

A new Cosmos – a novel Physics

The scientific reception of the heliocentric world view in the
Renaissance

MORITZ HÜTTEN

*Humboldt University Berlin and DESY Zeuthen (in 2013: MPIWG Berlin)
Platanenallee 6, 15738 Zeuthen*

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Abstract

This contribution aims at a better understanding of coeval criticism of the heliocentric world model proposed by Nicolaus Copernicus in 1543: Today, it is generally recognized that Copernican astronomy and the heliocentric world view had to win recognition against “unscientific” and irrational criticism by religious beliefs and in particular, the institutional Catholic church. In this contribution, I argue that this view strongly misjudges the scientific dispute in the 16th and 17th century at the crossroad between “old” Ptolemaic astronomy and the birth of modern science.¹ In fact, heliocentric (Copernican) understanding of the cosmos primarily did not have to be defended against repulsion by religious and ideological arguments, but against “tough” coeval scientific criticism. Thus, the pre-copernican astronomical world view should be considered rather as “different from today” and “incompatible” than as “poor” and “unscientific”.

The content of this contribution is explicitly intended to serve for didactical purposes in high school for several reasons: Firstly, it demonstrates several coeval physical misconceptions that were proposed against Copernican theory which are also repeated – intuitively – today by pupils in school. Secondly, it promotes a critical use of the term *misconception* in the sense that physics observations by pupils may be valuable, even if they are followed by wrong generalizations: theoretical explanations of observed phenomena possibly should be less considered as “wrong” or “right” than rather as “less or more adequate”. The same misconceptions that are produced by present-day pupils were the conviction of leading natural scientists in previous ages and were scientifically, and in most cases quite successfully, used over one and a half millennia to calculate astronomical and seasonal events. Thirdly, this essay gives some geometric and physics exercises which can be used also in school and might gain additional interest by the pupils because of their historic background and importance.²

