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WHY COPERNICUS WAS NOT A SCIENTIFIC REVOLUTIONARY

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Abstract

The paper discusses the reasons why Copernicus, with his heliocentric model of the solar system, introduced a turn but not a revolution in the problem situation of 16th astronomy. The Copernican model begins a transitional phase in astronomical thinking, which suggests that scientific revolutions should analytically be broken down into three-stage events which can best be captured in a chain-of-reasoning model of revolutions in science. This approach helps to locate the Copernican turn in the unfolding of the Copernican revolution.

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I. Introduction.

> Copernicus is neither an ancient nor a modern but rather a Renaissance astronomer in whose work the two traditions merge.[1]

It is a commonly held view that Copernicus was the author of a scientific revolution. Freud gave the most famous expression of this view when he interpreted the 'Copernican revolution' as a historical process, involving a threefold attack on human self-pride. In this series of blows to human pride Copernicus delivered the first strike by displacing humans from the perceived centre of the universe. Darwin inflicted a further wound by depicting humans as descendants of hominoid forebears who had split from the ape line on the evolutionary tree. At the beginning of the 20th century Freud saw himself as delivering the final blow by destroying the Enlightenment image of humans as purely rational agents.

Many historians of science disagree with this common assessment of Copernicus as a scientific revolutionary. While they often accept that the Copernican system has aesthetic advantages[2] or is 'more pleasing to philosophical minds'[3] they do not regard the Copernican system as a computational improvement over the geocentric model, as set

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[1] T. S. Kuhn, *The Copernican Revolution.* Cambridge (Mass.)/London: Harvard University Press. 1957. p. 182.
[2] D. J. Solla Price, 'Contra-Copernicus' in M. Clagett (ed.), *Critical Problems in the History of Science*. Madison: University of Wisconsin Press. 1962. pp. 197-218; Kuhn, *Copernican Revolution*, p. 172.
[3] O. Neugebauer, 'On the Planetary Theory of Copernicus', *Vistas in Astronomy* 10 (1968) §10.

forth in Ptolemy's *Almagest* (AD 140). Copernicus's critics argue that the Copernican switch from a geocentric to a heliocentric view is just a matter of the relativity of viewpoints but does not improve the mathematical accuracy of the planetary model because Copernicus still relies heavily on Greek geometric techniques. According to de Solla Price the mathematical part of the Copernican treatise is 'little more than a re-shuffled version of the *Almagest*.'[4]

The aim of this paper is to make a contribution to an area of study, which has been described as 'integrated history and philosophy of science'. The particular aspect investigated here is the question of scientific revolutions in association with the Copernican heliocentric model. The paper will first review the reasons why Copernicus is not regarded as a scientific revolutionary today. Denying the Copernican model of the solar system the epithet of a scientific revolution does not mean, secondly, that we should fall into the extreme position of denying Copernicus any credit at all. The Copernican system offered both empirical and theoretical advantages over the geocentric system. These advantages instigated a change of perspective, which will be described, following Kant, as a Copernican turn. Thirdly, the Copernican turn and the reasons why it falls short of a full-blown scientific revolution provide important clues regarding the assessment of some current models of scientific revolutions.

Judgements regarding scientific revolutions require an assessment of the problem situation, in which the said revolution took place. A problem situation is a reconstructed period in the history of science, in which contemporaries of the situation perceive a scientific problem within the presuppositional structure of their science, and attempt to solve the problem with techniques available to them. The problem situation of 16th and

[4] Solla Price, 'Contra-Copernicus' p. 215.

17th century astronomy involved the motion and order of the planets. Judgements whether a scientific revolution occurred requires an assessment of the transitions, which took place from one scientific tradition, considered to provide an inadequate solution in the face of a particular problem, to another, which is deemed to be a better solution to the problem. Such transitions have to be evaluated against certain criteria of what constitutes an adequate solution in the given problem situation. Such criteria cannot be reduced to empirical data or mathematical computations, since scientific theories themselves are conceptual structures, which carry commitments to philosophical views. These commitments are clearly detectable in the work of the Copernicans.

An approach to scientific revolutions in terms of problem situations shows that the Copernican turn is not compatible with Kuhn's paradigm model of scientific revolutions. By contrast, the various transitions involved in the Copernican revolution, from Copernicus to Newton, are better described in terms of a 'chain-of-reasoning' model. This approach enables us to locate the Copernican contribution more precisely in the chain of reasoning, which led to Newton.

