Leibniz's Defence of Heliocentrism

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Keywords: Copernican Revolution, dynamics, equivalence of hypotheses, Leibniz's heliocentrism, relativity of motion

Abstract: This paper discusses Leibniz's view and defence of heliocentrism, which was one of the main achievements of the Scientific Revolution (1543-1687). As Leibniz was a defender of a strictly mechanistic worldview, it seems natural to assume that he accepted Copernican heliocentrism and its completion by figures like Kepler, Descartes and Newton without reservation. However, the fact that Leibniz speaks of the Copernican theory as a *hypothesis* (or plausible assumption) suggests that he had several reservations regarding heliocentrism. On a first approach Leibniz employed two of his most cherished principles to defend the Copernican hypothesis against the proponents of geocentrism: these were the principle of the relativity of motion and the principle of the equivalence of hypotheses. A closer analysis reveals, however, that Leibniz also appeals to dynamic causes of planetary motions, and these constitute a much stronger support for heliocentrism than his two philosophical principles alone.

1. Introduction

Like many of Newton's contemporaries – R. Boyle (1627-91); P.L. Moreau de Maupertius, (1698-1759) –, G. W. Leibniz (1646-1716) was a believer in the mechanical worldview: a clockwork universe. I. Newton (1643-1727) still believed that the clockwork universe needed occasional adjustments – corrective interferences – on the part of the 'Artificer', making God a supreme engineer. But both Boyle and Leibniz saw the need for occasional repair work as a diminution of the power of the supernatural agent. Once the clockwork was set in motion by its divine author, the universal laws took over and kept it in reliable order. Leibniz holds that nature is subject to the laws of nature:

> The natural forces of bodies are all subject to 'mechanical laws'. (Leibniz 1715-16, Fifth Paper, Section 124, 237-38)
>
> I consider it sufficient that the mechanism of the world is built with such wisdom that these wonderful things depend upon the progression of the machine itself (…). (Leibniz 1698, 499)[1]

It is therefore natural to assume that Leibniz accepted Copernican heliocentrism, and its completion by figures like J. Kepler (1571-1630), R. Descartes (1596-1650) and I. Newton, without reservation. With the discovery and mathematical formulation of his three laws of planetary motion, Kepler had placed heliocentrism on a more secure footing than Copernicus's original version. In his *Tentamen de motuum coelestium* (1689), Leibniz showed himself to be fully aware of Kepler's achievements and proposed a mechanical theory to 'explain the causes of celestial motions'. In an assessment of the Leibnizian defence of heliocentrism it is therefore important to be aware of the development of the Copernican hypothesis from its originator through Kepler and Galileo to Newton.

On a first approach it looks, however, as if Leibniz's endorsement of heliocentrism was hedged by several reservations. (Cf. Finocchiaro 2005,Chapt. 5; Meli 1988) 1) On the *scientific* level, Leibniz continues to speak of heliocentrism in the Copernican manner as a *hypothesis*, even though the term had acquired a negative connotation at the hands of figures like Kepler and Newton. 2) On the *political* level, Leibniz shared Galileo's concern that the anti-Copernican censure of the Catholic Church could do serious harm to scientific

[1]The fact that Leibniz also held that the principles of mechanics were metaphysical principles does not change his commitment to the mechanical universe, since the mechanical laws can be derived from the metaphysical principles: 'everything happens mechanically in nature but the principles of mechanics are metaphysical.' (See Leibniz 1690a, 245; Leibniz 1695, 441; Leibniz 1710-6, 399; Antognazza 2003; Garber 1995)

progress and threaten its recent achievements. 3) On the *philosophical* level, Leibniz nevertheless offered a guarded defence of heliocentrism. He declared it more 'intelligible' than its rival – Ptolemaic geocentrism. He employed two of his most cherished philosophical principles to defend heliocentrism against the proponents of geocentrism. These were the principles of the relativity of motion and of the equivalence of hypotheses. Closer analysis shows, however, that Leibniz also advanced dynamic reasons, which offered stronger support in favour of Copernicanism than his two philosophical principles alone.

The purpose of this paper is to analyse how these considerations led Leibniz to a balanced approach to this still hotly debated topic of his day. Leibniz's defence cleverly steers its way between support for heliocentrism and avoidance of its condemnation by the Censors. It will be helpful to offer the reader a brief summary of Copernicus's achievements and to describe the changes in connotation, which the term 'hypothesis' underwent during the course of the 16th and 17th centuries: from an educated conjecture for Copernicus to a 'gratuitous' fiction for Newton. These changes in connotation reflect the development of heliocentrism during the course of the 16th and 17th centuries.

2. A Summary of Heliocentrism

For readers unfamiliar with the astronomical theory of Nicholas Copernicus (1473-1543), it may be useful to remind them of some of his achievements. In a departure from a long tradition, which had its roots in Greek thought, Copernicus proposed a *heliocentric* – sun-centred – view of the universe, in opposition to the established *geocentric* – Earth-centred - view, whose chief proponents were Aristotle (354-322 BC) and Ptolemy (100-175 AD). Copernicus made the Earth a planet, which orbited the central (mean) sun. To place the sun at the centre of the then known universe was not in itself an original idea. The Greek astronomer Aristarchus of Samos (çirca 310-230 BC) had already constructed a heliocentric world system, which made the Earth rotate daily on its own axis and annually around the sun. The diurnal rotation of the Earth was proposed by several thinkers throughout the ages (Herakleides, Buridan, Oresme, Nicolas of Cusa). But no technical details of Aristarchus's system have survived so that Copernicus became the first known astronomer to construct a coherent, mathematical system of planetary motion from a heliocentric perspective. In the Greek geocentric tradition all the planets and their motions were treated separately but