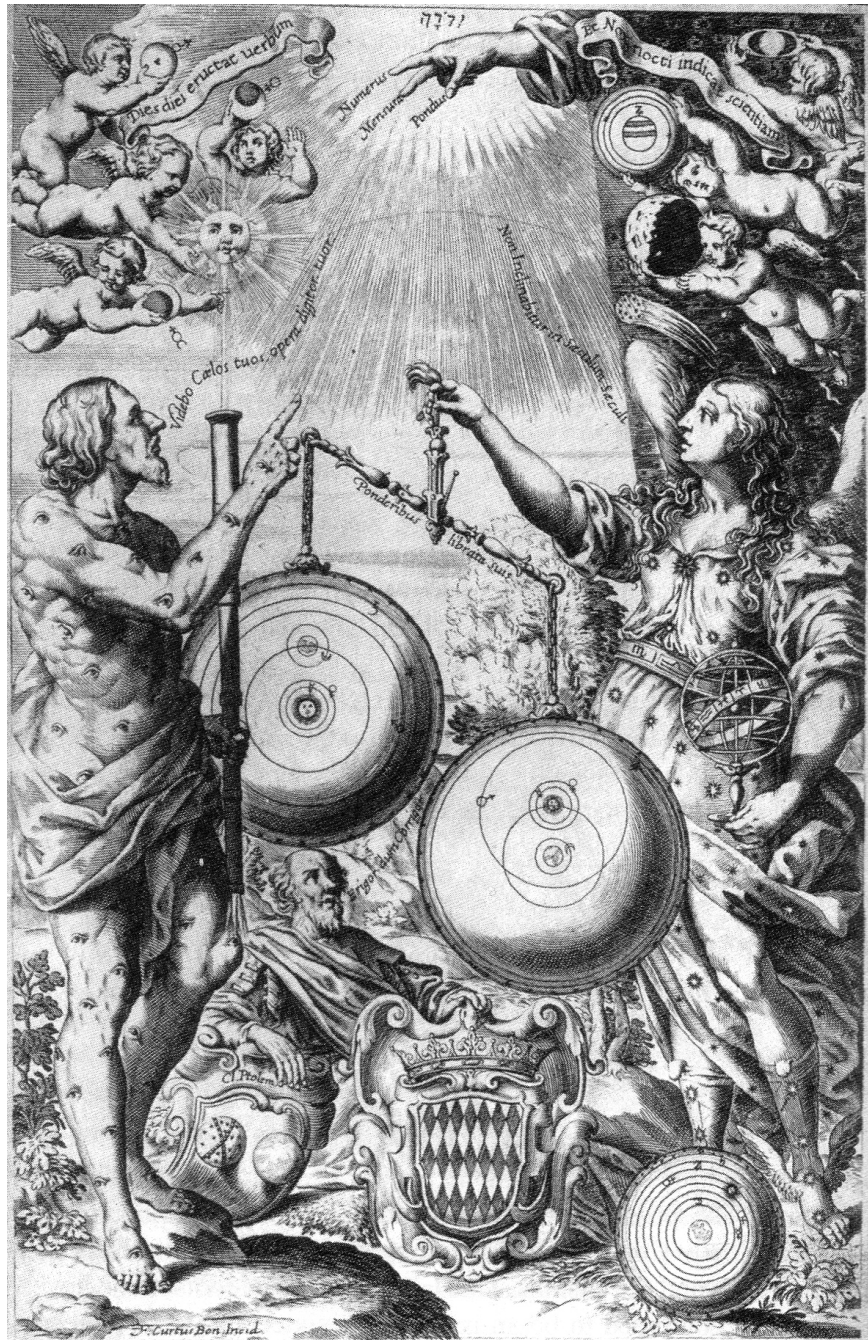


Figure 1: The heliocentric Copernican (left) and the geocentric Tychonian (right) planetary systems in direct contention in the view of Italian Jesuit astronomer Giovanni Riccioli in 1651. Apparently, Riccioli favors the Tychonian system, which outweighs the Copernican. The Ptolemaic cosmos is already ruled out and put aside in the lower right corner, with Claudius Ptolemy himself sitting below the scales. He states that he is “encouraged to correct himself” (*“Erigor dum corrigam”*), apparently from the very top.

The ancient view of the cosmos

Prior to the Copernican revolution, physics and astronomy were based for more than 1500 years on the writings of the greek philosopher Aristotle (384-322 BD) and the ancient world's "house astronomer" Claudius Ptolemy (Ptolemaios, 100-180 AD). In Aristotle's understanding, the earth – which was well considered as a sphere³ – statically rested in the center of the world. The world consisted of the four elements rock, water, air and fire, with the heavy elements rock and water tending to move towards the direction of the world's center (from what follows that the earth must form a sphere in the center of a three dimensional world) and the light elements air and fire tending upwards towards the heavens. The earth was then surrounded by various heavenly spheres, holding and moving the celestial bodies, namely – in the following order – the spheres of the moon, Mercury, Venus, the sun, Mars, Jupiter and Saturn.⁴ The outermost sphere finally contained the fixed stars.

Several centuries later, Greek astronomer Ptolemy in Alexandria improved Aristotle's model by a system of so-called epicycles and deferents, which allowed a precise calculation of the planets' positions, including the sun and the moon. His main writing *Syntaxis*, later throughout known under the name *Almagest* after adaption in Arabian science, was then used in some variations for centuries in the Arabian culture and Europe for calculating astronomical events, until it was finally replaced by Copernican astronomy.

Although Ptolemaic astronomy within a geocentric cosmos allowed a respectably good calculation of future astronomical events and the duration of



Figure 2: An early baroque ideal portrait of Ptolemy. Note the Jacob's staff, which was used to measure angular distances in the sky, until it was replaced by telescope based methods not before the late 17th century.⁶

seasons and the year, over the centuries, predictions of planetary positions within the geocentric models became noticeably imprecise. It was tried to solve these problems by introducing "ad-hoc" corrections in the form of additional nested epicycles. In his astronomical model, already Ptolemy used more than 30 of those circles "to save the phenomena"⁷, i.e., to predict the position of the planets with adequate precision. In the subsequent centuries, deviations of observations from predictions were tried to correct by further circles. But these extensions did not provide a sustainable solution: After certain times, deviations from the predictions recurred. At last, in the 16th century, the models increased up to 80 epicycles. Even worse, there was no consistent systematics in how to set-up these additional corrections: So at Copernicus time, there was a huge amount of complicated, competing planetary models, but still none of them being satisfying in the long term.