II. Falling Short of a Scientific Revolution.

This section briefly reviews some of the main reasons why many historians of science tend to withhold the status of a scientific revolution from the Copernican heliocentric model.

- Copernicus accepts the 'equipollence of hypotheses', a philosophical device which can already be found in Ptolemy's *Almagest*. This device encourages the acceptance of different geometric techniques, which are regarded as equivalent for the purpose of describing planetary motions. Two devices – one based on the eccentric circle (Figure I) and the other based on the epicylic circle (Figure II) – were of particular importance for the geometric modelling of the apparent motions of the planets, as seen from the assumption of a stationary or rotating Earth.

Copernicus regards the employment of both eccentric and epicyclic circles as equivalent techniques – both can be used to model planetary motion.[5] The Copernican indifference towards different geometric techniques shows that he is content with 'saving the appearances'. He is satisfied that these different kinds of 'motion' reproduce the appearance of planetary motion as obtained from observational data. But Copernicus is not concerned with the further question whether either of these different geometric techniques may be a better way of modelling the kinematics of planetary motions. Of these different models he says: 'I could not really say which one is right.'[6] Nor is he concerned with establishing whether these geometric devices can be regarded as a physical explanation of the apparent motion of the planets. Kepler later complained that his predecessors had sought the 'equipollence of their hypotheses with the Ptolemaic system.'[7] Kepler went on to investigate 'physical' causes of planetary motion – a process during which he abandoned many of the ideas still important to Copernicus.

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[5] N. Copernicus, *On the Revolutions of Heavenly Spheres*. Amherst, New York: Prometheus Books. 1543/1995. Bk. III, §20, Bk. IV, §4.
[6] Copernicus, *Revolutions*. Bk. III, §20.
[7] J. Kepler, *Epitome of Copernican Astronomy & Harmonies of the World*. Amherst, New York: Prometheus Books. 1618/1995. Bk. IV, Pt. II, §5.

Figure I: *Eccentric Motion*. Explanation of apparent non-uniform motion on the assumption of uniform motion. The sun moves uniformly around point (*Ecc*). Seen from the Earth (*E*), however, the uniform motion looks non-uniform. At point 1 the Sun appears furthest away from the Earth (apogee), while at point 2, it appears at its closest approach to the Earth (perigee).

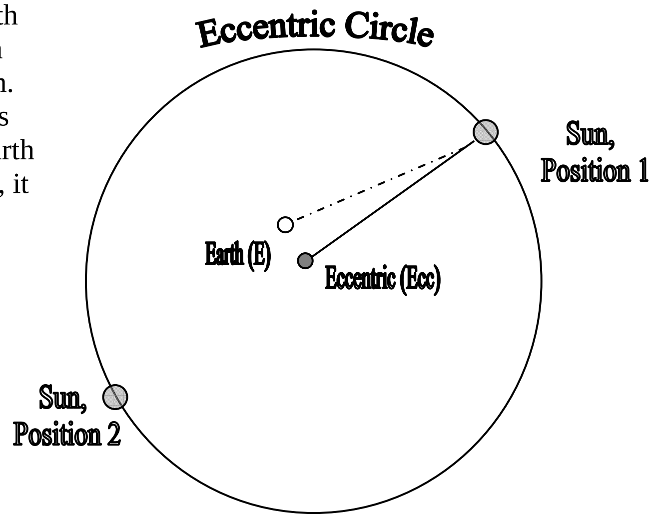
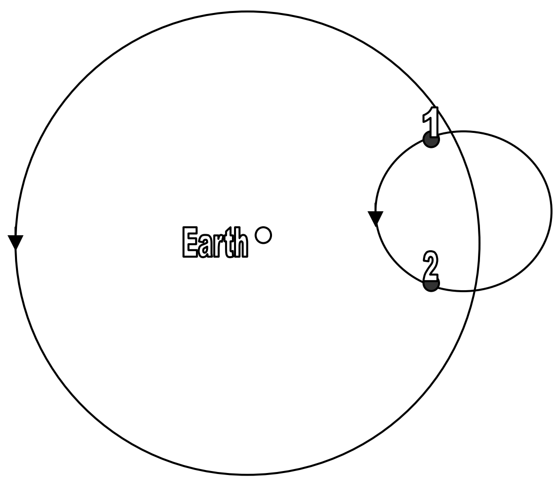


Figure II: *Epicyclic Motion*. Retrograde motion occurs, when the planet moves from P_1 to P_2 on its epicycle.



