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GALILEO AND THE DISCOVERY OF THE PHASES OF VENUS

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1. *Introduction*

In 1985, Richard S. Westfall re-proposed the thesis that Galileo "stole" the prediction of the existence of Venus's phases from his pupil, Benedetto Castelli.[1] I shall call Westfall's view the "dishonesty thesis".[2] According to the dishonesty thesis, it was the following chain of events that led to the discovery of Venus's phases.

The prediction of the existence of Venus's phases was made by Castelli in a letter presumably received by Galileo on 11 December 1610. Castelli pointed out that if Copernican astronomy was true then Venus should display phases and asked Galileo if he had observed such a phenomenon. Galileo had not observed Venus yet, but instantly understood the significance of his pupil's remark and on the spot decided to send Kepler a cipher announcing the discovery of Venus's phases, thus securing his priority.[3]

In this paper, I shall argue that the dishonesty thesis is untenable and propose two counter-arguments to it. The first is based on a mathematical reconstruction of Venus's phase cycle during the crucial period spanning summer to winter 1610. The second is based on the significance of the question of celestial light.

In Sections 2 and 3, I will present the first and second counter-arguments. In Section 4, I will briefly discuss some technicalities concerning the mathematical model used to simulate the evolution of Venus's phase cycle.

2. *Galileo's Observations of Venus*

The mathematical approach I adopt has been inspired by similar work by Owen Gingerich and William T. Peters, who, in 1984, re-constructed qualitatively the appearance of Venus in 1610.[4] The latter also noted that the peculiar "lingering" of the one-half phase reported by Galileo is a well-known phenomenon to modern observers and concluded that Galileo's observations "have the ring of a record of visual impressions rather than an account coloured by calculation".[5] As we shall see, mathematical simulation allows us to visualize Venus's phase cycle day by day and shows that the evolution of Venus's phases agrees with Galileo's observational reports to such an extent that it seems highly unlikely that he invented the story of his observations *a posteriori*, after receiving Castelli's letter.

On 30 December 1610, Galileo communicated to Castelli and Clavius the discovery of Venus's phases. As far as Venus is concerned, the content of the two letters is identical. Here is the relevant excerpt from Galileo's letter to Clavius:

> ... when Venus began to be visible in the evening sky [*nel principio della sua apparizione vespertina*], I started observing it and saw that its figure

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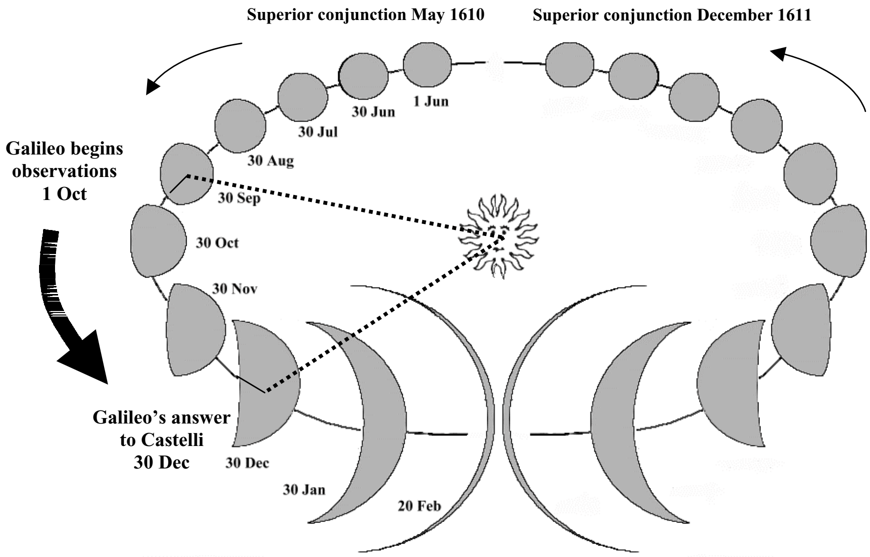

FIG. 1. Galileo's observations of Venus. The three-month period of Galileo's observations, from 1 October to 30 December 1610, is clearly marked by the dotted lines. Grey areas represent the illuminated parts of Venus. Both size and phase are represented in accordance with my mathematical model. Sizes are to be compared with each other. The images do not reproduce the absolute dimensions that Galileo would have seen through his telescope, but simply dimensions relative to each other. The line separating the dark zone from the zone illuminated by the Sun is an ellipse (cf. Section 4). Finally, note that I have assumed that Venus orbits the Sun along the ecliptic. Details on the mathematics used are given in Section 4.

> was circular, though extremely small. Afterwards, I saw [Venus] growing in magnitude significantly, though always maintaining its circular shape. Approaching maximum elongation [*digressione*], [Venus] began to lose its circular shape on the other side from the Sun and within a few days had acquired a semicircular shape. This shape it maintained for a number of days. More precisely, it maintained [this shape] until it began to move towards the Sun, slowly abandoning the tangent. It now begins to assume a notable corniculate shape. Thus, it will continue to decrease during the period in which it remains visible in the evening sky.[6]

First of all, when did Galileo begin to observe Venus? On the one hand, Galileo told Clavius that he had started his observations "when Venus began to be visible in the evening sky". On the other, he told Castelli that he had started his observations about three months earlier, that is, at the beginning of October.[7] But it is clear that "when Venus began to be visible in the evening sky" cannot coincide with the beginning of October. To explain this discrepancy we need to consider Venus's phase cycle in 1610 (Figure 1).

Figure 1 presents an overview of the variation in Venus's phase and magnitude, from the superior conjunction of May 1610 to the superior conjunction of December 1611. Both apparent size and phase varied enormously, though not following a uniform pattern of change. Galileo's expression "when Venus began to be visible in the evening sky" can only refer to some time in the late spring or early summer of 1610. On the other hand, the expression "[a]fterwards I saw [Venus] growing in magnitude significantly, though always maintaining its circular shape" must refer to a period after the beginning of October since a significant growth in magnitude became apparent only after the beginning of October. It is quite possible that Galileo's first observations of Venus might have begun in a rather casual way when Venus had just emerged from the superior conjunction with the Sun. Perhaps, in his reply to Castelli, Galileo decided to leave aside his first casual observations and focus on the more recent ones.[8] This conclusion is consistent with the fact that the substance of the two letters is absolutely identical. Thus, we can assume that Galileo began (according to the wording of the reply to Castelli) or resumed (according to the letter to Clavius) his systematic observations of Venus's phases about 1 October 1610 (see Figure 2 for the configuration of the planets on 1 October).

To reconstruct Venus's phase cycle during Galileo's period of observation, we need to know with sufficient precision a second item of information, namely the date of Venus's maximum elongation. We can mathematically establish that maximum elongation was reached between 10 and 20 December (see Section 4 for a discussion of this point). This allows us to infer that the period referred to by Galileo as "approach to maximum elongation" lasted for some time prior to some particular day between 10 and 20 December 1610 (how long it lasted we shall see in a moment). Figure 3 gives the phases on 10 and 20 December, when Venus finally passed maximum elongation and started becoming crescent. We can now turn to showing that Galileo's report matches the reconstruction of Venus's cycle.

Let us re-call Galileo's words,

> I saw [Venus] growing in magnitude significantly, though always maintaining its circular shape ... and within a few days [Venus] had acquired a semicircular

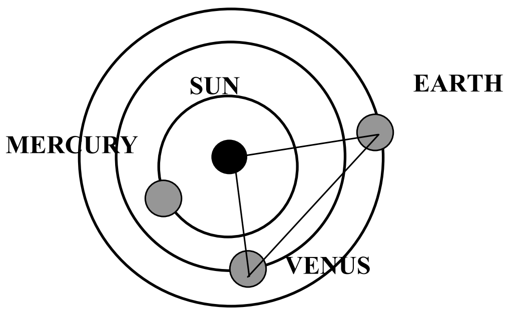

FIG. 2. The configurations of the planets on 1 October 1610.