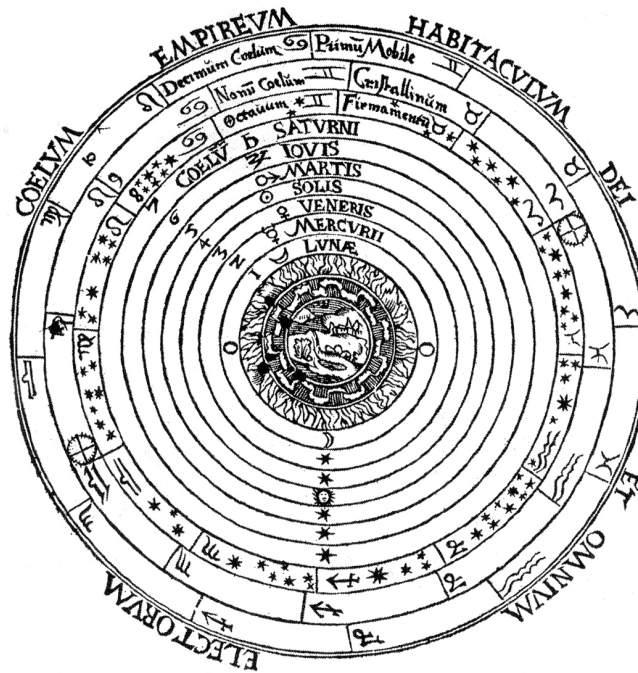


Figure 3: A popular illustration from 1533 of the Aristotelian universe. The falling rain and rising fire on earth are depicted below the schematic spheres of the heavenly bodies. Outside of the fixed stars there are still two more divine spheres under the outermost christian heaven, all three added to the antique cosmos by theological reasons. Note that this depiction was meant to be schematic already at its time and does not reproduce the sizes of the spheres (and thus the relative distances of the planets) assumed in pre-modern astronomy. For further details relating to quantitative geocentric astronomy see Kragh (2007).

Copernicus' revolution

In about 1510, Prussian-Polish astronomer Nicolaus Copernicus tackled the problem of the insufficient understanding of the planets' movements – explicitly with the encouragement of the Vatican, which was interested in improving the old Julian calendar (Kragh, 2007, p. 47). As the result of his studies, in 1543, he published his *De revolutionibus orbium coelestium* ("On the revolutions of the heavenly spheres"), which later was recognized as hour of birth of Copernican astronomy.⁸ In that book, Copernicus proposed to fix the sun's position and the sphere of the fixed stars, and to let all other planets move around the sun (besides the moon still orbiting around the earth).

At the time of publication, this proposal provided basically two advantages: Firstly, the qualitative observation of the planetary motions followed immediately from the heliocentric model without the need of epicycles. For example, the temporarily retrograde motion of the outer planets observed from the earth

and the observed limitation of Mercury's and Venus' orbits to positions close to the sun are immediately determined by a heliocentric planetary system. Secondly, in the heliocentric model, the radii of all planetary orbits around the sun can be determined quantitatively as a multiple of the distance between the sun and the earth. This calculation forms a nice high school geometry exercise and is depicted in the appendix.⁹

It is to be stressed that in 1543, these previous arguments were already exhaustive. Copernicus still assumed circular orbits of the planets. So, despite of his initial ambition to improve astronomical predictions, the quantitative projection of the planetary motions was not better than before: Copernicus again needed – and no less – epicycles as in the geocentric picture. Worse yet, his model clearly contradicted well confirmed physical knowledge of his time. In the following, I will show which criticisms were made towards Copernicus' model and why at the end, the heliocentric cosmos nevertheless prevailed.¹⁰

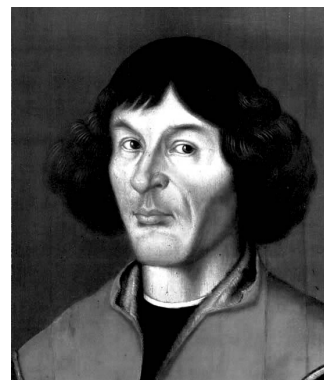


Figure 4: Portrait of Nicolaus Copernicus in the town hall of Toruń, Poland, about 1580.