Copernicus's aim was to derive all the observational data of the planets' orbits from the assumption of a moving Earth. Thus Copernicus became the first astronomer to propose a detailed account of the astronomical consequences of the Earth's motion, as part of a planetary system. (Kuhn 1957, 142-4; Weinert 2009, §3.1) It is important to observe that although Copernicus reports his own observations of the sky, these observations do not reach beyond the discoveries of his Greek predecessors. He does not discover *new* facts about the planets. It is equally important to realize that Copernicus still adheres to much of the Greek tradition in his mathematical techniques. Like his illustrious Greek predecessors, Aristotle and Ptolemy, he uses geometry to describe the motions of the then known 6 planets. Most importantly, Copernicus does not abandon the fundamental Greek idea that all celestial objects must move in circles around a central body, since the circle was considered to be the most perfect geometric figure. Perfection and harmony, to the Greek mind, characterized the heavens.

Given these few rudimentary facts about the Copernican system, especially his profound indebtedness to the Greek tradition, the obvious question, which many historians of science have asked, is whether the Copernican model constitutes a scientific revolution. The epithet 'Copernican revolution' is sometimes bestowed on the whole period from the publication of the Copernican treatise (1543) to the publication of Newton's *Principia* (1687) and sometimes on the Copernican theory itself. In the present context the question is only whether the Copernican theory itself is revolutionary, since there is little disagreement that the period from Copernicus to Newton constitutes indeed a scientific revolution. When Leibniz took up his defence of heliocentrism, he had the whole development of heliocentrism in mind. Answers to this question help to understand the whole extent of the Copernican revolution. Historical judgements on this question have therefore varied widely. The historian of science De Solla Price saw in Copernicus's book 'little more than a reshuffled version of [Ptolemy's] *Almagest*'. (De Solla Price 1962, 215) Arthur Koestler also detected little originality in Copernicus, characterizing him as a 'stuffy pedant', but also recognized in him a 'crystallizer of thought'. (Koestler 1964, 205, 113) E. Rosen found that 'Copernicus did not foment a "Copernican Revolution"' (Rosen 1984, 132-3), whilst for A. C. Crombie (1961, 168) the Copernican Revolution consisted in the link Copernicus established between the diurnal and annual revolution of the Earth and the motion of the planets. J. H.

Randall (1962, 308-15) was more willing to grant Copernicus the title of a scientific revolutionary, whilst H. Blumenberg (1955; 1965) acknowledged Copernicus above all as an intellectual reformer. Similarly, for O. Gingerich, Copernicus was a 'sensitive visionary who precipitated a scientific revolution.' (Gingerich 1993, 201)

Thomas S. Kuhn is best known for his book *The Structure of Scientific Revolutions* ([1]1962), which characterizes numerous brief episodes in the history of science, including Copernican heliocentrism, as 'revolutionary' periods. But Kuhn's most elaborate exploration of a scientific revolution is provided by the masterly analysis in his earlier book *The Copernican Revolution* (1957). In this book, Kuhn describes Copernicus as a *precursor* of a scientific revolution. His book *De Revolutionibus* (1543) is a 'revolution-making rather than a revolutionary text.' (Kuhn 1957, 183)

Kuhn's most careful investigation of a scientific revolution is to be found in his analysis of the early history of astronomy from the Greeks to Newton. In the book *The Copernican Revolution* (1957) Kuhn goes beyond the assessments of de Solla Price and Koestler and agrees with O. Gingerich that Copernicus is best described as a precursor of a scientific revolution. Unlike Rosen he sees in Copernicus's book *De Revolutionibus* (1543) a 'revolution-making rather than a revolutionary text.' (Kuhn 1957, 183) The Copernican system has aesthetic advantages, since it derives from the principle of a moving Earth a natural explanation of one of the gross planetary irregularities in Greek astronomy: the apparent retrograde (westward) motion of planets becomes a matter of the perspective of an Earth-bound observer who assesses the motion of planets around the sun against the background of the fixed stars. (Figure II) Although Copernicus abides by the Greek notion of uniform circular motion, he departs from Ptolemy by adopting a simple 'distance-period' relationship to assess the relative distances of the planets from the sun. The rule states that the further a planet is away from the sun, the longer is its orbital period. But Copernicus produced no decisive evidence, which could demonstrate that a Copernican hypothesis is more probable than a geocentric hypothesis. However, Kuhn's tone changes in *Structure*, where he states, in many passages, that the replacement of Aristotelian-Ptolemaic geocentrism by Copernican heliocentrism is a paragon of a scientific revolution. Copernicus is discussed in the same breath as Newton, Lavoisier and Einstein and is hailed as the originator of a new paradigm. (Kuhn 1970, 6, 66, 92, 116, 180, 200)

In order to appreciate the problem situation, which Leibniz faced, the question arises whether the Copernican model of 1543 was a scientific revolution or a precursor to a scientific revolution – two aspects of Kuhn's assessment of the situation. The answer to this question depends on the criteria adopted but, crucially, the criteria themselves must be adequate for a historical judgement of a particular episode, like the Copernican heliocentric model. To appreciate the reasons why the Copernican hypothesis does not amount to a scientific revolution, it will be helpful to add some further historical material regarding the Copernican model. It has already been mentioned that Copernicus's commitment to circular orbits and geometry marks a significant element of *continuity* between his work and that of his Greek predecessors. But there is also a significant element of *discontinuity*, hinted at by Crombie, which has not been sufficiently emphasized in the literature. Copernicus becomes the first astronomer to successfully treat the planets and the sun as a coherent *system*. As a cosmologist Aristotle had provided a qualitative model of the whole cosmos, consisting of two spheres. The *supralunary* sphere extended from the moon to the 'fixed' stars and was characterized by harmony, immutability, perfection and symmetry. As it was the realm of planetary orbits, the only possible trajectory for planets was the circle, since the circle was the most perfect geometric figure. The *sublunary* sphere extended from the (central) Earth to the moon and was characterized by imperfection, flux and change. As an astronomer Aristotle had proposed a concentric model of planetary motion according to which the planets were carried around the central Earth on homocentric shells, which consisted of a fifth element, called the ether. This planetary model was bound to be a failure because it could not account for the 'appearances': as the Greeks knew, planets do not keep the same distance from the 'centre' and consequently astronomers observe a change in brightness.

