was crossed out and not included in the *editio princeps*: *cf.* P. L. Rose, *The Italian renaissance of mathematics* (Geneva, 1975), 125; and Rosen, *op. cit.*, 25. Although not cited by Copernicus, his source was likely to have been Plutarch, *On the faces of the Moon*, 923A:

> Thereupon Lucius laughed and said: "Oh, sir, just don't bring suit against us for impiety as Cleanthes thought that the Greeks ought to lay an action against Aristarchus the Samian on the ground that he was disturbing the hearth of the universe because he sought to save the phenomena by assuming that the Heaven is at rest while the Earth is revolving along the ecliptic and at the same time rotating about its own axis" (Plutarch, *Moralia: Concerning the face that appears in the orb of the Moon*, ed. and transl. by H. Cherniss (Cambridge, Mass., 1957), 55; and, according to Rosen, *op. cit.*, 360, *Plutarchi opuscula LXXXXII: Index moralium omnium, & eorum quae in ipsis tractantur, habetur hoc quaternione: numerus autem arithmeticus remittit lectorem ad semipagina[m], ubi tractantur singula* (Venice, 1509), 932).

On the other hand, Copernicus does quote a passage from Pseudo-Plutarch in Greek that was included in the edition of Plutarch in 1509, cited above (N. Copernicus, *De revolutionibus orbium coelestium* (Nuremberg, 1543; facsimile reproduction, Brussels, 1966), Dedication to the Pope, f. iiij r; *cf.* chap. 5, f. 3v):

> Some think that the Earth remains at rest. But Philolaus the Pythagorean believes that, like the Sun and Moon, it revolves around the fire in an oblique circle. Heraclides of Pontus and Ecphantus the Pythagorean make the Earth move, not in a progressive motion, but like a wheel in a rotation from west to east about its own centre (transl. Rosen, *op. cit.*, 5 and, according to Rosen, this passage is found in Plutarch, *op. cit.* (ed. 1509), 328).

There is also a confused remark about Aristarchus in G. Valla, *De expetendis et fugiendis rebus* ... (2 vols, Venice, 1501): *cf.* Rose, *op. cit.*, 125; and Rosen, *op. cit.*, 360–1.

A similar passage is found in Cicero's *Academica* (ii.39.123) that was available in manuscript in Frauenburg and, according to Rosen (*op. cit.*, 341), Copernicus transcribed this passage in his copy of Pliny's *Natural history* (Venice, 1487; *cf.* Rose, *op. cit.*, 125; and P. Czartoryski, "The library of Copernicus", *Studia Copernicana*, xvi (1978), 355–96 (espec. p. 372)):

> The Syracusan Hicetas, as Theophrastus asserts, holds the view that the heaven, Sun, Moon, stars, and in short all of the things on high are stationary, and that nothing in the world is in motion except the Earth, which by revolving and twisting round its axis with its extreme velocity produces all the same results as would be produced if the Earth were stationary and the heaven in motion (Cicero, *De natura deorum; Academica*, ed. and transl. by H. Rackham (Cambridge, Mass., 1951), 627).

This passage is cited by Copernicus, *op. cit.*, Dedication to the Pope, f. iiij r, and in chap. 5, f.

3v; in both places "Hicetas" appears as "Nicetas".