- Copernicus was still committed to the Greek ideal of circular motion for planetary orbits. To be precise, Copernicus believed that planets were carried on spheres, which themselves performed circular motion around a centre.[8] In early Greek geocentric astronomy the centre coincided with the position of the Earth. But a simple homocentric model of planetary motion, according to which the planets orbit the central Earth on concentric rings, fails to match the observations. Planets move at varying speeds and distances from the central body and sometimes seem to go into retrograde motion. Retrograde motion is the apparent periodic westward deviation of planets, as seen from Earth, from their normal eastward motion. Various devices (Figure II) were introduced to cope with this difficulty. In order to improve the accuracy of his geocentric model even further, in particular with respect to retrograde motion, Ptolemy introduced a new device: the *equant* (Figure III), which was meant to explain the retrograde motion of the planets.[9] Copernicus strongly objected to the use of the equant because it violated the ideal of uniform circular motion. Although Copernicus puts the mean sun at the centre of his heliocentric model, he admits only circular motion, which forces him to apply minor epicycles to improve the 'fit' between his model and the apparent motion of the planets.

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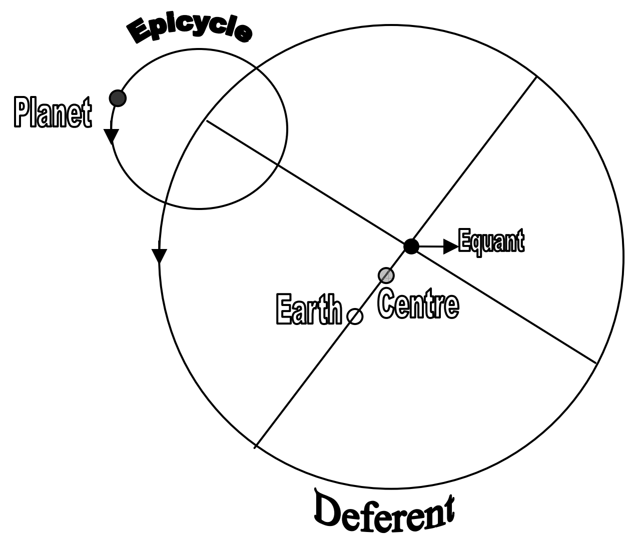
[8] See P. Barker, 'Copernicus, the Orbs, and the Equant', *Synthese* 83 (1990) 317-23; P. Barker, 'Constructing Copernicus', *Perspective on Science* 10 (2002) 208-27.

[9] See Copernicus, *Revolutions*. Bk. III, §15-6; C. Ptolemy, *Ptolemy's Almagest*. G.J. Toomer (ed.). London: Duckworth. 1984. §IX.6; [German Translation: *Des Ptolemäus Handbuch der Astronomie*. Bd. 1, 2, übersetzt von Karl Manitius. Leipzig: B. G. Teubner 1912]; H. Andersen, P. Barker and X. Chen, *The Cognitive Structure of Scientific Revolutions*. Cambridge: Cambridge UP 2006. Ch. 6.3.

Figure III: *The Equant*. Explanation of retrograde motion with a new geometric device, the equant. This representation is supposed to be a closer fit of the model to the data than the elementary homocentric model. From the point of view of the equant, the motion of the planet on the epicycle would appear uniform. Further flexibility is introduced by letting the Earth either sit at the Centre of the deferent or off-centre, as indicated in the diagram.



- Copernicus lacks dynamic concepts like inertia and gravity, which were needed to advance towards a physical explanation of planetary orbits. Copernicus possessed no modern concept of lawful physical behaviour, no notion of laws of science as quantified functional relationships between various physical parameters. The lack of these tools meant that Copernicus had to content himself with the geometry of kinematic relationships, like his Greek predecessors. When Kepler broke with the presupposition of circular motion, abandoned the idea of 'celestial spheres' and replaced geometry with mathematical analysis, which permitted him to establish the three laws of planetary motion, he went a significant step beyond the Copernican model of heliocentrism. In particular, Kepler began to think of the physical causes of planetary motion and thus introduced dynamic considerations. For these reasons, Kepler is regarded as the true revolutionary in astronomy.