Ptolemy, the mathematical astronomer, accepted Aristotle's cosmological principles – especially the centrality of a stationary Earth – but, for computational reasons, treated each planet separately and in isolation from each other. Furthermore, Ptolemy introduced a number of geometric devices – in particular epicycles, eccentrics and equants (see Figures I-III) – to bring the geocentric model in closer agreement with the 'appearances' (i.e. the known observable planetary orbits).

Copernicus departs from the mathematical treatment of individual celestial objects. Instead he binds the planets into a coherent system, with the sun at the 'centre', such that the removal or displacement of one element would disrupt the entire system. Such a commitment imposes an important constraint on the model, which became a permanent feature of astronomical model-building.

> 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. (Copernicus 1543, 6)

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. They were not altogether successful but the balance of successes and failures of the Copernican system provides useful indicators as to the criteria of scientific revolutions. Given these main lines of continuity and discontinuity it may be best to characterize Copernicus's work as a Copernican *turn*: a change in perspective but not a revolution, in line with Kuhn's original 1957 verdict.

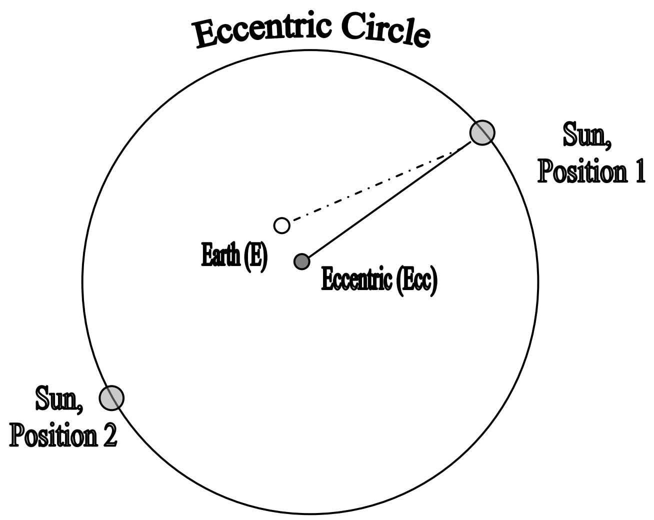
Let us briefly consider why the original Copernican position falls short of a scientific revolution and review some of the main reasons why many historians of science tend to withhold the status of a scientific revolution from the Copernican heliocentric model.

- Although Copernicus was a 'realist' regarding the physical distribution and order of the planets in the sky, he accepts the 'equipollence of hypotheses', a philosophical device which can already be found in Ptolemy's *Almagest*. It is also employed by Leibniz in his assessment of the Copernican turn. 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 epicyclic 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. Note that a planetary system, of the Ptolemaic or Copernican flavour, faces two observational anomalies, which it must explain. One is the apparent non-uniform motion of the planets around the 'centre', i.e. the known fact that the planets do not travel around the centre at a uniform speed, contrary to both the Ptolemaic and Copernican assumptions of the uniform circular motion of the planets around either the central Earth or the central sun. Ptolemy solved this problem by the employment of the eccentric circle. (Figure I)Despite his heliocentric hypothesis, Copernicus also still required small epicycles and eccentrics for his geometric constructions because he did not abandon the Greek ideal of circular motion.

The second anomaly was the apparent retrograde motion of planets, as seen from the Earth. All planets move from west to east around the 'centre' but at certain periods they seem to reverse their motion (Figure II) and appear to move temporarily from west to east, as measured against the 'fixed' stars. In the Copernican model the retrogression is satisfactorily explained through the distance-period relationship. The Earth, being closer to the sun than, say, Mars overtakes Mars in its annual journey around the sun, which creates the impression that Mars temporarily retrogrades. Leibniz cites this natural explanation as one of the advantages of the Copernican system. Ptolemy solved the problem by the device of epicyclic motion. (Figure II)

Copernicus regards the employment of both eccentric and epicyclic circles as equivalent techniques – both can be used to model planetary motion. (Copernicus 1543, Bk. III, §20, Bk. IV, §4) The Copernican indifference towards different geometric techniques shows that he is content with the Greek ideal of 'saving the appearances'. He is satisfied that these different kinds of 'motion' reproduce the appearance of planetary orbits 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.' (Copernicus1543, Bk. III, §20; cf. §15) 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'. (Kepler 1618-21, Bk. IV, Pt. II, §5)Kepler went on to investigate 'physical' causes of planetary motion – a process during which he abandoned many of the ideas still important to Copernicus.

Figure I: *EccentricMotion*. 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 positon 1 the Sun appears furthest away from the Earth (apogee), while at position 2, it appears at its closest approach to the Earth (perigee).



