Empiricism Without the Senses: How the Instrument Replaced the Eye

Ofer Gal and Raz Chen-Morris

Abstract The optical instruments developed through the seventeenth century allowed peering into the very far and the very small; a spectacle never before experienced. The telescope, and later the microscope, was now expected to answer fundamental questions and resolve cosmological riddles by direct observation into the foundations of nature. But this ability came at an unexpected price and with unexpected results. For Kepler and Galileo, the new instruments did not offer extension and improvement to the senses; they replaced them altogether. To rely on their authority was to admit that the human eye is nothing but an instrument, and a flawed one at that. Rather than the intellect's window to the world, the human senses became a part of this world, a source of obscure and unreliable data, demanding uncertain deciphering. Accurate scientific observation meant that we are always wrong.

1 Introduction

On receiving news of Galileo's observations of the four satellites of Jupiter and the rugged face of the moon through his newly invented *perspicillum*, Kepler in great excitement exclaimed:

> Therefore let Galileo take his stand by Kepler's side. Let the former observe the moon with his face turned skyward, while the latter studies the sun by looking down at a screen (lest the lens injure his eyes). Let each employ his own device, and from this partnership may there some day arise an absolutely perfect theory of the distances.[1]

This Hollywood-like scene of the two astronomers marching hand in hand toward the dawn of a new scientific era was no attempt by Kepler to appropriate Galileo's

[1] Kepler 1965 [1610], 22.

O. Gal
Unit for History and Philosophy of Science
The University of Sydney, Bar Ilan University

R. Chen-Morris
Science, Technology and Society Program
The University of Sydney, Bar Ilan University

C.T. Wolfe and O. Gal (eds.), *The Body as Object and Instrument of Knowledge: Embodied Empiricism in Early Modern Science*, Studies in History and Philosophy of Science 25,
DOI 10.1007/978-90-481-3686-5_7,

success or to diminish the novelty of the telescope.[2] On the contrary, Kepler repeatedly asserted how short sighted he was in misjudging the potential for astronomical observations inherent in lenses, and how radically Galileo's instrument transformed the science of astronomy. It was a deep sense of recognition that beyond their different scientific temperaments and projects, they shared a common agenda of a new mode of empirical engagement with the phenomenal world: the instrument. For Kepler and Galileo, empirical investigation was no longer a direct engagement with nature, but an *essentially* mediated endeavor. The new instruments were not to assist the human senses, but to replace them.

2 Galileo: An Instrument for an Eye

The eye, in this new scheme, was to become a part of the instrument. When Kepler describes the nipple shaped lens, which he suggests as an improvement to Galileo's telescope, he explains that the position of the observer's eye depends on the "spot where the rays from all points of the object under observation converge at a common focus (this is the function of the hyperbolic nipple)."[3] The rays coming parallel from a distant point are converged by the nipple shaped lens at the crystalline humor and are continually refracted within the eye until "they strike the retina." The resulting image is "quite confused" and in order to set it right, Kepler suggests another lens to manipulate these inner refractions by adjusting the coming of the rays as if "they come from some nearby point." The result will be that the rays will "find their points of convergence on the retina itself. This is the definition of clear vision."[4] Kepler does not differentiate between the "natural" ocular membranes – the crystalline humor and retina – and the artificial lenses and screens; they are all integrated into a continuous process that creates from the rays of light a clear picture on a flat opaque surface.

Kepler's account of his suggested improvement to Galileo's invention accords well with Galileo's own instructions for its use. Such special instructions are required, and provided in the first pages of his *Sidereus Nuncius*, because unlike

[2] Kepler's ulterior motives constitute the crux of Biagioli's recent reconstruction of this exchange (Biagioli 2006, esp. 33–39). Biagioli queries Kepler's hasty and enthusiastic reply to Galileo's request to assess his telescopic observations, when in fact Kepler had not yet seen a telescope or observed personally the celestial phenomena Galileo claimed to have seen. Biagioli claims that the distance between Galileo and Kepler and the partial information Kepler had regarding Galileo's status in the Florentine court contributed to this exchange. Albeit, one should notice that Kepler's inability to build a high power telescope was due to specific practical problems concerning lens production and not to lack of theory about how telescopes work and how lenses magnify. Kepler's embraced Galileo's telescope as a confirmation of his optical theories and of his proposed observational practice using instruments in preference of a naked eye.

[3] Kepler 1965 [1610], 20.

[4] Kepler 1965 [1610], 21.

optical predecessors such as the spectacles, the scientific instrument does not simply strengthen the weak eye. It thoroughly replaces the 'natural' function of the sense organ with reasoned procedure of observation, into which measurement and comparison are built and into which the eyes should be assimilated. Galileo first cautions the readers that they have to "prepare a most accurate glass that shows objects brightly, distinctly, and not veiled by any obscurity." He then asks them to verify the power of magnification through an exercise that demands both the ability to produce accurate geometrical drawings of two circles, one 400 times larger than the other- together with the ability to force the eyes to gaze each at different objects, yet still be able to compare their sizes. After adjusting the eyes to the instrument, Galileo proceeds to his sketchy instructions as to how to measure distances viewed through the telescope's lenses.[5]

These instructions did not reveal to Galileo's readers how fundamentally novel was the status he assigned to his instrument. The telescope was accepted with great fanfare and immediately embraced by the scholarly community.[6] In fact, it seemed like an excellent way to conduct innovative astronomy without being entangled with the cosmological ramifications of the new astronomical theories, and was enthusiastically endorsed for this reason by the Jesuits.[7] "Now no part of the sky escapes our glance," they rhapsodized about "the lynx eyes:"

> nor is the beauty of the moon so great as it was for us formerly. We have been able to distinguish the circular motions of Venus and Mercury, and who does not blush to see the sun occasionally disfigured? We have laid bare the stratagems of Mars in approaching the earth and we have exposed the attendance of Jupiter and Saturn, hitherto hidden away to no purpose.[8]

But these very words, written a decade after the introduction of the telescope, did nothing but set up the inevitable clash between the radical epistemology that Galileo attached to the new instrument and the traditionalist project to which the Jesuits were attempting to harness it. The occasion for drawing clear lines between the modes of instrument-aided observation was introduced by the appearance of a sequence of three comets in the European sky during 1618 (Fig. 1).