- Modern defenders of the computational equivalence of the geocentric and heliocentric models could add a further argument to their case by considering the explanation of the seasons on the two models. On the geocentric view the seasons are a result of a tilt of the eccentric, ecliptic circle by 23.5º with respect to the plane of the stationary Earth. The tilt of the ecliptic circle explains the sun's variation in latitude in different locations around the globe. The explanation is more cumbersome on the Copernican model. Copernicus naturally stipulates that the Earth is tilted at the same degree with respect to the solar plane.[10] But Copernicus introduces a third motion to the Earth, which he calls the 'deflexion of the axis of the moving Earth.' This movement can be visualized as a wobble in the Earth's axis in its orbit around the sun. The third motion (in addition to the daily and annual motion) has the function of explaining the change of seasons. This 'deflexion' is necessitated by the Copernican assumption that planets are not free-moving in space but are attached to spheres, which serve as their orbital vehicles. This means that the Earth's axis shifts its orientation in the annual orbit around the sun. As Kepler gets rid of the spheres, on which the planets are carried in the Copernican model, he is able to dispense with the third motion of the Earth. The axis of inclination remains constant with respect to the plane of the orbit around the sun. The Keplerian model of free-moving planets and a constant tilt of the Earth's axis with respect to the ecliptic are sufficient to explain the seasons.

[10] Copernicus, *Revolutions* Bk. I, §2, §11.

For all these reasons it seems that scepticism against Copernicus remains justified because the Copernican model displays too many similarities with Greek predecessors. Despite these drawbacks of the Copernican model it would be mistaken to regard Copernicus's *De Revolutionibus* (1543) as little more than a reshuffle of the *Almagest*. This negative assessment remains blind to some of the Copernican innovations, which initiate a turn in 16th century astronomy.

III. The Copernican Turn.

For reasons to be discussed in this section, the Copernican achievement is best characterized as a *Copernican turn*: a change of perspective. Copernicus shifts the focus of description from a stationary Earth to a moving Earth. But he holds that this shift has more than aesthetic advantages. He considers that a description of the kinematics of planetary motion from the point of view of a planetary Earth and a central sun will result in a more *coherent* account of the solar system. For his own reasons Kant was interested in a change of perspective and correctly characterizes the Copernican model as a turn (*Wende*) rather than a revolution.

> Failing of satisfactory progress in explaining the movements of the heavenly bodies on the supposition that they all revolved around the spectator, he [Copernicus] tried whether he might not have better success if he made the spectator to revolve around the stars and the stars to remain at rest.[11]

Kant never speaks of a Copernican revolution. He characterizes the 'initial thought of Copernicus' as a hypothesis, a view which he repeats in his *Streit der Fakultäten*

[11] I. Kant, *Critique of Pure Reason* Preface to 2nd edition, BXVII.

(1798). When he speaks of 'der erste Gedanke des Kopernicus'[12] Kant seems to refer to Book I of *De Revolutionibus*, where Copernicus announces a change of perspective from a geocentric to a heliocentric viewpoint. Such a change of perspective or turn does not yet constitute a scientific revolution. This subtle distinction is frequently overlooked in Kant scholarship where Kant's 'revolution in metaphysics' is often measured against the 'Copernican revolution' whose author is Copernicus.[13]

The Copernican turn – a change of perspective – brought some noteworthy empirical and theoretical advantages to astronomy. One of the *empirical* advantages is that the Copernican model accounts naturally for the appearance of retrograde motion. Retrograde motion now becomes the effect of the different orbital velocities of the planets around the sun. Another empirical advantage is that the Copernican model assesses the *relative* distances of the planets from the sun more accurately than the Ptolemaic model. For the interior planets (Mercury and Venus) the method of determination is simpler than for the outer planets. It relies on the observed maximum angle of elongation – when the planet, the Earth and the sun form a right angle. At the time of its greatest elongation (as seen from the Earth) Venus and Mercury are at acute angles of 46° and 23° from the sun, respectively. From the observation of these elongation angles, the relative distances of the planets can be determined.[14] A further empirical advantage of the Copernican model is that for the first time the order of the

[12] Kant, *Critique* BXVI.
[13] See M. Miles, 'Kant's "Copernican Revolution"', *Kant Studien* 97 (2006) 1-32.