As we shall see the equivalence of hypotheses is one of the central pillars of Leibniz's philosophy, which he deploys in his defence of the Copernican hypothesis. But Leibniz stood in the tradition of an evolved Keplerian version of Copernicanism. Like Kepler, he also appeals to dynamic notions to argue his case in favour of the Copernican 'hypothesis'.

- 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. (See Barker 1990; 2002) The title of his book refers to the 'revolutions of heavenly spheres'. He tells his readers that

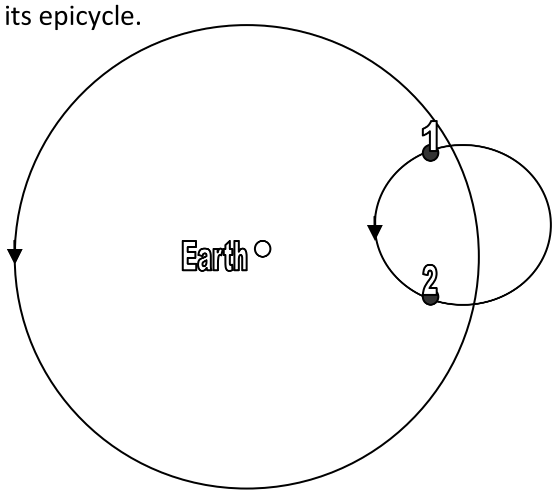
> the movement of the celestial bodies is circular. For the motion of a sphere is to turn in a circle (…). (Copernicus 1543, Book I, §4; cf. Book VI, §§1-2). [2]

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

[2] The original title of Copernicus's book was changed from *De Revolutionibus orbium mundi* to *De Revolutionibus orbium caelestium* in order to avoid the disapproval of the Church.

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 were introduced to cope with this difficulty. (Figure II) In order to improve the accuracy of his geocentric model even further, in particular with respect to

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

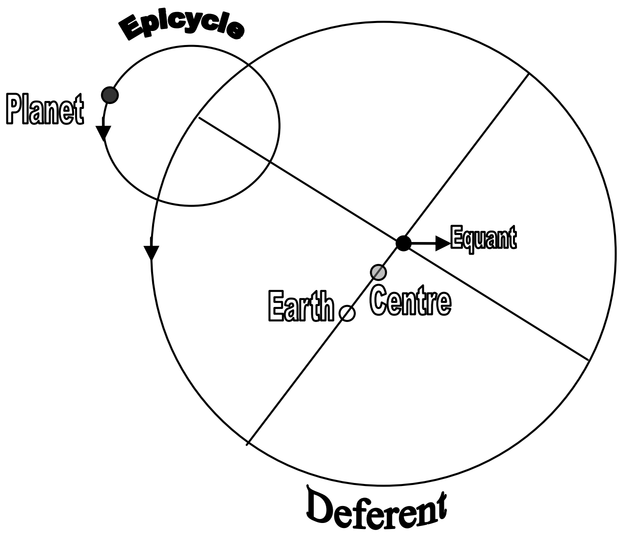


retrograde motion, Ptolemy introduced a new device: the *equant* (Figure III), which was meant to explain more precisely the retrograde motion of the planets. Copernicus strongly objected to the use of the equant because it violated the ideal of uniform circular motion. Although Copernicus puts the mean 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.

- 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. Leibniz, too, stood in the Keplerian tradition since he invented, independently of Newton, the differential calculus and proposed a vortex theory (1689) to account for the Keplerian non-circular orbits of the planets.

- 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 ismore cumbersome on the Copernican model. Copernicus naturally stipulates that the Earth is tilted at the same degree with respect to the solar plane. [Copernicus 1543, Bk. I, §2, §11] But Copernicus introduces a third

Figure III: *The Equant*. Explanation of retrograde motion with a new geometric device, the equant. (See Copernicus 1543, Bk. III, §15-6; Ptolemy 1984, §IX.6; Andersen/Barker/Chen 2006, Ch. 6.3) 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.



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 abandons 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.

Leibniz was aware of the developments in astronomy from the original Copernican to the later Keplerian, Cartesian and Newtonian versions of the theory. Leibniz was equally aware of the philosophical discussions surrounding the epistemological status of the heliocentric 'hypothesis': was it to be understood as a mere calculating device, in the instrumentalist fashion, or as a realist claim about the planetary system? Leibniz did not follow Kepler and Copernicus's only 'pupil' Rheticus in embracing a realist reading of the Copernican hypothesis. He not simply ignores the instrumentalist reading, which as reflected in Leibniz's writings, was still a viable option in his own time. As we shall see, the principle of the equivalence of hypotheses does not offer sufficient ground to declare the heliocentric hypothesis the clear winner in the dispute with the geocentric hypothesis. A realist or instrumentalist reading of the Copernican model depended on an understanding of the notion of 'hypothesis' in the 16th and 17th century. In order to explain Leibniz's defence of the Copernican model, we need to understand the career of the notion of 'hypothesis' and its changing connotation during the crucial period from 1543-1687, a period which is nowadays dubbed the 'Scientific Revolution'.