4. Copernicus, *op. cit.* (ref. 3), 10r.
5. Swerdlow, *op. cit.* (ref. 1), 471–8.
6. Swerdlow and Neugebauer, *op. cit.* (ref. 1), 56–60.
7. See Swerdlow, *op. cit.* (ref. 1), 478; *cf.* B. R. Goldstein and P. Barker, "The role of Rothmann in the dissolution of the celestial spheres", *The British journal for history of science*, xxviii (1995), 385–403.
8. Copernicus, *op. cit.* (ref. 3), 8v–9v; Copernicus, *On the revolutions of the heavenly spheres*, transl. by A. M. Duncan (London and New York, 1976), 47–50.
9. For the Greek text, see Aristotle, *On the heavens*, ed. and transl. by W. K. C. Guthrie (Cambridge, Mass., 1939), 198; transl. in A. C. Bowen, *Simplicius' Commentary on Aristotle,* De caelo *ii 10–12: An annotated translation* (in preparation). Guthrie's translation of this passage is faulty; a better translation is available in S. Leggatt, *Aristotle: On the heavens, I and II* (Warminster, 1995), 143.
10. For Scot's translation, see *Aristotelis opera cum Averrois commentariis* (Venice, 1495–96), 212va–b; *Aristotelis opera cum Averrois commentariis: Quintum volumen Aristotelis De caelo, ...* (Venice, 1562; reprinted Frankfurt/M, 1962), 136I–L. I am most grateful to José Chabás for checking the copy of the edition of 1495–96 at the library of the University of Barcelona (shelf mark: Inc 612–I). In Moerbeke's translation the expression in *ibid*. (ed. 1495–96), 212va, is *secundum rationem ... elongationibus*, whereas in *ibid*. (ed. 1562), 136G, it is *secundum rationem ... ipsis spatijs*; there are other differences between the two editions of Moerbeke's translation, but they do not affect the argument here.

    Gerhard Endress kindly made available to me a critical edition of Scot's Latin translation of Averroes's Comment 58 on *De caelo*, ii.10, prepared by F. J. Carmody (to be published with a critical apparatus edited by R. Arnzen in a volume under the general supervision of G. Endress in the series *Averrois opera*). I am also grateful to G. Endress for informing me that Ibn al-Biṭrīq's Arabic version of *De caelo* (which is quoted by Averroes) has ^{c}*alā naḥwi bu*^{c}*dihi* (Aristotle, *Kitāb al-samā' wa-l-*^{c}*ālam*, ed. by ^{c}Abd al-Raḥmān Badawi (Cairo, 1961), 267), and Michael Scot (correctly) translated it as *secundum suam remotionem*.
11. G. Endress, "Averroes' *De caelo*, Ibn Rushd's cosmology in his Commentaries on Aristotle's *On the heavens*", *Arabic sciences and philosophy*, v (1995), 9–49 (espec. p. 43). See Averroes, long commentary on *De caelo*, Comment 58, in Aristotle and Averroes, *op. cit.* (ref. 10), ed. 1495–96, 212vb–213ra; and ed. 1562, 136M–137H. The original Arabic of Averroes's Comment 58 on *De caelo* does not survive.

    Oresme (fourteenth century) translated *De caelo* into French and commented on it. In the case of the passage in *De caelo*, ii.10, he translates the words "in proportion" but comments that

    > With this theory, it is not necessary to assume that the planets' being lower than, or farther from, the sovereign heaven causes their proper movement to be fast proportionally or in a precise proportion (*proporcionelment ou selonc proporcionalité precise*), for, in addition, we must consider and compensate for the force (*la puissance*) and will or desire of the motive power (N. Oresme, *Le livre du ciel et du monde*, ed. by A. D. Menut and A. J. Denomy; transl. with an introd. by A. D. Menut (Madison, 1968), 491).

    In this context Oresme noticed another problem with Aristotle's version of the distance–period relationship, namely, the Sun, Venus, and Mercury all have the same period of revolution around the Earth. He suggested that the astronomers in Aristotle's time may have placed all three of them in the same heaven (*ciel*), but he did not cite any ancient source for this view (see Comment [4]). I have no reason to believe that Copernicus was aware of this passage; it is cited to indicate that scholars in the late Middle Ages were concerned with the interpretation of *De caelo*, ii.10, and it seems likely that Oresme was familiar with the Latin version of Averroes's commentary (see ref. 24, below).
12. On Copernicus in Italy, see Rose, *op. cit*. (ref. 3), 118–42.