Coeval criticism of Copernican theory

As a first objection, at Copernicus' time, it was hardly conceivable that the earth itself rotates around its own axis, which was necessarily implied by the Copernican theory to explain the difference between day and night. People stated that such a rotation clearly contradicted the observations: It was argued that a spinning earth was expected to rotate away under the clouds towards the east, so that the clouds should be observed to be constantly moving towards the west. Also it was asked why, on a rotating earth, loose things are not catapulted away from the surface. From today's point of view, these arguments intuitively sound fairly naive. But one has to keep in mind that to dissolve the first of these two criticisms, the concepts of momentum and angular momentum are needed, which did not exist at that time. To consistently refute the second argument, a concept of "gravitational acceleration" and its quantitative comparison with inertial (centrifugal) acceleration is needed.¹¹ Because there did not exist coherent concepts neither of gravitation nor of forces in general, it was not possible for the supporters of a rotating earth to satisfactorily argue against this objection.

A second repugnance of the heliocentric model was the fact that within this model, the earth was no longer statically located in the center of the universe. As all rock and water move towards the center of the world, why do, for an earth shifted out of the center, things still fall onto the earth's surface? Conversely, the fact that things fall onto the earth from all sides seemed to definitely prove

that it must rest in the center of the world. Obviously, this argument heavily depends on Aristotelian "gravitation" and can't be dissolved within Aristotelian physics – a moving earth demanded a different theory of gravitation, which was first presented by Isaac Newton one and a half centuries after Copernicus' proposition.

A third critique of Copernican theory was a quite sophisticated argument which included precise astronomical measurements already available in the mid 16th century: If the earth rotates around the sun, which is located in the center of the universe, then one should observe a small variation of the stars' positions during the year. Such an effect, called parallax, could not be observed by 16th century astronomers. From this it was correctly concluded that the stars must be very far away from both earth and sun to reconcile Copernican theory with the missing parallax. If one then compares the apparent angular diameter of the stars – viewed through the naked eye¹² – with the angular diameter of the sun, one finds that the stars must have diameters *at least* a hundred times bigger than the sun, what seemed highly implausible to Copernicus' contemporaries. This argumentation can be quantitatively calculated easily in high school and is shown in the appendix.¹³ In fact, the calculation is correct – the error in the argument is the wrong assumption for the angular diameter of the stars viewed from earth: The diameter observed with the naked eye is by no means related to the stars' real radii, but to the light's diffraction in the human eye (as well as caused by atmospheric distortion). This was first fully understood within the framework of wave optics in the beginning 19th century. But already soon after starting to observe the sky through the telescope, one noted the difficulty of determining the correct angular diameter of the stars: It was soon noticed that when viewing through the telescope, the diameter of a star's image did not increase corresponding to the amplification of the instrument.

There can be given even more scientific coeval objections against the heliocentric model, see, e.g., Kuhn (1957) or Kragh (2007). But finally, the Copernican concept prevailed, in spite of its heavy apparent contradiction to observation. In the following, I will illustrate why, although the Copernican theory produced so severe contradictions to the physics concepts of that time, it finally replaced the Ptolemaic planetary system.

The exhaustion of the criticism of Copernican theory

Despite its logical closeness and philosophical-theological authority, already in the Middle Ages, Aristotelian physics had been criticized for not being well in accord with observation: The assertion of Aristotle's mechanics that force is proportional to a body's velocity, was doubted already by the scholastic. Also, there were already in the Middle Ages considerations that anticipated the later concept of impulse, namely a concept called *impetus* (see, e.g., Kuhn (1957), p. 114ff). For example in 14th century, scholar writer Nicole Oresme noticed correctly that on a constantly moving ship, a falling body falls down in a strict vertical line *in the reference system of the ship* and is not left behind.¹⁴ At latest with Galileo Galilei's reflections and experiments regarding the law of falling bodies, Aristotelian physics was identified to be heavily deficient. But with Aristotelian mechanics loosing its authority, also the arguments against a rotating earth were deprived of its basis.

The authority of Aristotelian physics was challenged also in other contexts. There were observations of "new stars" in 1572 and 1604 (called *novae*¹⁵), which were in contradiction to the eternity of the sphere of the stars, postulated in Aristotle's writings. In addition to that, the precise observation of the orbits of bright comets in 1577 & 1618 (Figure 5) suggested the penetrability, and thereby uselessness, of the heavenly spheres.