3. On Hypotheses

Newton is famous for his statement: 'Hypotheses non fingo.' This Latin phrase can be rendered alternatively as 'I do not feign hypotheses'; 'I do not make use of fictions'; 'I do not use false propositions or premises or explanations.'[3] Historians of science have identified several senses in which Newton uses the word 'hypothesis.' Sometimes he meant a plausible though not provable conception. In his later years he came to regard a hypothesis as a gratuitous fiction. (Koyré 1965, 36-7)

That which cannot be derived from phenomena is called a hypothesis and these do not belong to experimental philosophy. (Quoted in Dijksterhuis 1956, 537; Burtt 1924, 215-20)

Newton was not the first scientist to worry about the term 'hypothesis'; the worry reaches back to the Greeks. The concern is about whether the geometric constructions, with which the Greeks attempted to explain the appearances, i.e. the observable behaviour of the planets, including the retrograde and non-uniform motion around the centre, have to be regarded as fiction or reality. This uncertainty about astronomical hypotheses is reflected in the attitudes of Aristotle and Ptolemy. Aristotle adopted a much more realist attitude than Ptolemy since he considered that his homocentric spheres, which carried the planets around their circular orbits, actually existed in nature. But his homocentric model cannot be correct because it fails to account for the 'appearances' – the variation in brightness of the planets and their temporary retrogression. In order to account for the observations, Ptolemy introduced his geometric devices (epicycles, eccentrics, equants, which made sense of the observations) but at the price of abandoning Aristotelian realism. Ptolemy adopted an instrumentalist attitude towards his geometric devices as useful fictions, which made sense of the observations, but he did not expect his geometric models to properly represent the celestial phenomena. (Ptolemy 1948, 600-1)

The contrast between instrumentalism (or fictionalism) and realism shaped the discussion of astronomers well beyond the death of Copernicus in 1543. (Cf. Donahue 1975; Westman 1975a)Duhem (1908: Chapt. 4) holds the view that this contrast – and the desire to overcome it – lay at the root of Copernicus's reform of astronomy. (An alternative, more technical reason, is that Copernicus was disturbed by Ptolemy's equant and wished to return to truly circular motion. Cf. Wilson 1975)Copernicus and his pupil Rheticus had corresponded about the usefulness of hypotheses in astronomy with the Lutheran theologian Andreas Osiander (1498-1552), who also adopted an instrumentalist

[3]Koyré (1965), 35; Dijksterhuis (1956), 541; Crombie distinguishes 3 senses of 'hypotheses': improvised propositions, heuristic aids, illegitimate fictions; Crombie (1994), Vol. II, 1071

interpretation of the Copernican hypothesis in order to protect his book from a 'realist' misinterpretation at the hand of a hostile clergy. (Cf. Wrightsman 1975) Copernicus and his pupil considered that certain astronomical hypotheses were more probable than others. More probability accrued to the heliocentric hypothesis than to the geocentric hypothesis, in view of the observations. Acceptable hypotheses in astronomy had to explain all the observable phenomena. They had to explain the phenomena in a coherent way. The Ptolemaic hypothesis, says Rheticus, does not suffice to establish the harmony of celestial phenomena. (Rheticus 1540, 132; see also Correspondence reprinted in Rosen 1959, 31-2; 1984, 125-6, 193-4, 198-205) Kepler later agreed that the Copernican hypothesis enjoyed more probability than the Ptolemaic hypothesis. The notion of hypothesis had great repercussions throughout the next 140 years. The ambiguity of the term as reflected in Newton's views on hypotheses in science, invited opposing interpretations of the Copernican model. In his *Dialogue Concerning The Two Chief World Systems* (1632), Galileo epitomizes the ambivalent status of hypotheses in the 16th and 17th century. The Preface states that his spokesman, Salviati, will defend the Copernican system but only as a purely mathematical hypothesis. But as the dialogue unfolds, Salviati is drawn towards probability arguments. Eventually he adopts the Copernican position that the acceptance of the dual motion of the Earth as a physical assumption leads to a more coherent explanation of the appearances. Note that these probability arguments invoke belief in a model, because its physical assumptions are more probable. It is not believable, says Kepler, that the 'fixed stars move at incalculable speed', whilst the Earth stands still. It is more probable that the apparent daily rotation of the fixed stars is an effect of the rotating Earth.[4] (Kepler 1618-21, Pt. II, §5) The Copernican hypotheses are more like conjectures than useful fictions. They

[4] Kepler's probability argument states that we should attach more plausibility to the heliocentric view because the evidence - the apparent motion of the 'fixed' stars in a 24-hour-rhythm about the earth – is more probable on the view that the earth rotates on its own axis. These probability arguments can be supported by a consideration of the angular velocities involved under the two scenarios. Under some simplifying assumptions, the angular velocity of the rotating earth for an 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 $5.45 \times 10^{6} \, {}^{m}\!/_{s} = 1.96 \times 10^{7} \, {}^{km}\!/_{h}$. 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. By comparison, the orbital velocity of the earth around the sun is 30km/s and the velocity of the sun around the galactic centre is 225km/s. The evidence – the apparent rotation of the sphere of fixed stars – is more likely on account of heliocentrism than on account of geocentrism. (See Weinert 2010)

have a much closer association with the phenomena than Newton would later accept. They form, as Rheticus tells us, the basis of inferences.

By contrast, labelling hypotheses as 'useful fictions' in astronomy had, according to Osiander, certain advantages. It reassured Copernicus's adversaries that his heliocentric model did not force them to abandon their cherished geocentric beliefs. Cardinal Bellarmine reminded Galileo that Copernicus had always spoken *hypothetically*: it is possible to use the motion of the Earth as a mathematical device to render the calculations more economic, since fewer epicycles and eccentrics are needed. However to affirm the centrality of the sun as a physical hypothesis is in conflict with the Scriptures.[5]

In order to avoida clash between the Church and heliocentrism, Osiander inserts his Preface in an attempt to present the Copernican hypotheses as mere calculating devices. They have the license to be false or replaceable as long as 'they reproduce exactly the phenomena of the motions.' (Osiander1541) By the time Newton appeared on the scene, and in the wake of Kepler's work, hypotheses had lost their appeal. Newton declared that the laws of motion are deduced from Phenomena and made general by Induction, and this is the highest evidence that a proposition can have in Philosophy. (Koyré 1965, 36-7; Dijksterhuis 1956, 544, 546-7) Phenomena are (reliable) observational or experimental data, from which are derived laws or axioms. Newton rejects any explanation of natural phenomena, which appeals to 'metaphysical' hypotheses, for which no evidence can be cited. It was against this historical backdrop that Leibniz took up his defence in support of heliocentrism (1689).