The three comets – especially the third – were most impressive and had been carefully observed in late November by astronomers all over Europe, initiating a masquerade of astronomical treatises in which anonymous writers, pseudonyms and false authorship paraded through the European astronomical community, examining the demarcation lines between appearances and substances, optical illusions and authentic events.

---

[5] Galilei 1989 [1610], 38–39.

[6] See Malet 2005, Shea 1972, and van Helden 1974.

[7] van Helden 1974, 53.

[8] Grassi 1619, 5–6.


COMETA ORIEN-
TALIS,
Kurtze vnd eygentliche Be-
schreibung deß newen Cometen/so im No-
vember deß abgelauffenen 1618. Jahrs in Orient/oder gegen
Auffgang der Sonnen allhie erschienen/vnd von men-
niglich gesehen worden.
Auß warhafften Astrologischen vnd Historischen
Gründen menniglich zur Nachrichtung gestellt/
Durch
M. Gothardum Arthusium Dantiscanum, P.C.Histor.
& Philo-Mathem. zu Franckfurt am Mayn.
2. Timoth. 3.
Instabunt tempora periculosa.
Franckfurt am Mayn/bey Sigismundo Latomo.
M. DC. XIX.

Fig. 1 The Comets of 1618

Galileo's entrée into this parade and the positions he expresses in it are very surprising. Never having observed the comets himself, he waited until an anonymous treatise by the Jesuit mathematician Horatio Grassi, *De Tribus Cometis Anni 1618 Disputatio Astronomica* (1619) introduced the issues of the scholarly discussion about these spectacular objects. Grassi's views are ones that Galileo should have been delighted with. Not only does he begin with the tribute to Galileo and his instrument cited above, his main conclusion is one that should have particularly appealed to Galileo: "our comet was not sublunar" he declares, "but clearly celestial."[9] Tycho Brahe had already arrived at this conclusion concerning the comet of 1577, as well as the *Nova Stella* of 1572, but the idea that comets and other transient objects are superlunary did not lose its revolutionary cosmological significance. The sharp dichotomy between the realm under and above the moon, which the heavenly position of comets undermined, was not an arcane scholarly conviction; it was well entrenched in religion and commonsense.[10] If Galileo was engaged in "a polemic against the Aristotelian and scholastic physics,"[11] as is commonly assumed, Grassi and Tycho should have been his close allies and the superlunary position of the comets his cherished weapon.

Yet Galileo chooses to join the discussion with a fierce assault on Grassi's *Disputatio*. He does it stealthily, dictating a *Discourse on the Comets* in Tuscan through his disciple and fellow academician Mario Guiducci (1619).[12] Grassi, however, is not fooled. He mocks "Galileo [for] order[ing] the matter to be discussed through intermediaries and interpreters" and joins the play of "secrets of mind" by replying with *Astronomical and Philosophical Balance*, apparently composed with other members of the *Collegio Romano*, under the anagram Lothario Sarsi of Siguenza (Sigensano 1619). For the celebrated climax of the debate Galileo unmasked and answered 'Sarsi's' Latin *Balance* (*Libra*) with his own – again Tuscan – *The Assayer* (*Il Saggiatore*, 1623), simultaneously denying that he was behind Guiducci *and* complaining about Sarsi's lack of manners in exposing him.[13] This was more than literary playfulness. In *The Assayer* Galileo not only discloses his own true identity and points to that of his rivals, but urges the reader to unmask Nature herself to see beyond "the bounty [of] her effects."[14]

Modern historians and philosophers of science, ensnared by these playful polemics, usually read *The Assayer* as a defense of Copernican astronomy against a complex of theological and conservative views of nature. But Galileo's arguments and those of Grassi's he chooses to refute demonstrate that the polemics are about the power and significance of instrumental observation. Yet Galileo does not defend the value of the telescope, which Grassi, we saw, has never doubted. Galileo takes

---

[9]Grassi 1619, 14.

[10]Concerning the significance of the superlunary position of comets see Van Nouhuys 1998. On the difficulties the Jesuits had with Tycho's cosmology see: Baldini 1992, 217–250; Blackwell 1992, esp. 148–153; Lattis 1994, 94–102, 211–216.

[11]Cassirer 1942, 316.

[12]Favaro asserts that "the pages of the first part … have corrections and additions in Galileo's handwriting. A second part … is entirely in Galileo's writing. The third part in Guiducci's hand … but there are correction by [Galileo]" and concludes that "the entire discourse may be said to be essentially his work." Quoted in Drake and O'Malley 1960, xvi–xvii.

[13]Galileo 1623, 169.

[14]Galilei 1623, 236. "La ricchezza della natura." In Galilei 1890–1909, 6: 281.

the opportunity of the discussion about comets to pursue his (and Kepler's) new empiricism, in which instruments are to replace the human senses.