Finally, the invention of the telescope in about 1608 and the discoveries Galilei made with it, provided further contradiction to the Aristotelian world view and moreover gave direct evidence for a heliocentric planetary system: Through the telescope, Galilei discovered the moons of Jupiter, proving that also other celestial bodies besides the earth may possess satellites. Galilei observed stars

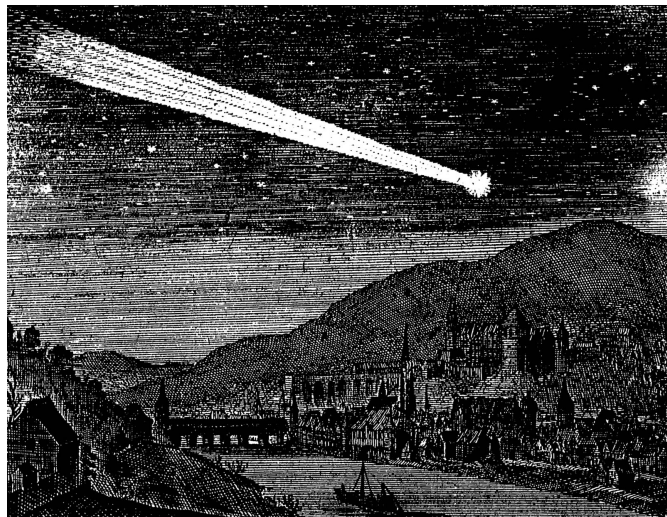


Figure 5: The Great Comet of 1618 above Heidelberg. Copperplate engraving by Matthäus Merian in the *Theatrum Europaeum* from 1635.

not visible through the naked eye, he discovered spots in the sun, he observed the phases of the Venus and finally could correctly resolve the angular diameter of the planets. Especially the case of the Venus' phases was a criterion to make a definitive decision between a geo- and a heliocentric cosmos: The observed phases were in clear contradiction with the Ptolemaic system and in generic concordance with a heliocentric system (Figure 6).

It should be mentioned that also the notion of the existence and the experimental production of vacua from the beginning 17th century by Boyle, Torricelli, von Guericke and others had an impact on astronomical questions.¹⁶ As vacua were not thought to exist in nature in pre-modern science, the space between the planets had to be filled with above mentioned crystalline spheres. In the Aristotelian view, heliocentric orbits caused the trouble of overlapping and mutually penetrating spheres. With the possibility of vacua, of course, these problems immediately disappeared: As those "container spheres" were no longer needed, the planets could be easily located on interlacing orbits.

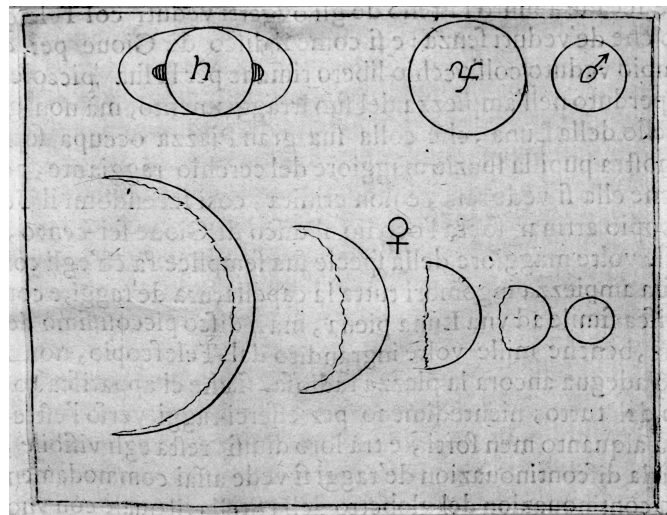


Figure 6: The sickles of Venus, below the drawings of Saturn, Jupiter and Mars, drawn by Galileo Galilei in *The Assayer (Il Saggiatore)* of 1623. Also, the changing size of the Venus when observed in superior and inferior conjunction is correctly reproduced by Galilei. In a geocentric model, if one assumed the sphere of Venus located between the earth and the sun, one would always observe *less than* a half-full sickle of the Venus. If one assumed the sphere of Venus being located behind the sun, one would always observe *more than* a half-full sickle,¹⁸ see also annotation 4.