Copernicus still used the term 'hypothesis' quite freely in his *De Revolutionibus*. The Greeks, he says, reserved the term 'hypothesis' for 'principles and assumptions.' Throughout his work Copernicus calls the motion of the Earth a 'hypothesis'. He does not mean it in Newton's pejorative sense. Copernicus is a realist about the motion of the Earth and the spatial distribution of the planets around the sun. But Copernicus is not a realist about the geometric devices, which he and his Greek predecessors employed to 'save the phenomena'. As mentioned above, Copernicus accepts the 'equipollence of hypotheses', as had his Greek predecessors. Thus he declares that the apparent irregular motion of the

[5] See Koestler (1959), 454; similar statements, reflecting Osiander's instrumentalist attitude, are found in Kuhn (1957), 191, 194; Crombie (1994), Vol. I, 599-600

planets can either be accounted for by the use of an eccentric circle, i.e. one whose 'centre is not the centre of the sun' or through an epicycle on a homocentric circle' (a deferent). (Copernicus 1543: 151) 'Accordingly, it is not easy to determine which of them exists in the heavens.' (Copernicus 1543: 154) By contrast Kepler aims to practice astronomy without the use of 'hypotheses', since he is interested in the physical causes of planetary motion.

> It can easily do without the useless furniture of fictitious circles and spheres. But there is such a great need of imagining the true figures, in which the routes of the planets are arranged, that we are impoverishing Astronomy and that the big job to be worked on by the true astronomer is to demonstrate from observations what figures the planetary orbits possess; and to devise such hypotheses, or physical principles, as can be used to demonstrate the figures which are in accord with the deductions made from observations. (Kepler 1618-21: 124)

Kepler goes beyond Copernicus by moving from kinematics to dynamics. This distinction between a kinematic description and a dynamic explanation of planetary motion becomes important in the defence of Copernicanism. When Leibniz took up this challenge, he employed two of his most fundamental principles – the relativity of motion and the equivalence of hypotheses. Strictly speaking these two principles will not deliver a decisive defence of Copernicanism since by the verdict of these two principles astronomical phenomena could be explained equivalently by the geocentric or the heliocentric hypothesis. As indicated above, the seasons can either be explained by the assumption that the path of the sun around the central Earth is inclined by 23.5° with respect to the plane of the Earth or by the assumption of an orbiting Earth whose axis of rotation is inclined by the same angle with respect to the stars. In the face of the equivalence of hypotheses Leibniz appeals to other criteria - like simplicity, intelligibility, probability - to argue in favour of an elimination of geocentrism. Above all, however, it is his attempt at a dynamic explanation of Keplerian elliptical orbits, which renders his case in favour of the Copernican hypothesis much more solid than a mere reliance on his kinematic principles.[6]

IV. Leibniz's Defence of Heliocentrism

[6] It is interesting to note that this ambivalent attitude towards hypothesis survived the consolidation of Newtonian heliocentrism. L. Boltzmann (1844-1906), for instance, calls hypotheses 'arbitrary pictures' (Boltzmann 1974, 161), whilst E. Mach (1838-1916) regards hypotheses as thought constructs, which aid the economy of thought. (Mach 1883: 468) Duhem himself concludes his survey of astronomy (1908) with a general plea for instrumentalism in science.

Galileo introduced into physics the principle of the relativity of motion. According to the principle of relativity, the kinetic motion of an object can be described from either a stationary or a moving reference frame. As long as the motion is inertial (either at rest or moving at constant velocity) both views are equivalent. They must lead to the same numerical results. It is a matter of choice, which system we regard as the frame at rest and the frame in motion, respectively. This makes no difference to the physics of the situation. Galileo offers a famous thought experiment to demonstrate the equivalence of inertial systems. In a cabin below the deck of a large ship observe the behaviour of 'flies', other 'small winged creatures' and 'fish in a bowl'. At first the ship is at rest. When the first set of observations is completed, let the ship proceed with uniform speed. The observations will reveal no difference in the behaviour of the creatures. (Galileo 1953, 199-201)

Leibniz was obviously aware of the Galilean relativity principle, since he employs a Galilean-type thought experiment against absolute motion. The principles of the relativity of motion and the equivalence of hypotheses are closely related. In fact, the (Galilean) relativity of motion implies the equivalence of hypotheses, as Leibniz observed in his *Specimen Dynamicum* (1695, 445; italics in original):

Therefore we must hold that if any number of bodies are in motion, we cannot determine from the phenomena which of them are in absolute determinate motion or rest; rest can be attributed to any one of them you may choose, and yet the same phenomena will be produced. It follows therefore (Descartes did not notice this) that the equivalence of hypotheses is not changed by the impact of bodies upon each other and that such rules of motion must be set up that the relative nature of motion is saved (…).