[14] See Kuhn, *Copernican Revolution* pp. 174-6; Copernicus, *Revolutions* Pt. I, Ch. 10; M. Zeilik, *Astronomy*. New York: John Wiley & Sons. [5]1988/[9]2002 pp. 41-2.

planetary orbits can be correctly determined from the observation of their relative distances

The determination of the order and relative distances of the planets in the heliocentric model highlights that the Copernican system has a *theoretical* advantage. Copernicus and his only disciple Rheticus emphasize that the Copernican model binds the planets into a *coherent* system. That the order and relative sizes of planetary orbits constitute a coherent system means that no arbitrary change can be made to the Copernican system. This, however, was the case in the Ptolemaic system, where the mechanics of each planet could be individually adjusted without affecting the mechanics of the other planets.

Contrary to what de Solla Price affirms[15], Copernicus was very aware of the importance of coherence; a theoretical value, which he stresses repeatedly in his book:

> And so, having laid down the movements which I attribute to the Earth farther on in the work, I finally discovered by the help of long and numerous observations that if the movements of the other wandering stars are correlated with the circular movement of the Earth, and if the movements are computed in accordance with the revolution of each planet, not only do all their phenomena follow from that but also this correlation binds together so closely the order and magnitudes of all the planets and of their spheres or orbital circles and the heavens themselves that nothing can be shifted around in any part of them without disrupting the remaining parts and the universe as a whole.[16]

[15] Solla Price, 'Contra-Copernicus' p. 199.
[16] Copernicus, *Revolutions* Preface p. 6.

> (The) Mobility of the earth binds together the order and magnitude of the orbital circles of wandering stars.[17]

Kepler also perceived this advantage very clearly:

> Ptolemy treats planets separately; Copernicus and Brahe compare the planets with one another.[18]

The conception of the coherence of planetary phenomena obliges the Copernicans to build a model of the planetary system, which must accommodate all the known empirical data. In this respect the Copernican model is partially successful. By correlating the movement of the 'wandering stars' with the 'circular movement of the Earth', not all phenomena, as Copernicus claims, but some phenomena follow. Note that in their appreciation of coherence as a scientific value, the Copernicans were surprisingly modern, since this appreciation is echoed in Einstein's work. Speaking of the general theory of relativity, Einstein wrote

> The great attraction of the theory is its logical consistency. If any deduction from it should prove untenable, it must be given up. A modification of it seems impossible without destruction of the whole.[19]

Although this theoretical advantage is acknowledged by critics, it is said to make no difference to the computational accuracy of the two systems, which remain 'formally equivalent'.[20] It is sometimes claimed that suitable modifications could have been made to the geocentric model to accommodate the empirical advantages of the Copernican

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[17] Copernicus, *Revolutions* Bk. V Introduction.
[18] Kepler, *Epitome* Bk. I, Part I, §5.
[19] A. Einstein, 'Was ist Relativitätstheorie?' (1919) in A. Einstein, *Mein Weltbild* . Frankfurt a./M.: Ullstein 1977. p. 131; Engl. Translation in A. Einstein, *Ideas and Opinions.* London: Alvin Redman. 1954. p. 232.
[20] Solla Price, 'Contra-Copernicus' p. 198.

system.[21] This implies that there exists a great latitude of theoretical choices to accommodate the available evidence (Duhem-Quine view). This latitude is possible because of the underdetermination of theories by the evidence. In the astronomical case the evidence available in 1543 could not have decided between the Ptolemaic and the Copernican models. If there is a latitude of theoretical choices – as the equipollence hypothesis seems to suggest – it seems that the computational accuracy with respect to the available data is the only relevant value. The focus on formal equivalence reveals a certain instrumentalist attitude towards scientific theories, as coherence is demoted to an aesthetic value. But we can see that coherence does real work when we consider the description of the apparent motion of the celestial sphere on the two models. Under some simplifying assumptions, the angular velocity of the spinning Earth for a heliocentric observer at the equator is $464\,{}^{m}\!/\!{}_{s} = 1670\,{}^{km}\!/\!{}_{h}$. The geocentric view, by contrast, has to assume an angular velocity of the 'fixed' stars about the stationary Earth. A calculation produces a value of $5.45\times10^{6}\,{}^{m}\!/\!{}_{s} = 1.96\times10^{7}\,{}^{km}\!/\!{}_{h}$. It is such an enormous rotational velocity of the stars – 19.6 million kilometres per hour, compared to 1670 km per hour for the earth at the equator – which the Copernicans consider implausible on mechanical grounds. When scientists like Copernicus and Einstein appeal to constraints, like coherence, they look beyond 'computational agreement with the data'. The introduction of further constraints often reveals a more 'realist' view of scientific theories. Copernicus adopts such an attitude at least in Book I of *De Revolutionibus*. The coherence of his model is a theoretical advantage, which (as the quote above reveals) has the job of bringing the model into closer agreement with the system modelled. For instance, the