The completion of the Copernican revolution by Kepler and Newton

After all, the above findings showed that a heliocentric universe can be possible – although at the end of 16th century, not all reservations about Copernican theory could be exhaustively resolved. Remember that mainly the problem of the computational non-advantage of the Copernican model to calculate planetary motions still persisted. But the adaption of a heliocentric world model finally inspired later scientists to advance the Copernican approach: The replacement of circular motions by elliptical orbits around the sun by Johannes Kepler in 1609 (in his *Astronomia Nova*) showed the predictive superiority of the heliocentric world model. At last, the Copernican revolution was completed by Isaac Newton who provided – himself in turn based on the works by Kepler – a self-contained and consistent physical theory of mechanics and gravitation from which all planetary motions in a heliocentric system could be deduced in perfect concordance with observation.

Conclusion

In summary, this contribution showed that Copernican heliocentric world view was confronted with serious scientific criticism, which claimed to rely on obvious and objective observational and experimental evidence. These physics arguments first in hindsight turned out to be misleading. The “errors” of these arguments could be realized first with new experimental evidence like the discovery of vacua, with the availability of new technical instruments like the telescope, and most importantly, first within a entirely new theoretical physical framework. So I hope this story can be told also in high school to encourage the pupils to look more critically at the phenomena: Because the adequacy or non-adequacy of an explanation – like “heavy bodies fall faster than light ones” – is directly connected to the underlying empirical and theoretical basis to which one is, often unconsciously, restricted, one should always keep in mind that any successful theory may turn out to become deficient when applying it to higher measuring accuracy or modified empirical contexts.

Notes

¹ Historians today argue that the popular view of intellectually poor and “dark” Middle Ages is possibly one of the biggest exaggerations in European historiography which has its origin in the Renaissance’s and Enlightenment’s needs to consolidate their self-conception, and which survived until today. For the Anglo-Saxon part, this viewpoint is promoted by Russell (1991), for the German-speaking part see Aufgebauer (2006).

² The content of this essay is mainly based on the following three works: The emphatically recommendable account by Thomas Kuhn on the Copernican revolution (Kuhn, 1957), the overall view on the history of cosmology by historian of science Helge Kragh (2007) and the classic presentation of the Copernican revolution by Alexandre Koyré (1957).

³ See annotation 1. The wrong allegation of a flat earth as common scholar opinion in the Middle Ages is the most prominent example for the misjudgment of medieval science.

⁴ In fact, the order of the planets’ spheres is not definite in a geocentric model. It seems natural to arrange the planets corresponding to their revolution periods, but such a scheme does not work for the bodies of sun, Mercury and Venus. Actually their relative order always had been a matter of ambiguity in geocentric astronomy and been fixed just by the normative authority of Ptolemy’s writings. See also annotation 8 and Kuhn (1957) for further details.

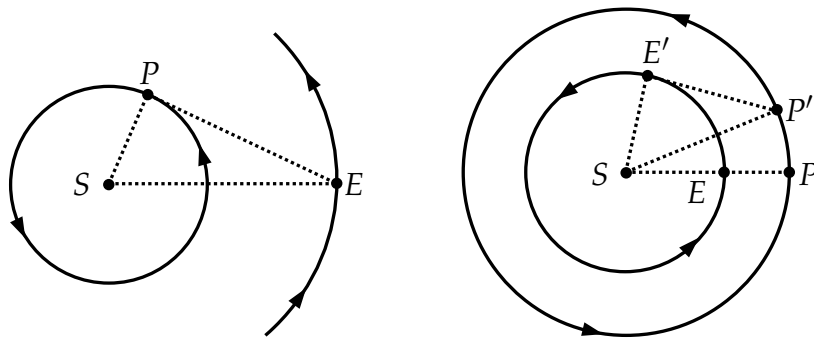
⁶ The depicted Jacob’s staff, laid into Ptolemy’s hands by the painter, was used in this form first in 15th century, but similar instruments were already used also by antique astronomers.

⁷ See the advisable work by Duhem (1969) for the changing approaches to scientific problems from antiquity to modern age.

⁸ Note the double meaning of the term ‘revolution’ in the context of giving birth to a later declared ‘Copernican Revolution’.

