Underdeterminism and the three systems

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This essay will be written in the style and form of a legal brief, one which might have been presented to the Church in its deliberations against Galileo for promoting and publishing works on the Copernican-Keplerian system. Thus, this brief will contain and present evidence regarding the three opinions on the world system, i.e. the Ptolemaic, the Copernican and Copernican-Keplerian, and the Tychonic system. The brief will also discuss the role of evidence as an arbitrator within astronomy. All information stated is based on what was accessible at the time, i.e. 1633. By the end, the court will have the necessary information to consider which system is more compelling, whether the charges brought against Galileo are reasonable, and deliberate on what counts as scientific fact by 1633's standards.

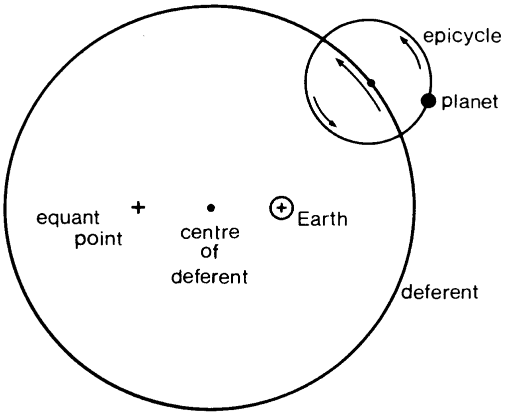
To begin, I will outline two key concepts within astronomy: the celestial sphere, and the two inequalities. From the reference frame of the Earth, the Earth seems stationary, and there appears to be a celestial sphere—a distant sphere where each star is fixed onto the inner surface, thus in motion yet fixed, relative to each other (Kuhn, 1995). The Sun traces a path across the sky, known as the ecliptic. The ecliptic is divided into twelve parts, with each part corresponding to a zodiac. Additionally, planets seem to be detached and independent of this celestial sphere, as they have their orbits and movements, moving eastward along the sign of the zodiac. However, the planets retrograde—at certain points in their orbits, they slow down, move westwards, come to a stop, and proceed eastwards, forming a loop in the sky. This retrograde motion is dubbed as the second inequality. The first inequality is the planets and the Sun's non-uniform angular velocity in the sky. For example, Mars is 40% faster in

Capricorn than in Cancer—Mars varies in speed as it travels in its orbit. These inequalities are significant, as a simplistic account of astronomy purely in terms of uniform circular motion will not explain these phenomena.

What are the key features of the Ptolemaic system? The Ptolemaic system was first put forth by Ptolemy in his *Almagest* (1998), which was first published in ca. 160 A.D., and was refined across the centuries. The system is geocentric, i.e. it states the Earth is stationary and is at the centre of the universe. There are several key features of the Ptolemaic system: it states that deferents, epicycles, points of eccentricities and equants exist. A planet traces a path called the epicycle, whose centre traces a path called the deferent. The deferent is similar to a traditional circular orbit. However, the Sun is not at the centre of the deferent; the centre is not occupied by anything. Instead, the centre of the deferent lies in between two points, the equant, which was never named the "equant" by Ptolemy, and the point of eccentricity, where the Sun lies. This description is contained in Figure 1. Ptolemy noted that if the Sun were at the centre of the deferent, his system would not account for the observation motion of the planets (recall the two inequalities). Conceptually, he believed that only through the compounded effects of these key features would account for the two inequalities, while maintaining his commitments, i.e. the Earth is stationary, &c.

Figure 1

An example of an equant, deferent and epicycle describing the motion of a planet



Note. Taken from Western University (n.d.). *Ptolemy's explanation of planetary motion through deferents, epicycles, and equants*. https://physics.uwo.ca/~jlandstr/planets/webfigs/survey/slide15.html

It is worth noting that by 1633, the Ptolemaic system had procedures which allowed astronomers to calculate the locations of the planets, within a margin of error of two to four degrees (Voelkel & Gingerich, 2001). This is significant as longitudes are used throughout all three world systems considered within this brief; it gives us a basis for comparison between systems, allowing one to consider the accuracy of a model, something one should account for if one judges the scientific status of a system. Furthermore, Ptolemaic supporters, in response to Tycho Brahe's aim of astronomy in reducing a model's error to within observational accuracy, argue that their system is "perfectable" (Ptolemy, 1998); one would only need to refine the parameters and variables of the Ptolemaic system to be within observational accuracy, i.e. be a model worthy of consideration and scientific status.