FIG. 3. The passage of Venus's phase from slightly gibbous to slightly crescent. The first figure is Venus on 10 December 1610, the second figure Venus on 20 December (sizes are relative to each other).

> shape. This shape it maintained for a number of days ... it maintained [this shape] until it began to move towards the Sun, slowly abandoning the tangent.[9]

Thus, Galileo observed two patterns:

> (a) Venus growing in magnitude and remaining *circular* for some time before undergoing the change in phase that it displays during the approach to maximum elongation, and
>
> (b) Venus "lingering over" the semicircular phase, that is, the peculiar fact that Venus maintains an approximate *semicircular* shape for a number of days (the duration of this "lingering" phenomenon was about one month, according to a more precise piece of information Galileo furnished subsequently).[10]

These are the patterns Galileo's telescope allowed him to observe from October to December 1610 and these are the patterns that mathematical simulation confirm. In fact, not until late December was Venus to display a marked crescent (*cf*. Figure 4).[11] It is also clear that Galileo was unable to observe an appreciable change from circular to semicircular shape until at least the first half of November, because he tells us that the "lingering" phenomenon lasted about a month and that Venus "maintained [the semicircular shape] until it began to move towards the Sun, slowly abandoning the tangent", i.e. slowly abandoning maximum elongation (which occurred between 10 and 20 December). Therefore, what Galileo calls "approach to maximum elongation" must have begun in the first half of November and lasted about a month.

As to pattern (a), it must be noted that even though mathematical reconstruction shows Venus clearly gibbous already on 30 October, Galileo interpreted its shape as circular during all the first part of his period of observation, that is until about mid-November (*cf*. Figure 4).

To understand pattern (b), we need to consider the whole pattern of change that Galileo was confronted with during Venus's approach to maximum elongation, and this is shown in Figure 5. During the first half of November, Venus's phase turned

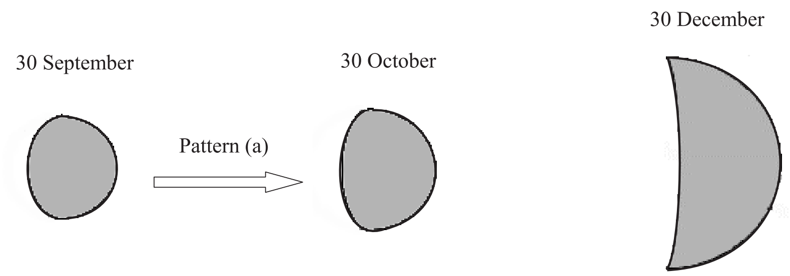

FIG. 4. Venus's shape on 30 September, 30 October and 30 December 1610 (sizes are relative to each other). For at least the first month of observations, Galileo attributed to Venus a circular shape.

from markedly gibbous into nearly semicircular and remained approximately such until maximum elongation, producing the "lingering" phenomenon.

Furthermore, when patterns (a) and (b) are together compared with the phase sequences of Figure 4 and Figure 5, they reveal another characteristic that is essential in order to establish the truthfulness of Galileo's claims. Patterns (a) and (b) are exaggeratedly non-linear.

How can this exaggeration be explained? In all probability, the limitations of Galileo's telescope are responsible for his tendency to overestimate the duration of the type of phase he could recognize.[12] In other words, these limitations may have caused an exaggeration of the non-linear effects that Galileo so clearly describes. The resolving power of his telescope was not sufficient to allow him to observe the slow change from moderately gibbous to semicircular (*cf.* the final images of Figure 5). This explains why he saw Venus circular until mid-November and reckoned that

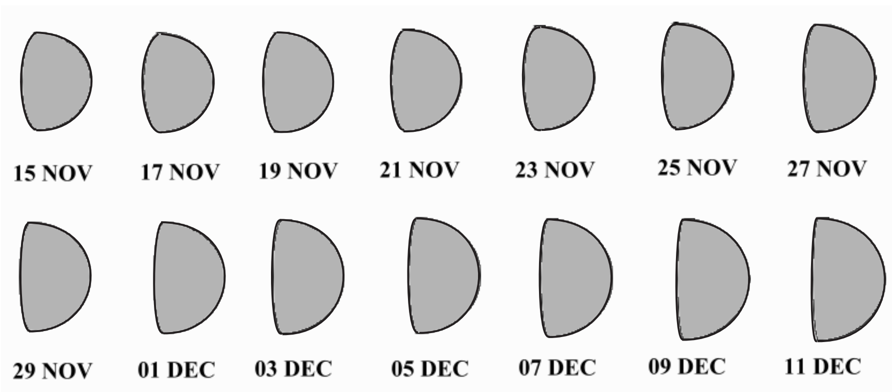

FIG. 5. The variation of Venus's phase and dimension during the approach to maximum elongation (sizes are relative to each other).

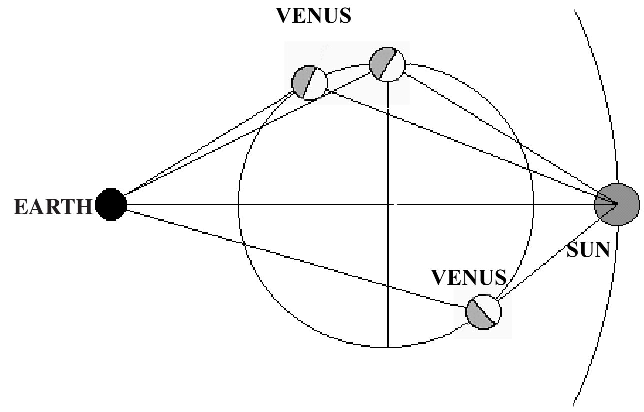

FIG. 6. A qualitative representation of Venus's phases in a simplified version of the Ptolemaic system when Venus is *always below* the Sun (Venus *always below* the Sun simply implies that Venus's epicycle is between the Earth and the Sun, *cf.* Fig. 8 for a three-dimensional picture). It has been assumed that the Earth's centre, the centre of Venus's epicycle and the Sun's centre lie on a straight line. By imagining placing the Sun between the Earth and the Venus epicycle on the line joining the Earth's centre and the centre of Venus's epicycle, the reader can visualize the mechanics of the phases when Venus is *always above* the Sun (*always above* the Sun simply means that the Sun is between the Earth and Venus's epicycle, *cf.* Fig. 8 for a three-dimensional picture).

the duration of the "lingering" phenomenon extended over a period of about one month. Clearly, this exaggeration can only have been the result of real astronomical observations. Theoretical prediction on the sole basis of Copernican faith would almost surely have led him to assume a more 'natural' pattern of behaviour, i.e. a linear one. And this leads us to Galileo's wait for Venus's crescent phase.

Galileo decided to wait until the end of December before answering Castelli's letter simply because until the end of December he was unable to discern clearly the corniculate shape with his telescope. At the beginning of his period of observation (1 October), Galileo attributed to Venus a circular shape. He subsequently observed it as it assumed a semicircular shape and remained thus for a number of days. He now wanted to ascertain that Venus would eventually become corniculate, for this had profound implications for the Ptolemaic system.