Galileo reveals these intentions by targeting Grassi's two main arguments for the superlunary position of comets. The first one is based on the same method Tycho had perfected a generation earlier to make his claims about the celestial position of comets:

> If the comet was observed from different places and compared with the stars of the firmament, and if it preserved the same distance from them, it must be regarded as either in the firmament or certainly not far removed from it. But if it underwent parallax, it must be placed below the firmament in proportion to the amount of the difference of aspect.[15]

Parallax calculations – the comparison of the angles of sight from different positions – was a traditional and most venerable method of observational astronomy. For Grassi and the Jesuits, it gained further support through their intricate network of scholars and institutions deployed all over Europe. When observers in "Milan and in Parma … from Innsbruck in Germany and from France and Belgium" report the same position for the comet, and when finally two particularly accurate observations from Rome and Cologne completely coalesce in time and place, Grassi feels validated. The claim for the superlunary position of the comets does not "exceed the boundaries of our knowledge" and remains within the realm of empirical modesty.[16]

Yet what for Grassi is a carefully measured factual conclusion is completely unacceptable for Galileo. "Parallax operates reliably," he lets Guiducci claim on his behalf, "in real and permanent things whose essence is not affected by anyone's vision; these do not change place when the eye is moved. But parallax does not function in mere appearances," and comets are among those

> reflections of light, images, and wandering simulacra which are so dependent for their existence upon the vision of the observer that not only do they change position when he does, but … would vanish entirely if his vision were taken away.[17]

Galileo's real target should not be mistaken. It is neither the case that he harbored some deep aversion to parallax considerations, nor that he was particularly committed to Aristotelian meteorology or convinced in the errors of Tycho's way, or even that he was indeed so careful in his own parallax observations as to limit them only to unquestionably solid celestial bodies. In a series of public lectures following the supernova of 1604, for example, he took a clear Tychonic position and used the lack of parallax to argue that the new star was super lunar.[18] What Galileo is really assaulting is a particular type of empiricism, encapsulated in Grassi's knock-down parallax argument:

[15] Grassi 1619, 11.

[16] Grassi 1619, 6.

[17] Guiducci 1619, 36–37.

[18] Galilei 1890–1909, 2: 277–284. Cf. Dupré 2003, 373.

> If at the same time from other regions the same star was also observed very near to the comet, no stronger and clearer argument could be hoped for by which it might be demonstrated that the comet had very little or no parallax, since this could be observed without any instrument and by *observation with the unaided eye*.[19]

This last clause captures for Galileo the Jesuit-Tychonic position on parallax, an approach to scientific observation which he is obliged to confront and against which he defines his own empiricism. For Grassi and the Jesuits, the final arbitrator and the measure of all observations is the "unaided eye." Their parallax observations are particularly trustworthy, they assume, because they can be conducted "without any instrument." Galileo's arguments aim at the conditions of visibility necessary for parallax measurements because he wishes to undermine the fundamental assumption of the Jesuits' epistemology – the reliability of observation by the naked eye:

> in order to have the comet appear as without parallax to all observers, and still originate in the elemental sphere, it would suffice for vapours … to be diffused on high and to be capable of reflecting the sun's light through distances and spaces equal to … those from which the comet is perceived.[20]

Parallax is liable to the baffling effects of appearances and optical illusions because it is dependent on the naked eye. This is the crux of Galileo's surprising assault: observation "without any instrument" is not preferable, it is, on the contrary, fundamentally suspect.

Galileo further focuses the attack on the naked eye in answering Grassi's other main argument for the superlunary position of comets. "It has been discovered by long experience," claims Grassi,

> and proved by optical reason that all things observed with this instrument [the telescope] seem larger than they appear to the naked eye; yet according to the law that the enlargement appears less and less the farther away [the observed things] are removed from the eye, it results that fixed stars, the most remote of all from us, receive no perceptible magnification from the telescope. Therefore, since the comet appeared to be enlarged very little it … is more remote from us than the moon, since when [the moon] has been observed through the telescope it appears much larger.[21]

This is the one argument that Galileo would not forgive. He would not allow that one can conclude about the distance of the comets from the failure of the telescope

[19]Grassi 1619, 14. Italics added. "Si enim in aliis etiam regionibus eodem tempore eadem stella cometae proxima observaretur, nullum maius atque evidentius optari poterat argumentum, quodemonstraretur nullum aut perexiguam parallaxim cometae fuisse, cum hocabsque ullo instrumento, unico oculorum intuitu, observari posset." Grassi in Galilei 1890–1909, 6: 31.

[20]Guiducci 1619, 40. One should note how much Galileo's argument is as removed from "opposition to the closed system of the schools," as Drake presented "The Assayer" in the preface to Drake and O' Malley, 1960, xxiii. Galileo's rejection of the parallax is based on proto-Aristotelian concept of the comets as resulting from exuding vapors, and furthermore, preserves "the Aristotelian duality" between heavens and the "elemental sphere."