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[21] See Kuhn, *Copernican Revolution* p. 224.

appearance of a 24-hour westward motion of the 'fixed' stars becomes a consequence of the eastward motion of the Earth on its own axis, just as the annual motion of the Earth naturally explains the retrograde motion on the Copernican system. We can capture these nuances by attending to different aspects, according to which models can represent aspects of the natural world.

Both the Ptolemaic and the Copernican models aim to be representations of planetary motions. But models may represent different aspects of the structure of the natural systems they intend to model. Typically, models either emphasize the *spatial* ordering of the components in the system – as for instance the spatial distribution of the planets around the sun in the solar system – or place more emphasis on the *mathematical* relationships between the parameters – as for instance in the functional dependence of one parameter on another. When the models emphasize the spatial order, they represent the *topologic structure* of the target system. When the mathematical relationship between the parameters comes to the fore, the models represent the *algebraic structure* of the system modelled.[22] In Book I of *De Revolutionibus* Copernicus clearly adopts a realist position with respect to the location of the Earth in the solar system. The spatial distribution of the planets in the heliocentric system differs drastically from the topologic structure of the geocentric model. From the topologic point of view the heliocentric model is a better representation of the solar system than the geocentric view because it fits the constraints, presented by the empirical data, much better than the geocentric

[22] For further details see R. Fürth, 'The Role of Models in Theoretical Physics', in R.S. Cohen and M. W. Wartofsky (eds.), *Boston Studies in the Philosophy of Science* V. Dordrecht: Reidel. 1969. pp. 327-40; **F**. Weinert, 'Theories, Models and Constraints', *Studies in History and Philosophy of Science* 30 (1999) 303-33; F. Weinert, 'Einstein and the Representation of Reality', *Facta Philosophica* 8 (2006) 229-52.

model. Recall that the topology of the Copernican model gives rise to the correct order of the planets and their relative distances from the sun. After Copernicus's death (1543) observations of the orbits of comets, the Jupiter moons and the phases of Venus began to shift the weight of credibility between the two rival models. The new evidence was more difficult to accommodate in the geocentric model, whilst it posed no problems of compatibility with the heliocentric model. But the Copernican model is not a major improvement over the geocentric model as far as the *algebraic* structures of these models are concerned. As we have pointed out the Copernican model still embraces the presupposition of circular motion of the spheres. As a consequence, Copernicus needs minor epicycles to account for the appearance of planetary motion. From the algebraic point of view, the Copernican system suffers both from a restriction to geometric methods to describe kinematic relations and from the 'equivalence of hypotheses'. For these reasons Copernicus's modern critics are correct to deny him the title of a 'scientific' revolutionary. But his system has some notable advantages, which are due to the superiority of his system with respect to the *topologic* structure of this model. These empirical and theoretical advantages justify the talk of a Copernican turn.

The assessment that Copernicus affected a Copernican turn, though not a scientific revolution, has implications for the question of what constitutes a scientific revolution. Reviewing the historical material is essential for assessing the appropriateness of various models of scientific revolutions which have been proposed in the literature. As it turns out the Kuhnian model does not fit the Copernican turn very well and should be replaced by an alternative model.