13. A. Achillini, *De orbibus* (Bologna, 1498; reprinted Venice, 1545); *idem*, *Opera omnia* ... (Venice, 1545), 34vb and 35ra: I am most grateful to Peter Barker for finding these passages and translating them. See also P. Barker, "Copernicus and the critics of Ptolemy", *Journal for the history of astronomy*, xxx (1999), 343–58 (espec. p. 349).
14. C. Genequand, *Ibn Rushd's* Metaphysics*: A translation with introduction of Ibn Rushd's Commentary on Aristotle's* Metaphysics*, Book Lām* (Leiden, 1986), 172.
15. For the Greek text, see J. L. Heiberg, *Simplicii in Aristotelis De caelo Commentaria* (Berlin, 1894), 471; transl. in Bowen, *op. cit.* (ref. 9).
16. Swerdlow, *op. cit.* (ref. 1), 440.
17. Swerdlow, *op. cit.* (ref. 1), 465.
18. Swerdlow, *op. cit.* (ref. 1), 466.
19. Duncan, *op. cit.* (ref. 2), 197 (slightly modified).
20. Rosen, *op. cit.* (ref. 3), 355, claims that Copernicus depended on B. Zamberti's Latin translation of Euclid (Venice, 1505); *cf.* P. Ver Eecke, *Euclide: L'optique et la catoptrique* (Paris, 1959), p. xxxvii.
21. Neugebauer, *op. cit.* (ref. 1), 92; *cf.* A. Van Helden, *Measuring the universe* (Chicago, 1985), 42–44.
22. These periods of Saturn and Jupiter are given in Copernicus, *op. cit.* (ref. 3), i.10, f. 9r.
23. According to Rosen, *op. cit.* (ref. 3), 355–6, information on Proclus's treatise was available to Copernicus in Valla, *op. cit.* (ref. 3), Book XVIII, chap. 23, sig. gg 6v; *cf.* Swerdlow and Neugebauer, *op. cit.* (ref. 1), 475.
24. Copernicus, *op. cit.* (ref. 3), 7v–8r; *cf.* Endress, *op. cit*. (ref. 11), 43: "Ibn Rushd [Averroes] declares that the conditions underlying Aristotle's exposition [in *De caelo*, ii.10] are reconciliable only with 'the opinion of those who say that the Sun is below Mercury and Venus, and not above ...'" (*Sed hoc non currit secundum ordinem nisi secundum opinionem dicentis quod sol est sub Mercurio et Venere et non supra*). The quotation is from Averroes's Comment 58 on *De caelo*, ii.10, in Aristotle and Averroes, *op. cit*. (ref. 10), ed. 1495–96, 212vb; ed. 1562, 136M. Averroes seems to think that the velocity of the Sun is greater than the velocities of Venus and Mercury but, even so, the Sun may lie above them, for its power may surpass theirs (*Et secundum hoc non est inconveniens quod motus Solis sit velocior motu Mercurij et Veneris, quamvis sit supra; et hoc erit propter abundantiam suae potentiae supra potentiam earum: ibid.*, ed. 1495–96, 213ra; ed. 1562, 137G). To be sure, his remark is based on a false assumption (where 'velocity' refers to mean angular velocity, i.e., 360° divided by the period), for the geocentric periods of the Sun, Venus, and Mercury are exactly the same. Later in *De revolutionibus*, i.10, Copernicus cited an observation, reported by Averroes in his "Paraphrase of Ptolemy", of Venus and Mercury being seen as spots on the Sun, from which it had been concluded that their orbs are both closer to the Earth than the orb of the Sun. This text, Averroes's *Epitome of the Almagest*, is only extant in an unpublished Hebrew translation, and Copernicus probably depended on a citation of it by G. Pico della Mirandola in his *Disputationes in astrologiam* (Bologna, 1495), x.4: see B. R. Goldstein, "Some medieval reports of Venus and Mercury transits", *Centaurus*, xiv (1969), 49–59 (espec. pp. 53–58); and J. Lay, "*L'Abrégé de l'Almageste*, un inédit d'Averroès en version hébraïque", *Arabic sciences and philosophy*, vi (1996), 23–61. The view of al-Biṭrūjī would have been available to Copernicus in Regiomontanus's *Epytoma Joannis de monte regio In almagestum Ptolemaei* (Venice, 1496), ix.1: see M. Shank, "The 'Notes on al-Biṭrūjī' attributed to Regiomontanus: Second thoughts", *Journal for the history of astronomy*, xxiii (1992), 15–30 (espec. pp. 17 and 27 n. 17). The earliest Latin edition of al-Biṭrūjī's *Astronomy* was published in Venice in 1531, and it was a translation from the Hebrew version, rather than from the original Arabic: see B. R. Goldstein, *Al–Biṭrūjī: On the principles of astronomy* (2 vols, New Haven, 1971), i, 3.
25. On these gaps, see G. J. Rheticus, *Narratio prima* (Gdansk, 1540); for a modern edition, see *Georgii Joachimi Rhetici Narratio prima*, ed. and transl. by H. Hugonnard-Roche *et al.* (Wrocław and Warsaw, 1982), p. 60, line 101 (Latin), p. 113 (French). In contrast to Rheticus's passing remark, Kepler described these gaps in detail and recognised that they were significant: see Kepler, transl.