[21]Grassi 1619, 17.

to magnify them, because he will not admit to this failure; the telescope magnifies regardless of distance:

> If a surface of a ball seen through the telescope at a distance of half a mile increases a thousand times, then so will the moon's disc increase a thousand times and no less; so will that of Jupiter and finally that of a fixed star.[22]

It is important to stress again that Grassi is an avowed supporter of the telescope and "the lynx eyes." The telescope is a legitimate, marvelous extension of the eye, strengthening its weaknesses and repairing its errors. Indeed, interpreting Galileo as arguing for this legitimacy, Grassi bitterly protests (under the name of Sarsi and on behalf of his Jesuit colleagues) what he perceives to be his portrayal as a scientific reactionary. Nothing is farther from the truth, the author of *Libra* complains; he is a champion of progress and a staunch defender of Galileo and his instruments:

> There were not lacking those who … asserted that … the telescope carries spectres to the eyes and deludes the mind with various images; therefore it does not display genuinely and without deception even those things which we observe close at hand, much less those which are far removed from us, except it will show them bewitched and deformed. We … publicly confuted the ignorance of those for whom this instrument was of no significance … we hoped that by protecting from invidious calumnies this telescope … we might therefore deserve well of [Galileo] rather than ill.[23]

There is no particular reason for Grassi to reject the telescope. Traditional mathematical optics provides him with a clear and trustworthy account of the principles of the instrument's operation:

> Objects are enlarged by the telescope because these objects are carried from it to the eye under a greater angle then they are observed without this instrument … according to optics, whatever things are observed under a larger angle seem larger.[24]

This analysis also provides him with an explanation, again in terms taken directly from traditional eye-centered, Euclidean-based optics, why the fixed stars, and presumably comets, should elude magnification:

> Be the visible objective whatever it may, the more it is removed from the eye the smaller and smaller the angle at which it is seen … thus, the angle of incidence of the images at the telescope scarcely vary after the objects have reached a very great distance, for then it is just as if all the rays fell perpendicularly on the lens.[25]

Note how 'modern' Grassi is, how well entrenched in the most contemporary cosmology: Copernican or Tychonian, Grassi's world offers "very great distance" for the fixed stars. Yet Kepler and Galileo's move towards the abolition of the dichotomy between eye and instrument, if Grassi is aware of either, has

[22] Galileo 1623, 220.

[23] Sarsi 1619, 80–81.

[24] Grassi 1619, 79.

[25] Grassi 1619, 82.

left him completely unaffected. The "visible object," for him, is seen *by the eye*. The telescope is of a different status altogether; it is a part of the medium *through* which vision occurs, and subject to the same mathematical analysis. It helps like any instrument might – hence the title *Libra* – but it does not change the principal onus of evidence and argument. This lies, always, with what "could be observed without any instrument and by observation with the unaided eye."[26]

With this loyalty to the naked eye, as far as Galileo is concerned, Grassi completely misses the import of the telescope. Grassi, we saw, was taken aback by the vehemence of Galileo's replies, and understood them as a defense of telescopic observation. But his baffled defense of his credentials in this respect was misplaced. Galileo had even less patience for his hearty support than for his mild criticism: "Sig. Sarsi, give up trying to exalt this instrument with this admirable new properties of yours unless you wish to throw it into utter disrepute."[27] His sarcasm aside, what is clear is that Galileo was not disturbed by Grassi's empirical claims but by his analysis and arguments, and disturbed enough that he felt compelled to reject both Grassi's support and his conclusions.

Galileo has no qualms about Grassi's geometrical analysis of magnification "for objects seen naturally." In that case, "the diminution of the angle is made in a continually greater ratio the more the object is removed."[28] But Galileo has little respect for the way objects are "seen naturally." From Galileo's point of view, the instrument does not extend the sense organ, but replaces it altogether, and in the process it is the naked eye that loses its legitimacy as a source of knowledge:

> The naked eye distinguishes none of these shapes [of the heavenly bodies] without the telescope. [29]

Galileo, then, does not reject Grassi's cosmological conclusions because he nurtures some deep-held belief in the sublunary nature of comets. Rather, he finds himself placing the comets in the "elemental sphere" because he is adamant to reject the implications of Grassi's main arguments to the contrary. Namely: that fixed stars, like comets, are not magnified by the telescope, which implies that the telescope does not magnify *all* objects; and that absence of parallax is *the* unassailable testimony for the great distance of comets, which implies the supremacy of what "could be observed without any instrument and by observation with the unaided eye."

It will be a mistake to think of Galileo as defending the telescope or apologizing for its failure to magnify very distant objects. There is no such failure, he insists:

[26] Grassi 1619, 14.

[27] Galilei 1623, 209.

[28] Galilei 1623, 221.

[29] Galilei 1623, 321. "Senza il telescipio, l'occhio libero niuna di cotali figure distingue." Galilei 1890–1909, 6: 359.

comets and fixed stars do not appear magnified *to the eye* because of a distortion produced *by the eye* and repaired by the telescope:

> what we meant by saying the telescope 'robs the stars of irradiation' … is that it operates upon the stars in such a way [as to circumvent] the irradiation which disturbs the naked eye and impedes precise perception.[30]

The eye introduces a spurious splendor around stars and comets that makes them appear larger. This is not real magnification, of course: the body of the celestial objects remains invisible to the naked eye. Because the telescope removes this "irradiation," the eye fails to notice that it has also magnified and made visible the celestial bodies themselves. This is not an *apologia* for the instrument. Rather, it is a charge against the eye, which errs twice: once in introducing the false "wig" and once in failing to notice the correction and magnification.[31] Grassi's claim that fixed stars and comets "suffered scarcely any enlargement" meant that they did not appear larger *to the eye*. But the eye, in Galileo's new radical instrumentalism, is no longer the main point of reference for visual phenomena, and definitely not the final adjudicator of their trustworthiness.