Contrary to Westfall's opinion that "[a]t no point during December was its [i.e. Venus's] shape compatible with the Ptolemaic system",[13] during December Venus's phase cycle in fact showed nothing incompatible with Ptolemy's system at any single point, except at maximum elongation, where Venus reaches the exact semicircular phase. In the Ptolemaic system, the perfect semicircular phase is the limit situation to which Venus's phase tends without ever reaching it. If Venus were *always below* the Sun (i.e. if Venus's epicycle were between the Earth and the Sun), then Venus should clearly display a pattern of phases similar (but not identical) to

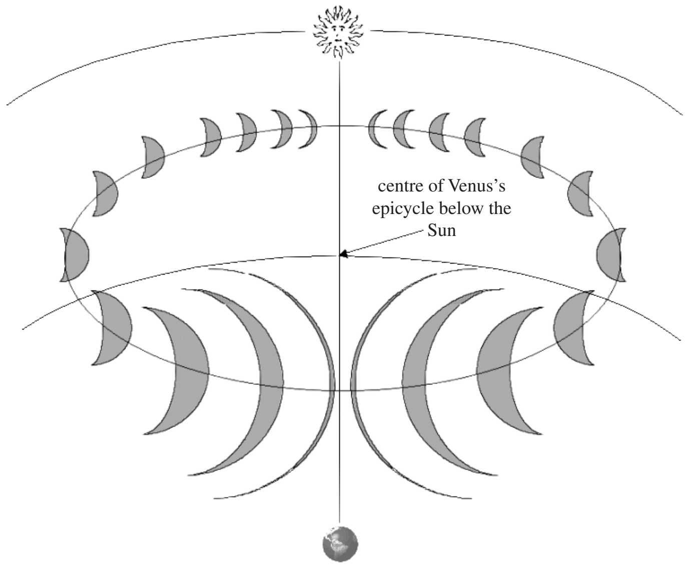

FIG. 7. The pattern of Venus's phases in a simplified version of the Ptolemaic system, in which Venus is *always below* the Sun. For the mathematics *cf.* Section 4. Venus's sizes are relative to each other.

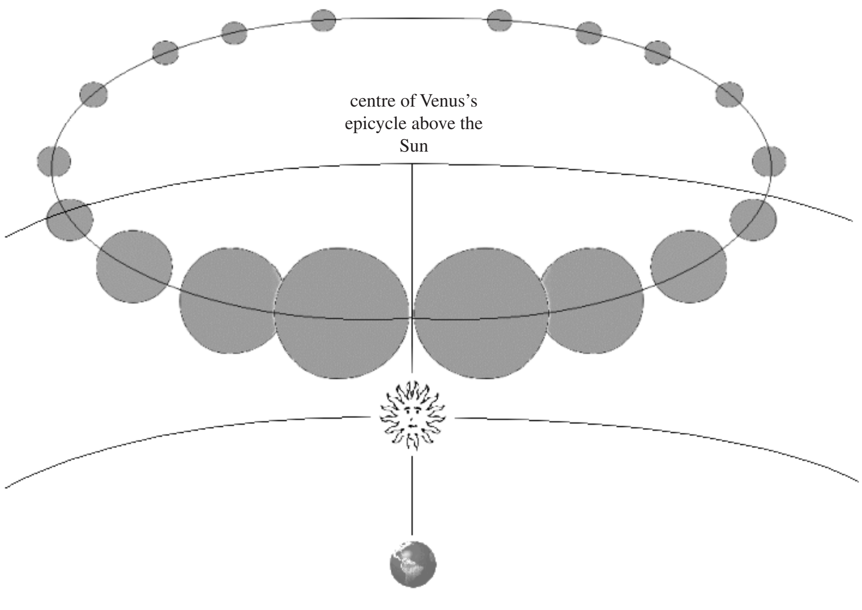

FIG. 8. Venus's phases in the Ptolemaic system when Venus is *always above* the Sun. For the mathematics *cf.* Section 4. Venus's sizes are relative to each other. Note that a slightly gibbous phase becomes appreciable only when Venus approaches inferior conjunction.

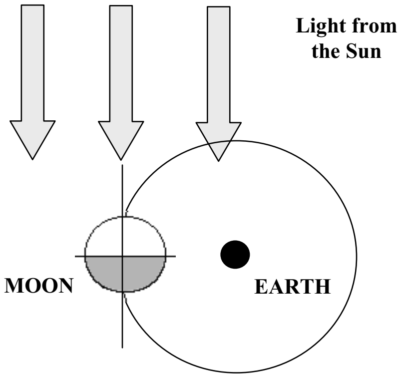

FIG. 9. A simplified model of the Moon at quadrature.

the pattern visible in late December 1610 (a pattern of crescent phases, *cf*. Figures 6 and 7). If Venus were *always above* the Sun (i.e. if the Sun were between the Earth and Venus's epicycle), then its phase should always be nearly circular or gibbous (Figure 8). This being so, until Venus reaches at least the semicircular phase, astronomical observation cannot prove that it descends below the Sun. Galileo was perfectly aware that Venus could be thought always to remain above the Sun, for in February 1611 he wrote to the Servite friar, Paolo Sarpi, that

> [w]e are now certain that Venus orbits the Sun, neither [revolving] below (as Ptolemy believed), where it would always show [a phase] less than one half of a circle, nor above (as Aristotle fancied), since if it were above the Sun one would never observe it crescent, but always much more than one half and almost always perfectly circular.[14]

What is truly incompatible with Ptolemy's system is the fact that Venus is *sometimes above* the Sun and *sometimes below* the Sun. While, as we have seen, in the Copernican system, Venus can be gibbous both before and after quadrature, it can be crescent only after quadrature, when it is between the Earth and the Sun. I believe that here Westfall may have been misguided by a 'linear' interpretation: he inadvertently supposed that the point of Venus's orbit at which the planet's phase turns from gibbous into crescent is the quadrature (as is approximately true for the Moon, *cf*. Figure 9).

If the passage from gibbous to crescent were at quadrature, then this change of phase would truly be incompatible with Ptolemy's system, since the quadrature coincides with the point at which Venus leaves the part of the orbit beyond the Sun to enter the part between the Earth and the Sun. In this case, one could probably arrive at Westfall's conclusion that Venus's phase would at no point during December 1610 have been compatible with Ptolemy's system. But Venus's phase cycle is

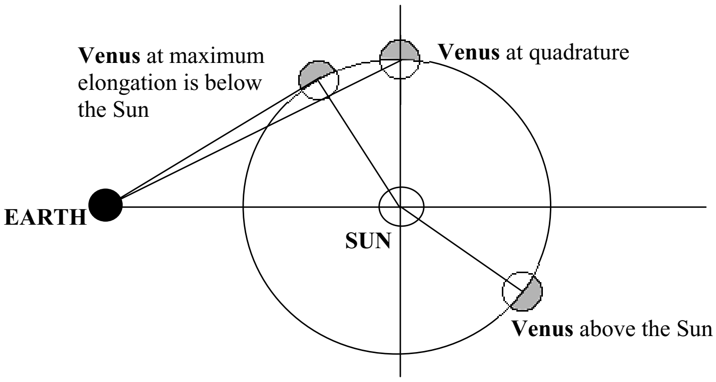

FIG. 10. Venus at maximum elongation, at quadrature, and beyond the Sun, in a simplified version of the Copernican system.

different from that of the Moon (*cf*. Figure 10).

As Galileo clearly pointed out to Paolo Sarpi, the crucial change in phase for Ptolemy's system is the passage from circular or nearly circular shape to crescent. A variant of Ptolemy's system with Venus always above the Sun could still accommodate the passage from nearly circular to gibbous.[15] At the beginning of his period of observation, Galileo had seen Venus showing the *circular* phase. He needed to see it assuming the *crescent* phase. When, towards the end of December, he satisfied himself that indeed Venus had started assuming the crescent phase, he broke his silence and wrote his letters to Clavius and Castelli.