⁹ From a heliocentric planetary system, with the planets moving on (approximately) circular orbits around the sun, the radii of the planets’ orbits, as a multiple of one astronomical unit (the radius of earth’s orbit), are directly determined by observations from earth. For an inner planet (Venus or Mercury) the calculation is as follows: Consider the moment, when the inner planet P , viewed from earth E , has reached its maximum elongation from the sun S (Figure 7a). Assuming circular orbits, at this moment, the triangle SEP is rectangular. The angle SEP is directly measurable and one gets $SP = SE \cdot \cos(SEP)$, with SE one astronomical unit.

For the outer planets the calculation is slightly more complicated: Consider the moment t_1 , when the earth E just overtakes the planet P on its circular orbit around the sun. At this moment of opposition, sun S , earth E and planet P can be assumed to located on a straight line (Figure 7b). Because the earth is moving faster around the sun, at a later time t_2 in the year, with the earth at position E' and the planet at P' , the sun and the planet can be viewed at a angle of exact 90 degrees. Now one obtains the angle



(a) The case of an inner planet (b) The case of an outer planet

Figure 7: Calculation of the orbital radius of a planet in the heliocentric system.

$E'SP'$ by subtracting PSP' from ESE' : Both angles PSP' and ESE' are known, when the periods of revolution T of the earth and the planet are known, because $\frac{t_2-t_1}{T_E} = \frac{ESE'}{2\pi}$ and $\frac{t_2-t_1}{T_P} = \frac{PSP'}{2\pi}$ accordingly. The revolution period T_P of planet P can be determined by the time interval between two consecutive oppositions. From the known angle $E'SP'$ now finally follows $SP' = SE' \cdot \sin(E'SP')$, with again SE' one astronomical unit. Note that expressing one astronomical unit in terms of meters is a completely different and more difficult question.

This whole calculation is taken from Kuhn (1957), pp. 175ff. In the appendix of that book the author provides even more historic calculations of astronomic quantities which can be used in school teaching.

¹⁰Note that until the 17th century, the universe (or cosmos) comprised basically the solar system.

¹¹In fact, the objection that things are not catapulted away from a rotating earth, can not be refuted until comparing the exact numerical dimensions of the counteracting forces, which is not possible without a full theory of dynamics and gravitation (namely, without Newtonian physics). While the gravitational acceleration is about $F_G \approx 9.8 \text{ m/s}^2$ on earth's surface, one obtains a negligible counterpoised centrifugal acceleration $F_G \approx 0.3 \text{ m/s}^2$ at the equator (and even less at higher latitudes).

¹² A measurement of the *apparent* (!) angular diameter of stars with the naked eye is described by Galileo Galilei in his *Dialogue Concerning the Two Chief World Systems* (chapter "Third Day") from 1632, here reproduced in the translation by Drake (1967):

"I hung up a light rope in the direction of a star (I made use of Vega, which rises between the north and the northeast) and then by approaching and retreating from this cord placed between me and the star, I found the point where its width just hid the star from me. This done, I found the distance $[d]$ of my eye from the cord, which amounts to the same thing as one of the sides which includes the angle $[\alpha]$ formed at my eye and extending over the breadth $[b]$ of the cord." [... This angle eventually is the same as the angular diameter of the star in the sky].

The setting of this observation is illustrated in Figure 8.

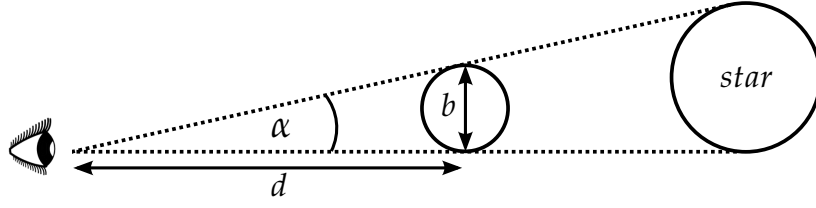


Figure 8: Galilei's method for determining the angular diameter α of a star with the naked eye.