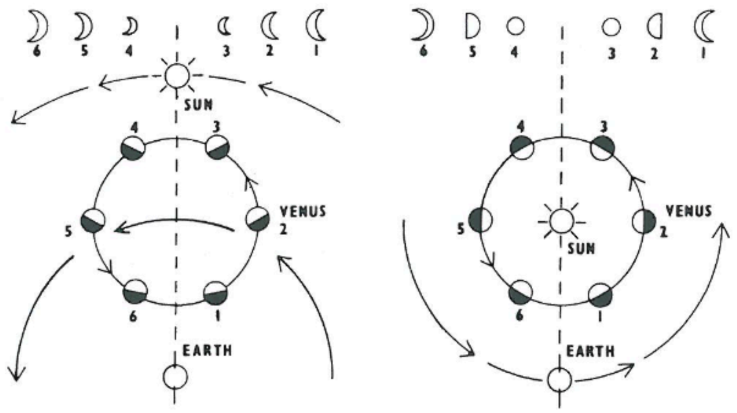
What are the key features of the Copernican system? The Copernican system debuted in Copernicus' *De Revolutionibus* (Copernicus, 1543; Kuhn, 1995). It has a different approach to account for the two inequalities. It states that the second inequality arises from the compound motion of the differing speeds of the planets (including the motion of the Earth), and how the planets are arranged. For example, the system states that Mars' orbit period is longer than the Earth's, thus when the two planets pass each other, Mars' apparent motion is in retrograde, in Earth's reference frame. Regarding the first inequality, Copernian used epicycles and deferents to account for why planets speed up and slow down at certain parts of their orbits (in the reference frame of the Earth). The planet's motion on the epicycle accounts for the speeding up and slowing down, while the deferent is the path taken around the Sun. Copernicus also believed that the sizes of planetary orbits are fixed, relative to each other. This is a consequence of heliocentrism, and in direct contrast to Ptolemy's system, although it does not provide a basis for comparison between systems, and thus does nothing regarding the problem of underdetermination. Another significant but subtle feature is how each fixed parameter imposes certain constraints or relationships. For example, fixing the relative orbits of each planet constrains the arrangements of the planets. If the consequences of certain constraints are logical, it seems that there is an underlying structure to the system, which would not be there if the system was arbitrary or irreflective of reality. This feature's significance is explored briefly in *Underdetermination and decomposition in Kepler's Astronomia Nova* (Mikaye, 2015), which will be discussed momentarily.

Kepler noted that all three systems were worthy of consideration as all three, in principle, matched observations, despite the vast differences in the arrangements of the planets in each system. He says this because "so far as astronomy, or the celestial appearances, are concerned, the three opinions are for practical purposes equivalent to a hair's breadth, and produce the same results." (Kepler, 1992). Kepler noted the dilemma in considering all three systems: there was a problem of underdetermination. Galileo et al. were unable to say for certain which system was true because they lacked access to sufficient information. Galileo had evidence which led to his opinion, but it was insufficient in determining which system is true. This underdetermination arises from the fact that we are constrained to the reference frame of the Earth. All our observations are "two-dimensional motions [...] of the actual three-dimensional motions of the planets." (Miyake, 2015). This is problematic for several reasons, as we will encounter non-unique solutions, i.e. competing world systems. Furthermore, when we want to decompose compound motions and attribute them to something meaningful, we would need to isolate "signatures", which requires fundamental knowledge of the inquired phenomena (Miyake, 2015); such a task is incredibly difficult. One would need to know how to properly decompose compound motion and then accurately attribute it to some physical cause.

Why did Galileo favour the Copernican-Keplerian system? The Copernican-Keplerian system was outlined in *Astronomia Nova* (1609; Kepler, 1992), which is a modified version of the Copernican system, where instead of Copernicus' nearly-circular orbits, the planetary orbits are elliptical, and governed by Kepler's three laws of motion. The use of ellipses is significant as it reduces the need for epicycles and deferents, while barely displacing the status of equants. Kepler's three laws did little to the status of the Copernican-Keplerian system, as the problem of underdetermination still stood. Galileo viewed the system favourably for several reasons, chief among them: the phases of Venus. Relevant to planetary motions, Galileo noted that the phases of Venus differed between the two systems (Ptolemaic and Copernican), as seen in Figure 2. When he made his observations of Venus, he saw the one described by the Copernican-Keplerian system, clearly distinct from the Ptolemaic description. Furthermore, Galileo could have argued the Ptolemaic system was somewhat arbitrary as it did not have the same astronomical structure as the Copernican-Keplerian system (i.e. constraints leading to meaningful consequences), thus being unique in a sense. Galileo might have also believed that the telescope was a viable means of ending the problem of underdetermination because he had made several significant discoveries because of it, e.g. the observation of the Moon's craters. Despite Galileo's belief, the Copernican-Keplerian system is not without its weaknesses.