3 Looking at the Sun

Kepler's excitement over Galileo's instrument was genuine. The coming of the telescope facilitated a new level of accuracy that far exceeds the abilities of the human naked eye. The resulting, artificially-produced image made Tycho Brahe's accurate and meticulous observations obsolete. Kepler, who regarded Brahe's observations as "the pinnacle" of human scientific enterprise, had to admit that "your telescope, Galileo, surpasses these attainments."[32] It is true that Tycho measured celestial degrees most accurately, but with the new instrument the astronomer "subdivides [Tycho's celestial degrees] with the utmost nicety into minutes and fractions of minutes." Consequently, the intellect, which until the invention of the telescope could have only abstractly fathom certain generalities about the heaven, could now be assisted with exact and concrete observations of the distant realms. The intellectual imaginations of ancient philosophers as well as of Copernicus,

---

[30] Galilei 1623, 324.

[31] This is a recapitulation of his arguments (including the hairy metaphor) in the *Sidereus Nuncius:* "The reason for this is that when the stars are observed with the naked eye, they do not show themselves according to their simple and, so to speak, naked size, but rather surrounded by a certain brightness and crowned by twinkling rays … Stars are therefore seen unshorn in the midst of darkness, but daylight can shear them of their hair … The spyglass likewise does the same thing: for first it takes away the borrowed and accidental brightness from the stars and thereupon it enlarges their simple globes." Galilei 1989 [1610], 57–58.

[32] Kepler 1965 [1610], 21–22.

Bruno and Kepler himself were disassociated from the limitations of sense experience. The telescope allowed the new philosopher to compare these fantasies on the shape and character of the planets to real observations.

The excitement was genuine, because by the time he was presented with Galileo's instrument, Kepler himself was already pursuing the astronomical use of optical (that is – lens based) instruments for some time. Even more important, Kepler shared with Galileo an understanding of the significance of the telescope: optical instruments were to take primacy in observation, and the eye would need to be integrated into them. This epistemological novelty, that Galileo would hint at in the *Sidereus Nuncius* of 1610 and attempt to explain in the controversy over the comets a decade later, was already explicated in Kepler's 1604 optical *opus magnum*, the *Optical Part of Astronomy* (*Ad Vitellionem Paralipomena*).[33] Kepler provides a vivid example for this new instrumental empiricism in describing his observation of a lunar eclipse through a *Camera Obscura.* Introducing an artificially-produced image, Kepler turns his instrument of observation into the locus of astronomical knowledge, and lets the human observer slip out of his optics:

> On 1602 21/31 December at 6h in the morning, through a device described in Ch. 2 [camera obscura] and an instrument made for this purpose, a description of which is furnished below, the moon made an image of itself brightly upon the paper lying below, inverted in situation, just as it was in the heavens, gibbous … You should not think that what I would consider to be in the moon's ray was in the paper, for both the gibbous face and the spot in its middle were carried over to all parts of the paper whatever that was placed beneath it; rather, indeed, it was from moving the paper that the spot was first discovered.[34]

The observation, Kepler stresses, is not *his*. It is no-one's. The image of the moon is not the culmination of a cognitive process. It does not require an observer; a piece of paper is enough. In fact, even the paper is not necessary: it can be moved around without affecting the production of the image.[35] A decade later and a few years before entangling himself in the debate over the comets, Galileo observed the sun

[33] Kepler 1937– [1604]; Kepler 2000 [1604]. We will use *Ad Vitellionem* (1937– [1604]) to refer to the original Latin and *Optics* (2000 [1604]) to refer to Donahue's translation.

[34] Kepler 2000 [1604], 259.

[35] The relation between the camera obscura and the eye is at the heart of the historiographic debate concerning Kepler's optics. For Straker (1971, and cf. Crombie 1953) the instrument represents Kepler's novel commitment to the mechanization of the eye and his indebtedness to the artisanal tradition. Kepler's claim that the locus of images is the retina rather than the crystalline humor, Straker argues, is an immediate consequence of comparing the eye to a camera obscura. Lindberg, in contrast, argues for Kepler's reliance on the perspectivist tradition, stresses that "only on one occasion did [Kepler] explicitly compared the eye to a camera obscura" (Lindberg 1976, 206). As we claimed above and will argue below, this debate is somewhat misdirected: Kepler's main motivation in equating the eye and the camera obscura is legitimating the instrument no less than understanding the eye.

spots in a similar way; only instead of the simple *Camera Obscura* he posited a telescope between the observed object (the sun) and the paper:

> Direct the telescope upon the Sun as if you were going to observe that body. Having focused and steadied it, expose a flat white sheet of paper about a foot from the concave lens; upon this will fall a circular image of the Sun's disk, with all the spots that are on it arranged and disposed with exactly the same symmetry as in the Sun. The more the paper is moved away from the tube, the larger this image will become, and the better the spots will be depicted … In order to picture them accurately, I first describe on the paper a circle of the size that best suits me, and then by moving the paper towards or away from the tube I find the exact place where the image of the Sun is enlarged to the measure of the circle I have drawn. This also serves me as a norm and rule for getting the plane of the paper right, so that it will not be tilted to the luminous cone of sunlight that emerges from the telescope. … By tilting the paper the proper position is easily found, and then with a pen one may mark out the spots in their right sizes, shapes, and position.[36]

As Galileo does in his lunar observations, Kepler relegates the eye to a secondary role, as the sunlight imprints (*stampata*) the image on the paper. The observer is turned into a draughtsman whose role is to stabilize and trace the outlines of the image.