¹³ According to Figure 9, the distance d_S to an observed star is:

$$d_S \gtrsim \frac{d_E}{\sin \frac{\beta - \alpha}{2}}$$

with d_E the distance of the earth to the sun. The radius of the sun is given by:

$$r_{\odot} = d_E \cdot \sin \frac{\theta_{\odot}}{2}$$

with $\theta_{\odot}$ the angular diameter of the sun viewed from earth. Correspondingly, the radius r_S of the stars is (θ_S : angular diameter of the star viewed from earth):

$$r_S = d_S \cdot \sin \frac{\theta_S}{2}$$

Combining these expression yields for the radius r_S :

$$r_S \gtrsim \frac{\sin \frac{\theta_S}{2}}{\sin \frac{\theta_{\odot}}{2} \cdot \sin(\frac{\beta - \alpha}{2})} \cdot r_{\odot}$$

About 1570, Tycho Brahe determined – without having a telescope available! – the angle $\beta - \alpha$, as illustrated in Figure 9, to the value (Kragh, 2007, p. 52):

$$\beta - \alpha \lesssim 1 \text{ arcmin.}$$

When trying to measure the angular diameter of the stars with the naked eye, (e.g., with the method described in annotation 11), one gets:

$$\theta_S \approx 1 \text{ arcmin.}$$

With the angular diameter of the sun of $\theta_{\odot} = 30 \text{ arcmin}$, one finally yields:

$$r_S \gtrsim 110 \cdot r_{\odot}$$

In fact, this result brought Tycho Brahe to propose a “compromise” between a Ptolemaic and Copernican planetary system, namely his Tychonian system with the earth at rest and the sun and the moon orbiting around it, but with all the other planets still orbiting around the sun (see Figure 1 on page 2 of this article). In fact, *there is* a parallactic effect

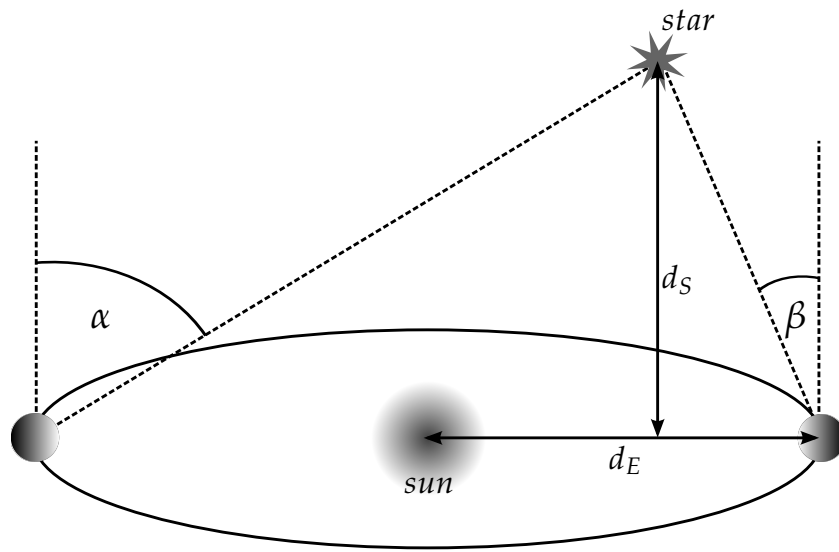


Figure 9: Measuring the parallax of a distant star when observing it two times in an interval of six months. The distance d_s between the earth and the star is assumed to be nearly constant during the earth's revolution around the sun (and thus being represented as in the figure), what is not fulfilled in this picture, but for sufficiently small angles α , β .

when observing the stars from earth, which was measured not before 1838 by Friedrich Wilhelm Bessel. He measured the parallactic movement of 61 Cygni, one of our closest neighbouring stars, to be $0.3 \text{ arcsec} = 0.005 \text{ arcmin}$, thus about 200 times smaller than the available measurement accuracy at Tycho Brahe's times.

¹⁴ Cited after Kuhn (1957, p. 116). Even more surprisingly, in Oresme's writings there can be found elements of the later Galilean relativity principle (see also Kuhn (1957). p. 116f).

¹⁵ From today's point of view, these events in 1572 and 1604 correspond to supernovae explosions.

¹⁶ This is nicely depicted in Shapin (1996).

¹⁸ A comprehensible animated illustration of the different appearance of the Venus in Ptolemaic and Copernican theory can be found at the webpage of the *Museo Galilei*, Florence, under the weblink (voiceover in Italian):

http://brunelleschi.imss.fi.it/esplora/cannocchiale/dswmedia/simula/isimula1_3.html

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