Leibniz applies this reasoning to Copernicus. But it raises the question whether one of the hypotheses may be said to be more probable than its rival. Leibniz deploys the criterion of simplicity:

That is to say, if the given phenomena appear the same, whatever may be the true hypothesis or however we may ascribe motion or rest to them, the same result will be produced in the unknown or the resulting phenomena, even with respect to the action of bodies upon each other. This conforms to our experience; we feel the same pain whether our hand strikes a stone which is at rest (…) or the stones strikes our hand at rest with the same velocity. Meanwhile we speak as the situation demands, in whatever way provides the more fitting and simpler explanation of the phenomena, just as we make use of the motion of a primum mobile in the study of spheres and must use the Copernican hypothesis in planetary theory. (Leibniz 1695, 445-6; italics in original)

Nevertheless, from the point of view of (Galilean) relativity it makes no difference whether we adopt a geocentric or a heliocentric view.[7] (Solla Price 1962, 198; Rosen 1984, 183-4) We can follow Ptolemy: regard the Earth as a stationary frame and the sun as a moving frame. Or we can follow Copernicus: regard the Earth as a moving frame and the sun as a stationary frame. According to the principle of relativity our choice makes no difference to the physics of the situation. As Leibniz says, so it appears to be. The Earth turns on its own axis once in a 24-hour rhythm to give us day and night. If the sun turned around the stationary Earth once in a 24-hour rhythm it would give us day and night. The seasons result from either a tilted plane of the sun around the Earth or a tilted orbit of the Earth around the sun. However there is more to a description of the solar system than mere kinematics. From a strictly kinematic point of view, the models are equivalent. The kinematic point of view is only concerned with pure motion, without regard to its causes. (Dijksterhuis 1956, I, §83; IV, §18, IV, C) This is the Ptolemaic and Copernican perspective. But there is also the question of dynamics: What causes the planetary bodies to move? Consider a slightly amended version of Leibniz's example: the encounter of a hand with a wall. Whether we regard the hand or the wall as being at rest, we experience the same pain. Physics informs us that both can be regarded as reference frame either at rest or in motion. The kinematics will be the same. But experience also tells us that the hand is more likely to move than the wall. The dynamic situation is no longer equivalent. The body causes the hand to move. The wall has no cause of motion. Kepler was preoccupied with the question of physical causes. He suspected that energetic rays from the sun drove the Earth around its elliptical orbit. When a planet shows its 'friendly face' to the sun, its magnetic lines attract it. When a planet shows its 'unfriendly face' to the sun, its magnetic lines repulse it. The game of attraction and repulsion constrains the planet to its orbital motion around the sun. (Kepler 1618-21, Pt. II, §93) As Newton later showed, this dynamic explanation was mistaken. Nevertheless, Kepler advanced dynamic arguments in favour of the orbital motion of the Earth. Once Newton showed why the planets stay in their elliptical orbits around the sun, the heliocentric model gave a better representation of physical reality than the geocentric

[7] Galilean relativity only applies to inertial motion. Einstein's general principle of relativity applies to both inertial and non-inertial motion. In General relativity it is possible to distinguish inertial from accelerated motion by observing the geometry of world-lines. (Thanks to an anonymous referee who suggested a clarification on this point.)

model. Newton improved the mathematical structure of the model. He provided a dynamic explanation of planetary orbits in a heliocentric model.

It seems at first that the central message of his essay 'On Copernicanism and the Relativity of Motion' (1689) is the equivalence of hypotheses. Leibniz affirms once again that 'motion is not something absolute, but consists in a relation.' (Leibniz 1689a, 91) Hence

an astronomer makes no greater mistake by explaining the theory of the planets in accordance with the Tychonic hypothesis than he would make by using the Copernican hypothesis in teaching spherical astronomy and explaining day and night, thereby burdening the student with unnecessary difficulties. (Leibniz 1689a,91)

Adopting a criterion of simplicity, the Copernican account is the 'truest theory', that is, the most intelligible one, since it avoids the 'perplexities' (like retrograde motion) with which other theories are burdened. In a letter of 1688, Leibniz calls the Copernican hypothesis 'confirmed by (…) many arguments drawn from new discoveries. (Quoted in Meli 1988, 21)

The truth of a hypothesis is nothing but its intelligibility. (Leibniz 1689a, 91; cf. Lodge 2003)

For if the truth of a hypothesis lies in its intelligibility and the Copernican hypothesis has 'greater intelligibility' than the geocentric hypothesis,

(…) there would be no more distinction between those who prefer the Copernican system as the hypothesis more in agreement with the intellect, and those who defend it as the truth. For the nature of the matter is that the two claims are identical; nor should one look for a greater or a different truth here. And since it is permissible to present the Copernican system as the simpler hypothesis, it would also be permissible to teach it as the truth in this particular sense. (Leibniz 1689a,92)

On this understanding astronomers need not hold back 'by the fear of censure.' By adopting this approach, Leibniz hopes to 'free Rome and Italy from the slander that great and beautiful truths are there suppressed.' (Leibniz 1689a,93) But is Leibniz not adopting Osiander's instrumentalist attitude? After all, Ptolemy already believed that his theory of eccentrics, epicycles and equants provided the simplest devices to account for the phenomena, without believing in their reality. Yet Ptolemy added that the hypotheses should only be as simple as to allow them to save the phenomena as accurately as possible. (Duhem 1908: Chapt. 3) Osiander, too, recommends the Copernican hypothesis for its simplicity and greater intelligibility, without admitting any correspondence to reality.

A closer reading, however, reveals that Leibniz goes well beyond Ptolemy's and Osiander's instrumentalism. In his *Specimen Dynamicum* (1689) Leibniz concludes his remarks on Copernicanism with an observation, which will allow him to express a preference for one of the competing hypotheses, not offered by the relativity of motion and the principle of simplicity.