by Duncan, *op. cit.* (ref. 2), 63–65. *Cf.* Van Helden, *op. cit.* (ref. 21), 44.

26. This passage is quoted in Latin in B. S. Eastwood, "Kepler as historian of science: Precursors of Copernican heliocentrism according to *De revolutionibus*, I, 10", *Proceedings of the American Philosophical Society*, cxxvi (1982), 367–94 (espec. p. 369). The translation, however, is mine. *Cf.* Martianus Capella, *De nuptiis Philologiae et Mercurii* (Vicenza, 1499). For a nuanced approach to the heliocentrism of Martianus Capella and its reception in the ninth century, see now B. S. Eastwood, "Johannes Scottus Eriugena, Sun-centred planets, and Carolingian astronomy", *Journal for the history of astronomy*, xxxii (2001), 281–324 (espec. p. 295).
27. For the Latin text, see Vitruvius, *On architecture*, ed. by F. Granger (2 vols, Cambridge, Mass., 1934), 216; transl. by P. Barker.
28. See Eastwood, *op. cit.* (ref. 26), 383ff.
29. Rheticus, ed. by H. Hugonnard-Roche *et al.*, *op. cit.* (ref. 25), 55.
30. Eastwood, *op. cit.* (ref. 26), 394.
31. N. Jardine, *The birth of history and philosophy of science: Kepler's* A defence of Tycho against Ursus (Cambridge, 1984), 197–207.
32. According to *Almagest*, ix.3; Toomer, *op. cit.* (ref. 2), 424: for Venus, 5 returns take place in about 8 years. Then $8 \cdot 365;15^d/5 \approx 584^d$.
33. Kepler, *op. cit.* (ref. 2), Plate 1, after f. 18; transl. by Duncan, 227 (Annotations to the plates); *cf.* W. M. Smart, *Text-book on spherical astronomy*, 5th edn (Cambridge, 1962), 422.
34. Swerdlow, *op. cit*. (ref. 1), 440, 490; Copernicus, *op. cit.* (ref. 3), 9v. Rheticus repeated the value that appears in *De revolutionibus*, but Maestlin corrected it to $7\frac{1}{2}$ months in his edition of Rheticus's *Narratio prima* (1596): see Rheticus, ed. and transl. by H. Hugonnard-Roche *et al.*, *op. cit*. (ref. 25), 113, 169.
35. According to *Almagest*, ix.3; Toomer, *op. cit.* (ref. 2), 424: for Mercury, 145 returns take place in about 46 years. Then $46 \cdot 365;15^d = 16801;30^d$; and $16801;30^d/145 \approx 115;52$ days or about 116 days.
36. Kepler, *op. cit.* (ref. 2), Plate 1, after f. 18; transl. by Duncan, 227 (Annotations to the plates); *cf.* Smart, *op. cit.* (ref. 33), 422.
37. Swerdlow, *op. cit*. (ref. 1), 499; Copernicus, *op. cit.* (ref. 3), 9v.
38. Vitruvius, *Ten books on architecture*, transl. by Ingrid D. Rowland, commentary and illustrations by Thomas Noble Howe, with additional commentary by Ingrid D. Rowland and Michael J. Dewar (New York, 1999), 111 (slightly modified). *Cf. L. Victruvii Pollionis ad Cesarem Augustum De architectura liber primus[–decimus]* (Rome, 1482).
39. *Cf.* Swerdlow and Neugebauer, *op. cit.* (ref. 1), 572–3, and the discussion on p. 58.