Galileo's telescope thrust into public attention the assumptions implicit in Kepler's highly professional new optics with its direct challenge to the traditional eye-oriented modes of astronomical observation. It compelled astronomers to reconsider their epistemological manual as to what is a valid observational practice, but not many were willing to adopt Kepler and Galileo's epistemology together with their instruments. The Jesuits, loyal to their mandate to employ the novelties of the New Science in the service of the mores of counter-reformation church,[37] were particularly conspicuous in their efforts to implement the new means and techniques of observation while completely ignoring the marginalization of the human eye that for Kepler and Galileo was a necessary implication. Their debate with Galileo over the sunspots was, in this respect, analogous to the comets debate to follow. Their representative, Christoph Scheiner, fiercely competed with Galileo for credit on the empirical discovery, and between them, Scheiner's interpretation of it was, metaphysically, the more radical: the spots, he suggested, were shadows of hitherto unknown planets. Epistemologically, however, he remained unwavering in his commitment to the superiority of the naked eye. Ignoring the obvious hazards, he insistently used his eyes to look at the sun. This in spite of the different filtering devices he had to apply in order to protect his eyes that distorted and obscured the observations. Like Grassi, Scheiner was proficient with the new instruments and techniques, and experimented with projecting images from the telescope on a white surface (Fig. 2). These projections, however, were not intended to produce pictures of the sunspots but merely to examine any flaws in the lenses as well as other optical effects produced by them. Scheiner invested much energy

[36] Galilei 1890–1909, 5: 136–137. Quoted and translated in Biagioli 2006, 190.

[37] *Cf.* Dear 1995, esp. Chapter 2, and Feldhay 2000.

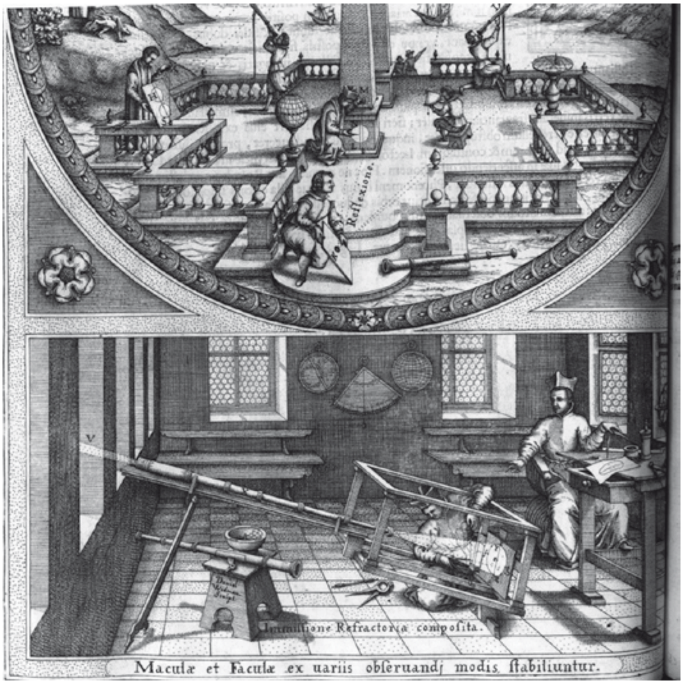

Fig. 2 Chistophoro Scheiner, Rosa Ursina (1626–1630)

to minimize the role of the instrumental mediation so the sunspots will be “seen without a tube, by the eye of any man.”[38]

Like the ensuing one over the comets, the controversy over the sunspots was not primarily over observations and their interpretation. Rather, it revealed a deeper level of contention concerning what the role of vision is in the production of knowledge. The Jesuits, following Scheiner, devoted most of their efforts to preserving the status of the eye as the guarantor of any knowledge of nature. Disregarding Kepler’s rejection of the traditional distinction between direct and mediated vision, Jesuit mathematicians held on to the Pauline belief in the supremacy of “face to face” acquaintance. In his 1613 large volume containing *Opticorum libri sex: Philosophis iuxta ac Mathematicis utiles* the Jesuit Fransciscus Agvilonius most emphatically reaffirmed traditional hierarchy of sight:

> All the things that are contained in Optics are considered under a triple reason, [compared] to the triple mode through which creatures come to know God. First direct [vision], that is our eye, as it turns towards the thing in front of it, so it is compared to the cognition of the minds of the blessed contemplating the presence of God, as St. Paul said: face to face. The second [part] is reflection [repercussion] that is the perception of those things, whose

[38]Galilei 1890–1909, 5: 59–61. Quoted and discussed in Biagioli 2006, 200–201.

> images come back to us from mirrors, this is not unlike that cognition, that through faith we see God in the created things as in a kind of mirror or in enigmas. Thence the third, that we call infraction; this is how the species of things are transmitted through dissimilar diaphanous [media], and from them [the species] enter the eye as if deformed and fractured. Thus some of the divinatory notions of the heathens, corrupted by many errors, are affected by the light of nature only.[39]

Whether he is ignorant of Kepler and Galileo's new concept of the eye and its place in visual perception or consciously rejecting it, Agvilonius' commitment to the traditional cognitive hierarchy and especially the distinction between mediated and direct vision remains unwavering: any mediation is a source of enigmas, distortions or heathen delusions and errors.

4 Kepler: the Eye as an Instrument

For Kepler, the introduction of the telescope provided another demonstration of the poverty of this hierarchy and the need to undo the supremacy of "face to face" vision that Grassi, Scheiner and Agvilonius assumed. Galileo's observations made it ever clearer that true knowledge of heavenly bodies was produced through the mediation of lenses and their complex and multiple refractions. Kepler was very explicit that his own treatise on optics was to provide optical foundations for a new, instrument-based astronomical observation*: artificiosa observationes*, as he calls them in the subtitle.