IV. Copernicus and Scientific Revolutions.

A number of conceptual models of scientific revolutions have been discussed in the literature, the most famous of which is Kuhn's paradigm model.[23] Very briefly, Kuhn regarded scientific revolutions as wholesale changes of paradigms (conceptual structures), which were instigated by anomalies. Between these revolutionary periods, scientists were engaged in periods of normal science, in which the ruling paradigm is not questioned. But the Copernican turn does not really fit the criteria of Kuhn's view of scientific revolutions.[24] According to the above considerations, Copernicus must be seen as continuing a period of *normal* research in astronomy since there was no notable anomaly, which threatened the geocentric view. There were no reasons to radically question the accepted paradigm. Copernicus made no new observations and did not question the presupposition of the circle. He even intended to reinstate the Greek tradition of circular motion against the Ptolemaic use of the equant. The only incompatibility between the Copernican model and the Greek paradigm concerned the topologic aspect of his model. But the instrumentalist interpretation of Osiander showed how this aspect could be minimized. It reaffirms the equipollence of hypotheses. Osiander wrote an anonymous Preface to *De Revolutionibus*, in which he presents the heliocentric view as a calculational device on the same level as the geocentric view. Both models, according to Osiander, account geometrically for the appearances, even if the heliocentric model is a more elegant representation. But neither of the models can be invested with claims to realism, since the astronomer cannot establish the 'true' causes of planetary motions.

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[23] T. S. Kuhn, *The Structure of Scientific Revolutions*. Chicago: The University of Chicago Press. [2]1970.

[24] See M. Heidelberger, 'Some Intertheoretic Relations between Ptolemean and Copernican Astronomy', in G. Gutting (ed.), *Paradigms and Revolutions*. Notre Dame/London: University of Notre Dame Press. 1980. pp. 271-83.

Kuhn also claims that at least a partial communication breakdown occurs between proponents of rival paradigms. But it cannot be maintained that a communication breakdown existed between the Copernicans and the Aristotelians, since the writings of Copernicus and Rheticus explicitly engaged with the geocentric tradition in a deliberate effort to establish that the heliocentric model has distinct advantages over the Ptolemaic model. Equally Osiander's famous Preface is a deliberate attempt, in full awareness of the explosiveness of the Copernican ideas, to pull Copernicus back into the astronomic tradition.

If only kinematic considerations come into play the equivalence of the geocentric and heliocentric views has also been affirmed as justified by the principle of relativity. It states that, from a geometric or kinematic point of view, a moving Earth is indistinguishable from a stationary Earth for the purpose of describing the phenomena.[25] But such a strictly computational point of view ignores the dynamic question of physical causes and the different aspects of the representational force of scientific models. It also ignores that scientific theories must satisfy philosophical constraints, like the value of coherence, which will affect the credibility of the models differentially. Coherence was a progressive feature of the Copernican system, which would bear fruit in the work of Kepler and Galileo.

Note that in his 1957 book Kuhn does not regard the Copernican revolution as an illustration of the paradigm model. Rather, Kuhn speaks of a 'revolution by degrees': 'the *De Revolutionibus* initiates a small innovation which presents science with new

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[25] See Solla Price, 'Contra-Copernicus' p. 203; M. Born, *Einstein's Theory of Relativity*. New York: Dover. 1962, p. 345.

problems.'[26] Kuhn does not develop these ideas. But in the context of Kuhn's work on the Copernican model they can be construed as a hint that the Copernican turn can be better explained on a 'chain-of-reasoning model' of scientific revolutions.[27] This model emphasizes traces of conceptual descent between scientific theories. It explains the conceptual continuity and discontinuity between paradigms as the result of reasoning processes and argumentative patterns. As the Kuhnian term 'paradigm' is fraught with misleading associations (communication breakdown, incommensurability, and perceptual relativism) it may be better to speak of *traditions* to designate the conceptual networks in the history of science. Such scientific traditions are still characterized by the core elements of what Kuhn came to call 'disciplinary matrices': an ordered set of elements. A matrix comprises a number of conceptual elements: symbolic generalizations, like fundamental laws; exemplary problems, on whose solutions students can practice the techniques of the discipline; scientific values, like consistency, coherence, testability, unification; and metaphysical convictions, like a belief in an ordered universe, an independent, external reality and deterministic laws. These symbolic elements act as constraints: they are restrictive conditions on models as representations of the natural world and on theories as explanatory structures. Symbolic scientific constructions must satisfy a number of constraints in order to qualify as admissible scientific statements about the natural world. (Circular motion was a powerful constraint on the admissibility of planetary models into astronomy before Kepler.) But there are key differences between

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[26] Kuhn, Copernican Revolution p. 183; cf. J. L. E. Dreyer, A History of Astronomy from Thales to Kepler. Dover. 1953. pp. 342-2.