In summary, Castelli's letter cannot have been the spark that ignited Galileo's programme of observation of Venus. It was simply too late. If he only then had started observing Venus, he would have seen it already nearing the exact semicircular phase, thus completely missing the non-linear patterns of change. And he could not possibly have been able to calculate the duration of one month for the "lingering" phenomenon. In other words, Galileo cannot have predicted Venus's non-linear patterns of behaviour by re-constructing them 'backwards'. For a Copernican it might have been easy to predict that Venus should display phases. However, it is one thing to predict this type of behaviour qualitatively and quite another to predict the non-linear patterns of change of Venus's phases. A quantitative analysis would have required of Galileo a sophisticated mathematical theory that he did not have. There remains only one possibility, namely, that Galileo really did observe Venus's non-linear patterns of behaviour.

3. *The Discovery of Venus's Phases and the Question of Celestial Light*

Westfall argues that on 11 December 1610, Galileo, prompted by Castelli's prediction, sent Kepler the cipher announcing "his" discovery of Venus's phases, even though he had not yet observed Venus.[16] This interpretation of the episode of the cipher is totally implausible, even if Stillman Drake's opinion that Galileo wished to avoid the risk of being anticipated by another astronomer were true.[17] To see why, we need to turn to the consequences — not considered by the dishonesty thesis — that the discovery of Venus's phases had for the debate on the nature of celestial light.

Owen Gingerich noted that the round, disk-like appearance first observed by Galileo was incompatible with the Ptolemaic system if Venus shone by reflected light, but pointed out that "until the phases began to appear he [Galileo] *could not rule out the possibility that Venus shone by its own light* ...".[18] I shall further develop Gingerich's argument, showing that Galileo was indeed deeply concerned with the long-debated question of celestial light and fully aware that his discovery was potentially able to settle it. To substantiate this line of reasoning in a proper historical context, I will consider two contemporary responses to Galileo's discovery of Venus's phases in connection with the question of celestial light, one from a Copernican and one from an anti-Copernican point of view. More specifically, I will examine the hitherto unstudied reactions to Galileo's observations of Venus by Kepler and by Scipione Chiaramonti, the then famous Aristotelian attacked by Galileo in the *Dialogue concerning the two chief world systems*. Both Galileo's awareness of the implications of the phases and Kepler's and Chiaramonti's reactions strongly suggest that celestial light was still a totally open question and that, when Galileo sent Kepler the cipher on Venus, he would not have staked his reputation on Castelli's purely theoretical prediction without a reliable observational basis.

Edward Grant has furnished a detailed account of the *status quaestionis* of celestial light from the late Middle Ages to the seventeenth century.[19] Scholastic authors were divided on this issue. Albert of Saxony, for example, attributed to Aristotle and Averroës the conviction that the Sun was the sole source of light, and to Macrobius and Avicenna the idea that the Moon received light from the Sun, but that all the other planets and stars are self-luminous.[20] However, Albert of Saxony and Nicole Oresme thought that the question could not be determined, though they favoured Aristotle's and Averroës's opinion. It is worth noting that the prediction of phases was made in the Middle Ages. According to Grant, "supporters of the Avicennan and Macrobian position argued that if all the planets had their light from the Sun and possessed none of their own, planets ought to exhibit variations in light — that is they ought to undergo phases — just as the Moon does".[21]

The question of celestial light did not simply concern the difference between opaque bodies that reflected solar light and self-luminous bodies. In fact, the most common opinion (adopted by Albertus Magnus and Albert of Saxony) assumed that planets and stars "were transparent and could therefore receive solar light throughout the extent of their bodies".[22] In other words, planets and stars would be visible to us because their bodies are impregnated with solar light that they subsequently transmit to us. In addition to the light received from the Sun, Albert of Saxony conceded that the planets might possess some light of their own. This mixed theory became more and more popular during the sixteenth and seventeenth centuries.[23] At the end of the sixteenth century, the Coimbra Jesuits summarized this position by declaring that "the more common assertion of the astronomers is that both the fixed stars and the planets receive their light from the Sun but nevertheless possess some light by themselves".[24]

Yet during the late sixteenth and early seventeenth centuries the discussion on the nature of celestial light became more complex. Thus we find the Jesuit Giovanni Battista Riccioli, in his *Almagestum novum* — a monumental astronomical treatise published in 1651 — discussing in detail four major theories that were still current amongst his contemporaries.[25] Galileo himself, in the Third Day of the *Dialogue concerning the two chief world systems*, mentioned the argument from luminosity as Copernicus's explanation for the lack of apparent change in size and shape of Venus when observed with the naked eye. According to Galileo, it was precisely because of this lack of observational evidence that Copernicus "declared that Venus was either luminous in itself or that its substance was such that it could drink in the solar light and transmit this through its entire thickness in order that it might look resplendent to us".[26] But Galileo was wrong in attributing to Copernicus a firm opinion concerning the light of Venus, as has been shown by Edward Rosen.[27]

This résumé should suffice to prove that the question of celestial light was alive and well in Galileo's time and afterwards.[28] To understand why Galileo thought his discovery was relevant to the issue of celestial light we need to turn to letters he sent Kepler via the Medici ambassador in Prague. In these letters, Galileo expanded on the question of celestial light.

In the letter of 1 January 1611, Galileo revealed the meaning of the cipher and asserted that the discovery of Venus's phases had eventually afforded "*certa e sensata dimostratione*" of two "great questions": (1) that all planets are opaque [*tenebrosi*] by nature, and (2) that Venus revolves around the Sun.[29] Galileo also stressed that the first of these questions had remained until then unresolved and had resisted the efforts of the greatest minds.[30]

Kepler immediately acknowledged the significance of Galileo's observations in relation to celestial light. In the Preface to his *Dioptrice* (1611), he published Galileo's letters of 13 October 1610, 11 December 1610, 1 January 1611, and 26 March 1611.[31] Commenting on Galileo's letter of 1 January 1611, Kepler marvelled at the fact that Venus could shine more than Jupiter simply by reflecting solar light. On the basis of some experiments of his own concerning a discernable variation in Venus's light caused by various modes of winking the eye, and which he had previously expounded in his *Astronomiae pars optica* (1604), he ventured to hypothesize that "there is no escaping the conclusion that the star of Venus revolves around its own axis most swiftly, showing in succession the various parts of its surface that are more or less receptive to solar light".[32]

But the discovery of the phases spurred Galileo to theorize about the light coming from far beyond the sphere of Venus. In his letter of 26 March 1611, he raised the issue of the *adventitious irradiation* surrounding the bright objects visible through the telescope.[33] He now asserted that he had "*certa dimostratione*" that not only the planets are opaque and receive their light from the Sun, but that the fixed stars shine by their own light. It is worth quoting in its entirety the relevant excerpt from Galileo's letter.