Published 5 years before the advent of the telescope, the main artificial instrument of observation to occupy Kepler's attention in the *Ad Vitellionem* is, as we saw, the *camera obscura*. Kepler first establishes its legitimacy and efficiency by demonstrating that the image obtained through it is indeed that of the observed object.[40] He goes on to elucidate by way of physical simulation its underlying principle, namely – the formation of an image on a screen behind a small aperture:

[39] Agvilonius 1613, 3. "Continetur omnis Optice triplici fere videndi ratione … triplici etiam modo quo deum creaturae cognoscunt, … comparauit. Prima directa, quae est oculi nostri, sic, ut in rem propositam intendit, cum illa cognitione componitur qua beatorum mentes praesentem Deum, facie ad faciem, ut D. Loquitur Paulus, contemplatur. Altera repercussa, sive earum rerum perceptio, quarum a speculis ad nos imagines revertuntur, cui non absimlis est illa cognitio, qua Deum per fidem in rebus creatis, veluti quodam speculo aut aenigmate videmus. Tertia denique, quam infractam vocant, ea est, qua rerum species per dissimilia diaphana transmissae, et ab iisdem quasi deformatae ac fractae in oculos immittuntur. Sic Ethnici divinitatis notionem aliquam, sed multis erroribus vitiatam, naturae solius lumine affecuti sunt."

[40] For the import of the camera obscura in the study of Kepler's optics see f.n. 35.

> I set a book in a high place, which was to stand for a luminous body. Between this and the pavement a tablet with a polygonal hole was set up. Next, a thread was sent down from one corner of the book through the hole to the pavement, falling upon the pavement in such a way as to graze the edges of the hole, the image of which I traced with chalk. In this way a figure was created upon the pavement similar to the hole. The same thing occurred when an additional thread was added from the second, third and fourth corner of the book, as well as from the infinite points of the edges. In this way, a narrow row of infinite figures of the whole outlined the large quadrangular figure of the book on the pavement.[41]

The threads from the book's corners pass through the polygonal hole, grazing its edges and projecting images in the shape of the hole – a hole-shaped image for each corner of the book. The four images of the book's corners are arranged on the floor in reverse order, and when this process is repeated from (ideally) every point of the book, a multitude of hole-shaped images will be projected on the floor, arranged in the (reversed) pattern of the book.

This is a neat solution to an age old mystery, but the solution is not where the novelty of Kepler's optics rests. Neither the phenomenon of pinhole images, on which the *camera obscura* is based, nor its account in terms of intersecting rays is new to the optical tradition.[42] Explanations of the phenomena based on geometrical analysis of rays were available to the optical tradition at least since Levi ben Gershon (Gersonides) in the beginning of the fourteenth century.

Kepler's novelty is in setting the stage to the radical instrumentalization of observation he would share with Galileo by eradicating from his explanation any references to the eye and human vision. For the perspectivist account from Gersonides to Maurolyco in the first half of the sixteenth century, the pinhole image was not just a reliable projection of its source. It was a unique *re-presentation* of the sun.[43] The circular image was not *caused* by the sun and by light; it was the true form of the sun or the perfect dissemination proper of light, as John Pecham in the late thirteenth century explains:

> The spherical shape is associated with light and is in harmony with all the bodies of the world as being to the highest degree conservative of nature, all parts of which join together most perfectly within itself. This is why a raindrop assumes roundness. Therefore, light is naturally moved toward this shape and gradually assumes it when propagated some distance.[44]

Understood this way, the circularity of the image does not simply testify to a property of its source; it is a sign of the image's indubitable authenticity. This essential relation between source and image completely disappears from Kepler's account, together with the exactness of representation it insures. There is nothing unique to the

[41] Kepler 2000 [1604], 56.

[42] See Aristotle 1984, Problems Bk 15, Ch. 6, 911b1, 2:1417; Pecham 1970, 67. See also Lindberg 1968, 1969; Thro 1996, 20–54.

[43] *Cf.* Lindberg 1969, 303 ff. For Maurolyco on pinhole images see Zik and Hon 2007.

[44] Pecham 1970, 70–71.

circularity of the pinhole image: a rectangular body will produce a rectangular image, as the experiment with the book shows. Neither does the pinhole image *represent* light: it is light that is simulated by the threads pulled through the hole, but the image projected on the pavement can be of any object, not necessarily luminous – a book. The trustworthiness of the projection, for Kepler, does not rest on its perfect loyalty to the object projected but on understanding the physical process of projection. Indeed, Kepler discovers, one cannot hope for such loyalty: The book-pattern on the floor is created by a "narrow row" of partially overlapping "figures," so not only is the image reversed, its boundaries are fuzzy. Moreover, these stains are reflections of the *aperture*. Even for those perspectivists, like Maurolyco, who appear to suggest a similar account, the image cast through the aperture is composed of many images *of the luminous body*. These are merged together as the distance of the screen from the aperture grows and the images of the source grow respectively.[45] Kepler's "figures" bear no resemblance to the light source. The complete, smooth, upright perception of the book on the pavement is a construct.