Figure 2

The phases of Venus



The appearance of Venus predicted by the
Ptolemaic and Copernican systems

Note. Left: Ptolemaic, right: Copernican-Keplerian. Taken from *Letters on Sunspots*, translation published in *Discoveries and Opinions of Galileo (1957)*.

What are the key features of the Tychonic system? The Tychonic system was outlined by Tycho Brahe in *Of More Recent Phenomena of the Ethereal World* (1588; Thoren, n.d., p. 8; Schofield, n.d., p. 41), a geoheliocentric model where five planets orbit the Sun, with Venus and Mercury moving in opposite directions from the others, while the Sun and Moon orbit the Earth (which is stationary). A key feature of the Tychonic system is its minor and major epicycles; in accounting for the motion of the Sun, Brahe stated the Sun has both a minor and major epicycle, which contested the role of the Sun's equant proposed by other systems. The compound motion of these epicycles yielded the same observations and results, hence the underdetermination problem. As stated earlier, Brahe shifted the astronomical aim to observational accuracy, i.e. matching models with observations. Brahe had extensive data because of his cutting-edge instruments and methodologies (which led to the Rudolphine tables). Brahe corrected for parallax error and atmospheric refraction. He successfully corrected for parallax only for observations above 45 degrees, while anything under was overcorrected. He was also suspicious of past data, seeing each as a possibility for further complexities of unknown or underdetermined phenomena, or simply instances of human error. Furthermore, Brahe proposed a distinguishing test between the Tychonic and Copernican systems: the annual parallax of the stars. Brahe's observations whose instruments were accurate to within one to two arcminutes, observed no parallax, suggesting that either the Earth is stationary, or that the distance of the stars was far further than believed at the time. The Copernican system had a weak response to this "test", which took the position that the stars are more distant than thought, which impacted the status of the Copernican-Keplerian system.

The court has seen how each system debated over the specific features of astronomy, from the parallax of the stars, to the motion of the Earth, &c. Note that while one could attack the specifics of the system, it does little to affect the "general theory" (Mikaye, 2015). For example, Galileo was convinced by the phases of Venus, but it only confirmed one feature of the Copernican-Keplerian system, against the Ptolemaic. The Tychonic's status remained unchanged in light of this evidence. Thus, a specific piece of evidence does arbitrate a specific feature's status, but it does little to affect the overall theory's status. This is a direct result of the problem of underdetermination. Thus, the court has been made aware of the problem of underdetermination within astronomy, specially regarding how pieces of data act as evidence for specific features, but does little regarding the truth of systems. Furthermore, if one considers the accuracy of predictions as a method of arbitration, one should note that there is nothing, in principle, limiting the Ptolemaic system's degree of accuracy. Therefore, whether accuracy is a relevant or deciding factor in the arbitration and demarcation of scientific fact is a consideration for this court.

References

Copernicus, N. (1543). De Revolutionibus. *Johannes Petreius*.

Galileo, G. (1957, March 1). *Discoveries and Opinions of Galileo* (Stillman Drake, trans.). Anchor Book. ISBN: 0385092393.

Kuhn, T. S. (1995). *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought*. Harvard University Press. ISBN 0674171039.

Kepler, J. (1992). *New astronomy* (W. H. Donahue, Trans.). Cambridge University Press. https://doi.org/10.1086/289846 (Original work published 1609)

Miyake, T. (2015). Underdetermination and decomposition in Kepler's Astronomia Nova. S*tudies in History and Philosophy of Science 50*, pp. 20-27. https://doi.org/10.1016/j.shpsa.2014.09.008.

Ptolemy (1998, November 8). *Ptolemy's Almagest* (Toomer, G. J., Trans.). Princeton University Press. (Original work published ca. 150 AD) ISBN: 9780691002606.

Schofield, Christine (n.d.). *The Tychonic and semi-Tychonic world systems*. Cambridge History of Astronomy on Tycho and Tychonism.

Tycho Brahe (1588). *Of More Recent Phenomena of the Ethereal World*.

Thoren, Victor (n.d.). *Tycho Brahe*. Cambridge History of Astronomy on Tycho and Tychonism.

Voelkel, J. R., Gingerich, O. (2001). Giovanni Antonio Magini's "Keplerian" Tables of 1614 and Their Implications for the Reception of Keplerian Astronomy in the Seventeenth Century. *Journal for the History of Astronomy*, 32(3), 237-262. https://doi.org/10.1177/002182860103200305.

Western University (n.d.). Ptolemy's explanation of planetary motion using the devices of the deferent, epicycle, and equant. https://physics.uwo.ca/~jlandstr/planets/webfigs/survey/slide15.html.