> The principle argument of my discourse derives from the telescopic observation that the nearer the planets are to the Sun, or to us, the more light they receive [from the Sun] and reflect towards us. Thus Mars, at its perigee, when it is nearest to us, is seen much brighter than Jupiter, though its size is less than Jupiter's and one can hardly deprive it of the irradiation that prevents us from observing its disk bounded and round.... Now, since we clearly see that the Sun greatly illuminates Mars when it is near, while the light from Jupiter is much weaker ..., and that of Saturn most weak and darkened, since the latter is much further [from us], how should the fixed stars, incredibly further [from us] than Saturn, appear, if they received light from the Sun? Very weak indeed.... Yet the opposite is true.... Thus I believe that we should philosophize correctly and assign the cause of the scintillation of the fixed stars to the vibration of the splendour native to their intimate substance, whereas on the surface of the planets the light coming from the Sun terminates and is reflected.[34]

In Galileo's view, both the planets and the fixed stars show some irradiation. But while that of the planets is adventitious — though in the case of Mars the telescope can hardly eliminate it — that of the stars is "native to their intimate substance" and therefore cannot be eliminated. So, the stars shine because they emit light and their scintillation derives from the "vibration" of their light, whereas the planets are opaque and can only shine because they receive light from the Sun. But why is irradiation observed even in the planets, and where does it actually form? Evidently Galileo does not have the answer yet. This difficulty, however, did not prevent Kepler from clearly recognizing the cosmological significance of the relationship between Venus's phases, the opacity of the planets' bodies, and celestial light. He concluded his comments on Galileo's letters on Venus and celestial light with an elegant simile that incorporated a reference to both the "*sensate esperienze*" and the "*certe dimostrazioni*" of Galileo's method. "Galileo's mind", says Kepler,

> by using the telescope like a ladder, ascends the highest and ultimate walls of the visible universe, perlustrates everything directly, and with most subtle reasoning looks down on our shacks, the planetary bodies, comparing the outermost with innermost [things], the highest with the lowest [things], by means of solid arguments.[35]

The implications of Galileo's discovery of Venus's phases for the question of celestial light were perfectly understood even in the anti-Copernican field.[36] Scipione Chiaramonti (1565–1652) — better known for his opposition to Galileo, Kepler, and Tycho — was a polymath and an Aristotelian natural philosopher who prided himself on being knowledgeable about mathematics.[37] He wrote a interesting tract on the phases of the Moon (published posthumously), in which he showed notable mathematical competence.[38] The force of the impact of Venus's phases and light on Chiaramonti's Aristotelianism is revealed by the shift that it caused in his epistemology, from the rigorously Aristotelian position he put forward in the anti-Galilean *Difesa* of 1633 (against Galileo's *Dialogue*) to the somewhat unorthodox conclusions reached in the *De universo* of 1644.[39]

In 1633, Chiaramonti pledged full allegiance to the Aristotelian principle of the certainty of sense experience. It was on this purely Aristotelian basis that he rejected the reliability of the telescope.

> I attribute to the senses, absolutely considered, though in their appropriate disposition, at the convenient distance, and within a pure medium, the right judgement of their object. This is necessary [to save] the evidence of principles and of the demonstrations dependent on principles.... On the other hand, he [i.e. Galileo] attributes to the *occhiale*, or telescope, incorruptible truth and perfection, and an increase in the power of sight. Yet the contrary is true, because this instrument is based on refraction, which invariably causes some deception, sometimes enormously distorting appearances.[40]

In this passage, Chiaramonti sees a conflict between what can be perceived through the senses "in their appropriate disposition, at the convenient distance, and within a pure medium" (Venus does not show phases to the naked eye) and what is "constructed" through the telescope (the phases). But, for Chiaramonti, in order to save the whole fabric of Aristotelian science, the certainty of sense experience cannot be called into question and the telescope must be rejected. It is refraction that explains the illusory telescopic appearances. Thus, Chiaramonti's strict adherence to the Aristotelian principle of the certainty of sense experience rules out the possibility of accepting the telescope.

A few years later, in *De universo*, Chiaramonti's position had changed considerably. He begins by noting that it is extraordinary that phases not observable by the naked eye become visible with the telescope; even more so, he continues, since when Venus allegedly shows its corniculate phase, it is supposed to be nearly forty times as large as when it is circular.[41] But, he asserts, Venus can never appear semicircular or gibbous. For, according to him, when it is above the Sun, it must be circular — as Galileo himself proved — and when it is below the Sun, since it never recedes from the Sun more than 47°, it cannot reach the semicircular phase, nor, *a fortiori*, the gibbous phase. And this, Chiaramonti claims, is due to the fact that the semicircular phase can appear only when Venus's angular distance from the Sun is 90°, and the gibbous phase only when the angular distance is greater than 90°. The truth of these assertions, Chiaramonti concludes, has been mathematically proved in his tract on the phases of the Moon (his explanation of the Moon's phase cycle is basically the same as ours, *cf.* Figure 10).[42] The mathematical details of Chiaramonti's model of the Moon's phases are irrelevant, but it is clear that his theory of the Moon's phases led him to believe that the same pattern must apply to Venus. Chiaramonti drew the conclusion that Galileo's telescopic observations of the phases were "fallacious and amounted to fraud [*impostura*]".[43]

As to celestial light, after rejecting the phases, he consistently rejected the opacity of Venus, though he admitted that he could not arrive at an exact conclusion as to the nature of celestial light and conceded that the question should to a certain extent remain open. Only the Moon, in his opinion, shines by reflected light.[44] Chiaramonti had clearly understood that Venus's phases and the opacity of its body could only be rejected together. But instead of simply falling back on his earlier critique of the telescope — based on the principle of the certainty of sense experience — he now preferred to rely on the strength of mathematics. Aristotle's principle of the certainty of sense experience was thus 'degraded' by Chiaramonti to the status of a consequence necessitated by mathematical cogency.

The conclusion Chiaramonti had reached was tantamount to forsaking the fundamental principle of the certainty of sense experience, for a very clear reason. Refraction and the telescope could impair the senses, but perhaps not to the extent of totally impairing "the right judgement of their object" (as terrestrial observations might have suggested). Now, either deception caused by refraction was, in Chiaramonti's view, no longer a conclusive argument for denying the reliability of Galileo's observations of Venus, or he did not know how to explain that "enormous" deception. He resorted to eliminating mathematically the possibility that Venus's phases exist. But in doing so, he implicitly left his Aristotelian epistemology vulnerable to an explanation of the telescope that might definitely rule out deception caused by refraction. And without deception — that is, with the senses restored to "the right judgement of their object" — either the principle of the certainty of sense experience would have been proven wrong (if Chiaramonti had persisted in arguing that the phases were not real), or the mathematical reasons he was so proud of would have become untenable (if he had acknowledged the existence of the phases).

To sum up, it is highly unlikely that when Galileo sent Kepler the cipher on Venus he would have bet on the existence of the phases without actually observing them. He was fully aware that celestial light was a thorny question still unsettled amongst his contemporaries and that his discovery could potentially resolve it. Kepler's and Chiaramonti's reactions show that in both the Copernican and the anti-Copernican fields the implications of the discovery of Venus's phases were grasped with great acumen. Galileo must have realized that if Venus shone by its own light then the pattern of the phases might be unpredictable.

4. *The Mathematical Model*

A few words on the mathematical model I have used to calculate Venus's positions, magnitudes and phases in the Copernican and Ptolemaic models are in order. On 1 March 1611 Venus reached inferior conjunction with the Sun. This prediction was made by Giovanni Antonio Magini, the then famous astronomer and human computer.[45] Galileo himself verified that Venus indeed approached inferior conjunction (though it was very "high", i.e. north of the ecliptic).[46] Conjunction can be used as a starting point in order to calculate backwards the position of Venus relative to Earth with sufficient precision. Assuming standard astronomical values for Venus's period and mean distance from the Sun, one can work out a simple formula for the distance of Venus from Earth by simply hypothesizing that both Venus and Earth follow circular orbits and move with uniform angular speed (the errors introduced by this approximation are not significant for our purposes, *cf.* the final part of this section).

Let us refer to Figure 11. With simple trigonometry one can work out Venus's distance from the Earth, Δ, as a function of angle α. On 1 March 1611, at inferior conjunction, we have $\alpha = 180°$. The intermediate positions follow from the fact we can assume $\alpha = \omega_V - \omega_E$, where ω_V, ω_E are the angular speeds of Venus and Earth.