[27] D. Shapere, 'The Structure of Scientific Revolutions' (1964), reprinted in G. Gutting (ed.), *Paradigms & Revolutions*. Notre Dame/London: University of Notre Dame Press. 1980. pp. 27-38; D. Shapere, 'Meaning and Scientific Change' (1966), reprinted in I. Hacking (ed.), *Scientific Revolutions*. Oxford: Oxford University Press. 1981. pp. 28-59; D. Shapere, 'Evolution and Continuity in Scientific Change', *Philosophy of Science* 56 (1989) 419-37; cf. H. Andersen *et al*., *Cognitive Structure*. 2006.

the Kuhnian paradigm model and the chain-of-reasoning model of scientific revolutions. Kuhn tends to discuss paradigms as worldviews to which scientists are strongly committed and which shape their perception of the external world. Scientific traditions, by contrast, may be regarded as providing tools in the hands of scientists in their attempt to solve particular problems. If the particular problem requires Newtonian mechanics, the scientist will use it with as much ease, in a given problem situation, as when it requires quantum mechanics. A further key difference is that the core elements of a tradition change *differentially*; and they change for conceptual and empirical reasons. A change in a core element does not necessarily herald the collapse of a tradition. In the 14th century the Aristotelian theory of motion came under scrutiny in the Parisian School of Nominalism; this criticism gave rise to the impetus theory of motion as a conceptual alternative. Although the impetus theory arguably served as an important stepping stone in paving the way for Copernicanism, it did not threaten the geocentric view for a long time. These differential changes in the conceptual and empirical elements are examples of *reasoned* transitions. They are reasoned transitions because they arise from problem situations, in which attempted solutions are evaluated through chains of reasons and arguments. We can trace the lines of arguments in the development of conceptual traditions and their components: of theories of *motion* and the arrangement of *planets* from geocentrism to heliocentrism. We can evaluate these operations in the chains of reasoning. Chain-of-reasoning transitions emphasize the slow transformations of conceptual networks, traditions, through the weight of arguments and evidence.

Integrating these insights we arrive at an analytic 3-stage model of the Copernican revolution as a series of successive, related, events in the problem situation of 16th and 17th century astronomy:

1. A switch of perspective in the approach to the perceived problem: as we have seen this aspect is clearly present in Copernicus's work and leads to the Copernican turn. The Copernican turn is not just a matter of taste but provides a coherent model, which brings both empirical and theoretical advantages to the description of the solar system.
2. The introduction of new observations, methods and techniques with problem-solving ability: this aspect is precisely lacking in Copernicus. He stays largely within the presuppositional structure of traditional astronomy; he relies on established Greek techniques, defends the equipollence of epicyclic and eccentric modelling and lacks any dynamic conception of planetary motion.
3. A convergence of evidence and expert opinion on to a new tradition through chain-of-reasoning transitions: this convergence took place, ranging from Copernicus to Kepler, Galileo and ultimately Newton. Central to chain-of-reasoning transitions in the 16th century astronomy is the importance of new discoveries (e.g. orbit of comets, Jupiter moons and the phases of Venus) and the development of dynamic models of planetary motion (starting with Kepler and culminating in Newton). In these transitions the credibility of the models began to shift. The new evidence and the availability of dynamic considerations bestowed more credibility on the Copernican-Newtonian model and withdrew credibility form the geocentric model.

Kuhn’s insistence that the incommensurability of paradigms does not mean their incomparability, only their untranslatability into each other has been much debated. It does not pose a problem on the present model. It is to be expected from the reasoned transitions between a geocentric and a heliocentric approach that key terms like ‘planet’ have different meaning in the two traditions and that they cannot be translated from geocentrism into heliocentrism like a foreign word is translated into English. It is to be expected from the analysis of reasoned transitions that deletions and the acquisition of new elements are likely to occur.

In terms of a chain-of-reasoning view the Copernican model still shares too many conceptual and empirical elements with the geocentric tradition to qualify as a scientific revolution. Although the Copernican heliocentric model makes some reasoned conceptual transitions (topologic centrality of the sun, coherence) they are not sufficient to establish a new tradition in astronomy. This new tradition arguably began with Kepler who introduced dynamic consideration into astronomy and new mathematical techniques. But Copernicus’s reasoned transitions are sufficient to credit him with a Copernican turn.[28]

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