But whenever the equipollence of hypotheses is involved, every factor contributing to the phenomena must be included. (Leibniz 1695,450)

Equally, 'truth is found not so much in phenomena as in their causes.' (Leibniz 1695: 446) As we shall see now these additional factors are the dynamics of planetary motions. The equivalence of hypotheses shows that all hypotheses are equally possible but dynamics demonstrates that not all hypotheses are equally probable. Thus, it is more probable that the appearance of certain celestial motions, like the 24-hour rotation of the fixed stars is the result of the Earth's motion on its own axis.

The criteria of intelligibility and simplicity cannot be decisive in moving from an instrumentalist to a realist position, for Leibniz concedes that 'the Ptolemaic account is the truest one in spherical astronomy.' The simplest hypothesis is not necessarily the true one – contrary to what Leibniz writes to Huygens in September 1694 (Leibniz 1690b,308) – for Ptolemy also appealed to the criterion of simplicity, whilst adopting an instrumentalist position regarding his geometric devices. There must be other reasons to prefer the Copernican hypothesis. Leibniz writes to Huygens in June 1694 that 'other than extension and its variations, which are purely geometric things, we must acknowledge something higher, namely force.' (Leibniz 1690b, 308) In other words, there are additional criteria to judge astronomical hypotheses, in particular dynamical reasons.

Although Leibniz was aware of Newton's theory of gravitation, he was dissatisfied with Newton's account and attempted his own mechanical explanation of planetary motions by way of a vortex theory. He hints at it in his paper on Copernicanism (1689): Kepler's laws, he claims, can be given a physical explanation 'by means of a vortex around the sun.' (Leibniz 1689a,93) He divides planetary trajectories into two components: a) harmonic circulation and b) paracentric motion.

And thus we may consider a planet to be moved by a two-fold motion, or composed from the harmonic circulation of the orbit of its carrying fluid, and from a paracentric motion, as if of a certain weight or an attraction, that is an impulse towards the sun, or the primary planet.

(…) the paracentric motion of the planets is required to be explained, arising from the force of the circulation on a planet being made to change orbit, and composed from the attraction between itself and the sun. (Leibniz 1689b, §§8-9)

The sun is compared to a magnet, as in Kepler's dynamical explanations, but in order to account for the stability of the elliptical orbits, in agreement with Kepler's laws, Leibniz stipulates that paracentric motion consists of an attracting and a receding part, with respect to the sun. (Leibniz 1689b, §27) During its harmonic circulation the planet at first falls towards the sun and is then repelled by the magnetic force. With his attempted solution Leibniz stands more in the tradition of Kepler and Descartes than in the footsteps of Newton, whose solution appeared at the same time. But it is clear that Leibniz is at pains to formulate his causal theory of planetary motion in such a way that it is in accordance with Kepler's laws. (Leibniz 1690b,309-11; Leibniz 1689b) By contrast both Galileo and Descartes ignored Kepler's laws. (See Schmaltz 2015)

By accepting Kepler's laws of planetary motion, Leibniz accepts the Copernican system as a reality, since Kepler's laws take the sun as a focal point of planetary orbits. He also dispenses with epicycles and eccentrics, in line with Kepler's stipulation. The relativity of motion only applies to kinematics, proved through geometrical demonstrations' (Leibniz 1689a, 92) But Kepler's laws require a physical explanation. Whilst Leibniz attempts such a dynamic explanation in terms of Cartesian vortex theory, the Newtonian way is to derive these laws from the laws of motion. Leibniz's vortex theory suffered the same fate as its Cartesian cousin. Irrespective of the inadequacy of the vortex theory, from the dynamical point of view Leibniz's defence of the Copernican hypothesis looks considerably stronger than Osiander's instrumentalist approach. For the equivalence of hypotheses does not bestow a greater degree of credibility on the rival hypothesis; and the simplicity of a hypothesis is relative to background knowledge. In theory, Aristotle's homocentric circles are simpler than Ptolemy's geometric devices but not in view of the observable appearance of planetary motion.

Dynamic causes, however, allow a much stronger defence of the Copernican hypothesis, since they can be coupled with probability considerations. Some causes are more probable than others: the hand is more likely to move than the wall. Leibniz even claims that the 'magnetic properties', which planets like the Earth, Jupiter and Saturn 'exert' on their respective moons, as well as the natural explanation of retrograde motion, constitute confirmation of the Copernican view. (Leibniz 1689a, 93) He could have derived even stronger evidence from Galileo's observations of the phases of Venus or the bounded elongation of inferior planets.

5. Conclusion

It looks at first as if Leibniz offered only a guarded defence of the Copernican hypothesis: **a**) the relativity of motion and the equivalence of hypotheses do not allow him a stronger stance; **b**) he wants to protect the reputation of the Catholic Church, which would only allow an instrumentalist interpretation (as expressed by Osiander and Bellarmine); **c**) nevertheless, the Copernican hypothesis can be regarded as more intelligible than the Ptolemaic one.

The greater intelligibility of the Copernican hypothesis is revealed, despite the equivalence of hypotheses, by its greater simplicity. It should be added that it is only simpler than Ptolemy in its Keplerian form for it dispenses with Copernican epicycles and spheres. It is the Keplerian version of heliocentrism, which Leibniz defends. It is also revealed by the dynamic reasons – the vortex theory – at which Leibniz hints in his paper on Copernicanism and which he spells out in greater detail in his letter to Huygens (1690) and his *Tentamen* (1689). Although the vortex explanation does not succeed, it reveals that Leibniz was eager to provide a causal theory which respected Kepler's laws. The sun does not exert a magnetic attraction on the planet but a gravitational force. What matters, however, is that Leibniz goes beyond kinematics towards dynamics. It is the dynamic reasons, which ultimately provide the best defence of heliocentrism.

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