Angle ε is the parameter used to calculate Venus's phase. Let us call it the 'perspective' angle. We can assume that the Sun's light illuminates one half of Venus because of the great distance of Venus from the Sun. At maximum elongation, for example, ε is equal to 90° and we see Venus semicircular. I have adopted a simplified model for the calculation of the curve separating light from darkness on Venus's surface. It proceeds as follows. With reference to Figure 12, imagine we observe Venus in such a position that the perspective angle is ε. Then we have the following equation for the curve separating light from darkness, the 'terminator', where *P* is a generic point on this curve:

$$Z_p = \sqrt{(R^2 - Y^2)} \cdot \cos(\varepsilon),$$

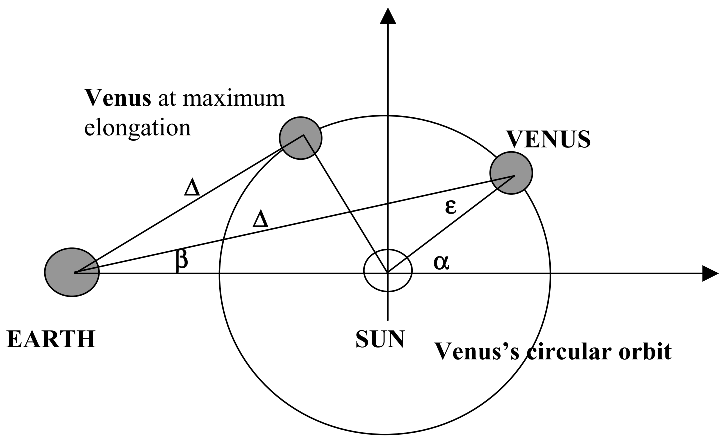

FIG. 11. A simple model of the distance of Venus from Earth.

which is an ellipse (R is Venus's radius and the image is projected onto the plane $X = 0$ since all visual rays can be considered parallel to the X-axis because of the great distance between Venus and our point of observation).[47] Venus's apparent size is calculated by assuming that Venus's apparent diameter is inversely proportional to Δ.

By assuming that the centre of the Earth, the centre of the Sun and the centre of Venus's epicycle lie on a straight line and placing Venus's epicycle between the Earth and the Sun, one obtains a simplified version of the Ptolemaic model, in which Venus is *always below* the Sun. By placing the Sun between the Earth and Venus's epicycle, one obtains a simplified version of the Ptolemaic system, in which Venus is *always above* the Sun. The mathematics is essentially the same as that used for the Copernican model.

The positions of the planets given in Figure 2 has been calculated with *Home Planet*, a software package for sky simulations.[48] All the other computations have

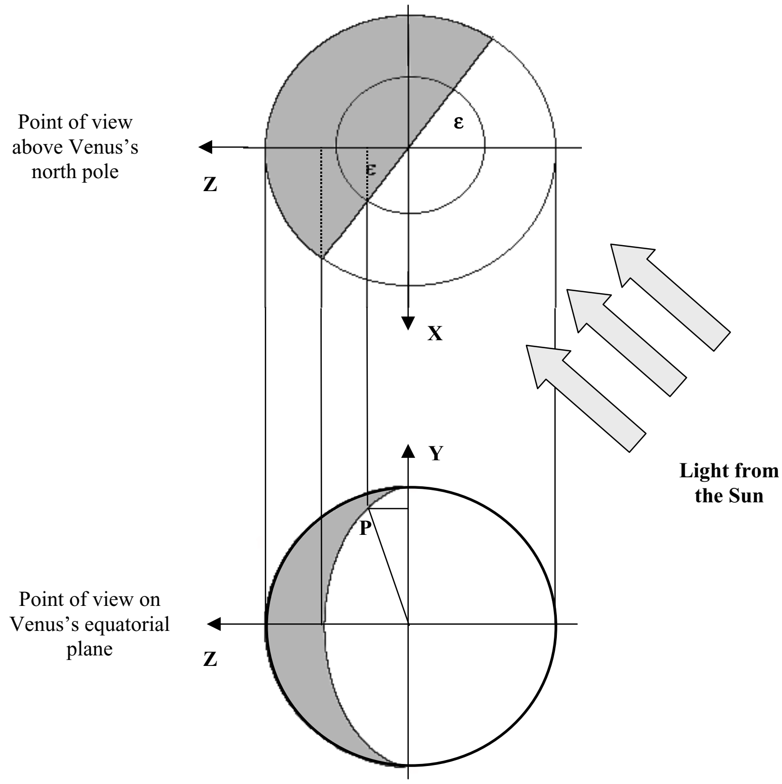

FIG. 12. The curve dividing light from darkness on Venus's surface (the grey area represents darkness). In the first image Venus is seen from above while in the second image the point of view is on the equatorial plane.

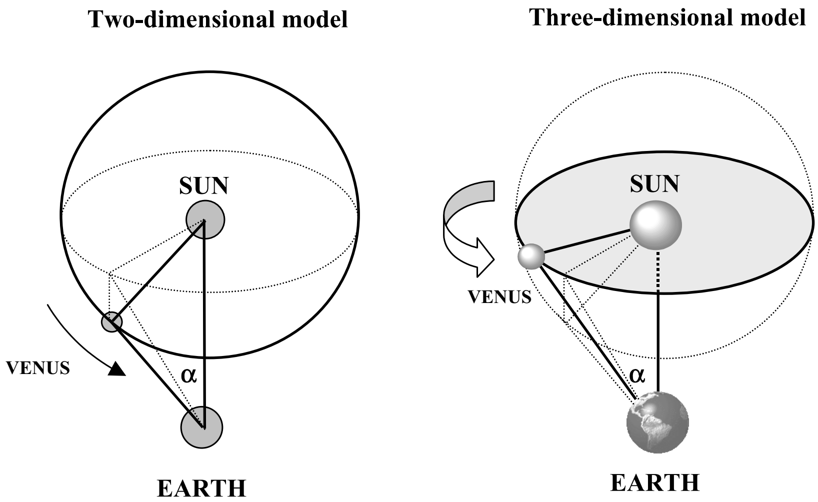

FIG. 13. The influence of Venus's latitude on the date of maximum elongation. On the left hand side, maximum elongation according to my two-dimensional model. On the right hand side, the real situation with maximum elongation occurring some time earlier. At the inferior conjunction of 1 March 1611, Venus was very "high" (its latitude being about 6°). Let α be the angle between Venus and Sun observed from Earth. Since maximum elongation is measured by α, then when Venus is "high" α becomes maximum some time earlier than the date predicted by my two-dimensional model.

been carried out with *Mathcad 5.0+*, a software package by *Mathsoft*.

Finally, the prediction of the time of Venus's maximum elongation deduced by the sky simulator data (between 10 and 20 December 1610) is in accord with the date obtained with my simplified model based on the assumption of circular and uniform orbital motions. However, it must be noted that my model runs a bit late and predicts a maximum elongation date a few days later than the sky simulator. This delay is immaterial since we need not establish this date with absolute precision and for our purposes the 'window' between 10 and 20 December is sufficiently accurate. The delay is due to the simplification introduced by the assumption of a two-dimensional model that does not take into consideration the latitude of Venus. In fact, at inferior conjunction, on 1 March 1611, as Galileo noted, Venus was very "high", i.e. north of the Sun (about 6°).[49] Figure 13 shows in a purely qualitative way how the latitude of Venus, which has been neglected in my model, affects the date of maximum elongation. Dimensions are greatly exaggerated in order to make the phenomenon more evident.

REFERENCES

1. Richard S. Westfall, "Science and patronage: Galileo and the telescope", *Isis*, lxxvi (1985), 11–30. I have quoted the article from Peter Dear (ed.), *The scientific enterprise in early modern Europe: Readings from "Isis"* (Chicago and London, 1997), 113–32, pp. 127–9.
2. Westfall, "Science and patronage" (ref. 1), 127ff. "Dishonesty" is used by Westfall, on p. 131. See also Rudolf Krämer-Badoni, *Galileo Galilei* (Munich, 1985). The author qualifies the whole episode as a "Pikanterie" (*ibid*., 79), a "Schwindel" (*ibid*., 82), and "ein unerfreuliches Trickspiel" (*ibid*.). The Italian historian, Raffaello Caverni, was the first to propose the dishonesty thesis at the turn of the nineteenth century. Caverni's interpretation of the episode has been rejected by Westfall ("Science and patronage" (ref. 1), 130). In 1919, Antonio Favaro, the editor of the National Edition of Galileo's works, refuted Caverni's main argument, in his article "Galileo Galilei, Benetto Castelli e la scoperta delle fasi di Venere", *Archivio di storia della scienza*, i (1919–20), 283–96. Favaro's refutation was based on a gross error made by Caverni, who had attributed to the hand of Vincenzo Viviani a copy of a letter that had been written by Castelli himself. *Cf*. the details in *ibid*., 290–1. There is no proof that Galileo actually received Castelli's letter on 11 December 1610. This hypothesis simply suits the dishonesty thesis. The Italian original of Castelli's letter is published in the National Edition of Galileo's works (Galileo Galilei, *Le opere di Galileo Galilei*, Edizione Nazionale, ed. by Antonio Favaro (20 vols, Florence, 1890–1909); hereafter *OGG*). I have quoted the National Edition using the following abbreviation: *OGG*, followed by the Roman numeral of the volume and page numbers in Arabic numerals.
3. Westfall, "Science and patronage" (ref. 1), 126ff. See Castelli's letter in *OGG*, x, 480ff.
4. Owen Gingerich, "Phases of Venus in 1610", *Journal for the history of astronomy*, xv (1984), 209–10, and William T. Peters, "The appearances of Venus and Mars in 1610", *Journal for the history of astronomy*, xv (1984), 211–14. The work by Gingerich was based on a modern pattern projected backwards in time by offsetting a difference in dates of 37 days. Peters's work was more quantitative and arrived at a diagram showing the percentage of Venus's illumination during the second half of 1610.
5. Peters, "The appearances" (ref. 4), 213.
6. *OGG*, x, 500, my translation.
7. *OGG*, x, 503. *Cf*. Galileo's answer to Castelli in *OGG*, x, 502–5.
8. *OGG*, x, 503.
9. *OGG*, x, 500.
10. On 25 February 1611, Galileo wrote a letter in which he was more precise than in his account to Clavius and said the Venus remained semicircular for about one month at the time of maximum elongation. The person to whom the letter was written is not known. *Cf. OGG*, xi, 53.
11. In his letters to Clavius and Castelli, Galileo also predicted the future evolution of the phases. "Now [i.e. on 30 December], it [Venus] begins to assume a notable corniculate shape. Thus, it will continue to decrease during the period in which it is visible in the evening sky and, in due course, we shall see it in the morning sky, with its thin corns on the other side from the Sun..." (*OGG*, v, 500).
12. See Peters's attempt to observe Venus with a replica of Galileo's telescope. *Cf*. Peters, "The appearances" (ref. 4), 211–14.
13. Westfall, "Science and patronage" (ref. 1), 130.
14. *OGG*, xi, 48, my translation. The letter is dated 12 February 1611. What was Galileo's source for the attribution to Aristotle of this order of planets? It might have been either Cristoph Clavius or some other scholastic material. Actually, Aristotle does not mention the question of the order of the planets. According to Edward Grant, Clavius attributed to Aristotle the descending order Mercury, Venus, Sun, and referred to this order as the "Egyptian system". This order is not in Aristotle's works in the places cited by Clavius in his *Sphere*, but in the pseudo-Aristotle's *De mundo*, which Clavius also cites. *Cf*. Edward Grant's discussion in his *Planets, stars, and*

orbs: The medieval cosmos, 1200–1687 (Cambridge, 1994), 312ff. See also Albert Van Helden, *Measuring the universe: Cosmic dimensions from Aristarchus to Halley* (Chicago, 1985), 20–23. Van Helden discusses in detail Ptolemy's ideas on the order of the planets. In Galileo's *Juvenilia* there is a scholastic tract on the *Order of celestial orbs*, in which Galileo attributes to the Egyptians the descending order Mercury, Venus, Sun and quotes the pseudo-Aristotle's *De mundo*. See *OGG*, i, 50. For an English translation and an attempt to show that this tract depends on material from the *Collegium Romanum*, *cf*. William A. Wallace, *Galileo's early notebooks: The Physical Questions* (Notre Dame and London, 1977).

15. Roger Ariew argues that "the existence and qualitative appearance of the phases of Venus do not seem to constitute a *crucial* anomaly for Ptolemaic astronomy". The author does not furnish any explanation for this assertion. He speaks of "some modifications" needed to accommodate Venus's phases in Ptolemaic astronomy without further expanding on this question. *Cf.* Roger Ariew, "The phases of Venus before 1610", *Studies in history and philosophy of science*, xviii (1987), 81–92, p. 86. I cannot think of any modification that could save Ptolemaic astronomy in the face of the *complete* cycle of Venus's phases. Nor am I aware of any attempt to accommodate Venus's complete phase cycle in the Ptolemaic system during the seventeenth century. On the contrary, there is evidence that, in the seventeenth century, accommodating Venus's phases in an astronomical system implied the abandonment of Ptolemy's system. For example, Andrea Argoli, a successor of Galileo at the chair of mathematics at Padua University, believed that both the Ptolemaic and the Copernican systems were untenable and proposed a semi-Tychonic system, in which Mercury and Venus rotated around the Sun, while the other planets rotated around the immobile Earth. In his *Pandosion sphaericum*, Argoli acknowledged that such a planetary system had already been put forward by Martianus Capella, but pointed out that until the seventeenth century no-one had calculated ephemerides according to this system. He was keen to stress that he had achieved this by publishing tables for almost the entire seventeenth century. *Cf.* Andrea Argoli, *Pandosion sphaericum* (Padua, 1644), 10. On Argoli, see Christine J. Schofield, *Tychonic and semi-Tychonic world systems* (New York, 1981), 175–6, and Maria Laura Soppelsa, *Genesi del metodo Galileiano e tramonto dell'Aristotelismo nella scuola di Padova* (Padua, 1974), 71–79.
16. Westfall, "Science and patronage" (ref. 1), 126 and 129. The cipher was vague and simply said that Venus showed phases similar to those of the Moon. As we have seen, from 1 October 1610 to 11 December 1610 Galileo had attributed to Venus a change of phase from circular to semicircular. He must have reckoned that this was enough to attribute phases to Venus.
17. Stillman Drake thinks that Galileo decided to write to Kepler on 11 December because he "risked anticipation by another astronomer", possibly by astronomers at the Collegium Romanum. See Stillman Drake, "Galileo, Kepler, and phases of Venus", *Journal for the history of astronomy*, xv (1984), 198–208. Quotation from: Stillman Drake, *Essays on Galileo and the history and philosophy of science* (3 vols, Toronto, Buffalo and London, 1999), i, 400.
18. Owen Gingerich, "Astronomical scrapbook: Galileo and the phases of Venus", *Sky and telescope*, lxviii (1984), 520–2, reprinted in his *The great Copernican chase and other episodes in astronomical history* (Cambridge, Mass., and Cambridge, 1992), #13, emphasis mine.
19. Edward Grant's discussion in Grant, *Planets, stars, and orbs* (ref. 14), 392ff.
20. *Ibid*., 392.
21. *Ibid*., 401.
22. Quoted in *ibid*., 402.
23. *Ibid*., 403.
24. Quoted in *ibid*., 403.
25. The first theory, which Riccioli attributed to Macrobius, held that all stars (except the Moon) were self-luminous. Amongst the followers of this thesis, Riccioli quotes Cardanus and, more recently, Kepler (from the *Astronomiae pars optica* of 1604, in which Kepler discusses light phenomena regarding the heavenly bodies and concludes that since Venus remains visible below the Sun it must emit its own light). The second theory stated that all stars and planets shone

because of the light received from the Sun. This he attributed to Plato's *Timaeus* and amongst the moderns to the Jesuit Father, Christoph Scheiner. The third theory was by a modern, Ismaël Boulliau. In the latter's *Astronomia Philolaïca*, according to Riccioli, the opinion was put forward that all stars and planets were partly lighted by the Sun and partly possessed their own light. The fourth theory was attributed by Riccioli to Giordano Bruno, Kepler, and Galileo. According to it, the planets were opaque bodies that shone because of the light received from the Sun, while the fixed stars emitted their own light. Riccioli himself favoured the thesis that the planets received their light from the Sun, i.e. the fourth one, although he did not concede that they were opaque bodies. He thought that their matter resembled that of metals, or rather that of precious stones of various colours. Thus, he concluded, planets are not opaque bodies similar to our Earth. Giovanni Battista Riccioli, *Almagestum novum* (2 vols, Bologna, 1651), i, 495ff.

26. Galileo Galilei, *Dialogue concerning the two chief world systems*, 2nd edn, ed. and transl. by Stillman Drake (Berkeley, Los Angeles and London, 1967), 334.
27. Rosen pointed out that Galileo, in his interpretation of Copernicus's ideas on celestial light, was actually misled by a misprint contained in the first edition of the *De revolutionibus*. *Cf.* Edward Rosen, "Copernicus on the phases and light of the planets", *Organon*, ii (1965), 61–78. I have quoted the article from Edward Rosen, *Copernicus and his successors* (London and Rio Grande, 1995), 81–98. According to Rosen, Copernicus did not hold any personal opinion on this matter, but simply attributed to the followers of Plato the argument that all heavenly bodies are dark and shine because they receive light from the Sun, and believed that this argument was used by Platonists against Ptolemy's arrangement of the planets, which placed Venus and Mercury below the Sun. Copernicus therefore does not appear to have had any theory on celestial light and the phases of Venus. It was Galileo who attributed to Copernicus the explanation of the absence of phases based on the hypothesis that Venus was either self-luminous or made of such material that it could imbibe solar light and re-transmit it to Earth. But, according to Rosen, "that Venus was transparent or self-luminous was a theory imputed by Copernicus to the followers of Ptolemy". *Cf. ibid*., 93–97.
28. If, for example, Venus was only partially opaque and transmitted light both by reflecting some solar light and by irradiating some light that had been absorbed by its body, the appearance of the phases would consequently have been affected to such an extent as not to be predictable. This conclusion would be perfectly reasonable in the framework of what Grant, as we have seen, believes to have been the most popular of the medieval theories, the mixed theory. This mixed theory, in various forms, was still a plausible hypothesis in Galileo's time, especially before the advent of the telescope. Grant, *Planets, stars, and orbs* (ref. 14), 408–9. The author quotes a number of seventeenth-century authors on celestial light.
29. *OGG*, xi, 12.
30. "... sin qui dubbie tra i maggiori ingeni del mondo", *OGG*, xi, 12.
31. Johannes Kepler, *Gesammelte Werke*, iv: *Kleinere Schriften 1602/1611*, ed. by Max Kaspar and Franz Hammer (Munich, 1941), 345–54.
32. Kepler, *op. cit.* (ref. 31), 350, my translation.
33. According to Galileo's *theory of adventitious irradiation*, it was the veil of humidity on the surface of the eyeball that was responsible for the formation of the adventitious luminous halo visible around bright objects. This theory, according to Galileo, explained why the luminous halo was not magnified by the telescope and why its shape and size practically remained the same for all objects (although he pointed out that by pressing the eyeball with a finger one could affect its appearance). Galileo concluded that if this halo was caused by humidity covering the eye, we should not marvel at its not being enlarged by the telescope, since it is formed behind the telescope, not beyond it. *OGG*, vi, 84–85.
34. *OGG*, xi, 61–62, my translation.
35. Kepler, *op. cit.* (ref. 31), 353, my translation.
36. Alan Chalmers noted that the telescope posed a threat to the teleological aspects of Aristotelianism

and was perceived as such by some of Galileo's contemporaries. He reached the conclusion that "Galileo undermined in practice standards implicit in Aristotelian methodology". This is confirmed by the case of Scipione Chiaramonti. *Cf.* Alan Chalmers, "Galileo's telescopic observations of Venus and Mars", *The British journal for the philosophy of science*, xxxvi (1985), 175–84, p. 183.

37. *OGG*, xiii, 337.
38. Scipione Chiaramonti*, Opuscula varia mathematica nunc primum in lucem edita* (Bologna, 1653).
39. Scipione Chiaramonti, *Difesa di Scipione Chiaramonti da Cesena al suo Antiticone, e libro delle nuove stelle dall' oppositioni dell' autor de' Due Massimi Sistemi Tolemaico, e Copernicano* (Florence, 1633). The book is not only a painstaking rebuttal of all the criticisms levelled at Chiaramonti by Galileo in the *Dialogue*, but contains critical comments on a number of other issues raised in the *Dialogue*. *Cf.* also Scipione Chiaramonti, *De universo* (Cologne, 1644).
40. Chiaramonti, *Difesa di Scipione Chiaramonti da Cesena al suo Antiticone* (ref. 39), 55, my translation.
41. Chiaramonti, *De universo* (ref. 39), 184.
42. *Ibid.*
43. *Ibid.*
44. As to the other planets, he adopted a teleological criterion whereby Nature granted different degrees of perfection to all bodies. Thus, he reasoned, on the celestial bodies Nature had bestowed light in ascending order of perfection from the Moon to the stars. But since the Sun was clearly the brightest object and yet not the highest one, Chiaramonti admitted that as regards the planets above the Sun the luminosity order was perhaps not respected by Nature and the question became one of religion rather than of philosophy. Chiaramonti, *De universo* (ref. 39), 185.
45. *Cf. Ioannis Antonii Magini Patavini, Ephemeridum coelestium motuum continuatio, Ab Anno Domini 1608 usque ad Annum 1630 iuxta Copernici observationes accuratissime supputatarum*, 2nd edn (Frankfurt, 1610), 168.
46. *Cf.* Galileo's letter of 25 February 1611 (ref. 10).
47. The ellipse can easily be derived by calculating the intersection between a plane (containing the origin of the frame of reference, parallel to the Y-axis, and forming an angle ε with the Z-axis) and a spherical surface (whose centre is the centre of the frame of reference) representing Venus's surface. The intersection is of course a circumference. By projecting this circumference onto the plane $X = 0$ one obtains the ellipse. An elliptical curve was derived for the line separating light from darkness in the case of the phases of the Moon by Scipione Chiaramonti. *Cf.* Chiaramonti, *Opuscula varia mathematica* (ref. 38).
48. The *Home Planet* package is in the public domain and available at the following internet address: http://www.fourmilab.to/homeplanet/homeplanet.html. The Help file contains references to the mathematical literature on which the software is based.
49. Galileo hoped that since Venus was so "high" he could eventually observe it even at its inferior conjunction with the Sun. *Cf. OGG*, xi, 53.