What Galileo would try to affect with his fierce rhetoric – the takeover of astronomy by *artificiosa observationes* – Kepler attempts to legitimize by turning optics into a mathematical-physical study of the production of images by light:

> from the Sun, and from the colors illuminated by the Sun, species exactly alike are flowing, diminished by the flow itself, until for whatever reason, they fall on an opaque medium, where they paint their source: and vision is produced, when the opaque screen of the eye is painted this way[46]

In any act of visual perception, light is a necessary mediator in communicating visual data. It is light that carries images, bouncing of "an opaque medium" and falling on an "opaque screen." If the screen happens to be the eye, "vision is produced," but there is nothing unique to the eye: any screen will do.[47] Even though there can be no doubt that Kepler is deeply indebted to the perspectivist tradition,[48] indebtedness he generously acknowledges by titling his book after Witelo, Kepler's transformation of optics is a fundamental.

The subject matter of traditional optics was human vision. Vision, so was its basic assumption, is a direct acquaintance of the visual faculty with visible objects, and optics is the study of the agents whose function is to communicate these objects to the eye.[49] This communication – the optical process – has always been self-evidently teleological. It was aimed at providing adequate images of visible objects for the intellect: "a species produced by a visible object has the essential property

---

[45] See Lindberg 1985, esp. 37–40; and Lindberg 1984, esp. 134–135, also Zik and Hon 2007, esp. 561.

[46] Kepler 1937– [1604], 41–42.

[47] Kepler 1937– [1604], 41–42.

[48] This is the central argument of Lindberg 1976.

[49] For the role of these visual impressions in medieval spirituality see: Park 1998, 254–271; Hamburger 2000, 47–69.

of manifesting the object of which it is the likeness" says Pecham.[50] Kepler was well aware of this: "Aristotle defines light," he writes, "not … in its nature, but to the extent that it is characteristic of the process of vision."[51] The teleology survived throughout the Renaissance, for practical as well as theoretical optics: "Alberti's picture," Alpers points out, "begins not with the world seen, but with a viewer who is actively looking out at objects."[52] And indeed, summarizing scholastic optics for his audience of painters, humanists and art patrons, it is this teleology that Alberti chooses to stress:

> Philosophers … Say that surfaces are measured by certain rays, ministers of vision as it is (*quasi visendi ministris*), which they therefore call visual rays, since by their agency the images of things are impressed upon the senses.[53]

The physical nature of the "ministers of vision" was debated since antiquity: simulacra or forms, visual rays or species, but their teleology and authenticity were never in doubt. Grosseteste, for instance, founds them on the premise that it is an essential property of the visible object itself, its agency or 'virtue', which 'multiplies' itself until it made itself present to the eye:

> A natural agent continuously multiplies its power from itself to the recipient, whether it acts on sense or on matter. This power is sometimes called species, sometimes a likeness, and it is the same thing whatever it may be called.[54]

Following Grosseteste's teachings, Roger Bacon underscores the essential relation which assures the fidelity of the visual agents, the multiplied species, to the visible object: "species is similar in essence and definition to the agent and the things generating it." [55] The authenticity of species was a fundamental assumption not only of optics but of medieval Aristotelianism as a whole; optics legitimated natural philosophy by accounting for the fundamental knowability of His Creation.[56] Visual rays guarantied the veracity of vision and the geometrical analysis of their propagation was always subordinate to the assumption of their intentionality and their consequent indubitability.[57] So was the analysis of the eye, as Pecham stresses: "vision takes place by the arrangement of the species on [the surface of] the glacial humor *exactly* as [the parts] of the object [are arranged] outside."[58] This is so, precisely because "*unless* this

[50]Pecham 1970, 161.

[51]Kepler 2000 [1604], 45. Cf. Smith 1981.

[52]Alpers 1983, 41.

[53]Alberti 1972, 41.

[54]Grosseteste 1912, 60.

[55]Bacon 1983, 7. "species sit similes agenti et generanti eam in essential et diffinitione." Bacon 1983, 7. For an extensive treatment of species in medieval optical theory see especially: Smith 1981; Spruit 1994. Tachau 1982 provides an authoritative treatment of the issues involved in medieval theory of species, and also Tachau 1988. See also Denery II 2005, esp 82–96.

[56]Smith 1981, 569.

[57]For the teleological nature of the Aristotelian theory of perception cf. Descartes 1998, 159–161.

[58]Pecham 1970, 121. Italics added.

were so, the eye would not see the object distinctly."[59] Optics, Pecham assumes, is a theory of visual perception, and any such theory that failed to account for the adequacy of the seen image is *ipso facto* false.

Kepler does away with this line of reasoning. The optical process, he declares, is strictly the effect of light: "genuine vision occurs when the folding door or pupil of the eye is exposed most closely to the arriving ray of light."[60] Gone are all intentional agents, and with them – the privileged import of the eye. Passively receiving "illumination" like any instrument, the eye is not merely comparable to "a closed chamber": the cornea is truly nothing but a lens; the retina nothing but a screen, essentially the same as the paper or the pavement; the pupil is just another aperture, "for the pupil takes the place of the window."[61]

This is Kepler's way of justifying the new observational astronomy. With light as the sole agent of all optical phenomena, there is no fundamental epistemological difficulty with observing the distant celestial phenomena: the mathematical nature of light and the assertion that the rays do not decay, only disperse (propositions 6 and 7 of *Ad Vitellionem*) turns distance into nothing but an element in the geometrical analysis of observation.[62] Even more important, with light there is no epistemological difficulty with *artificiosa observationes*. The image on the pavement is reversed and fuzzy, but so is the one on the retina. The instrument is trustworthy not because it does not interfere with the visual flow, but because it is no worse than the eye.[63]

5 Epistemological Considerations

Kepler was well aware of the primary rival to radical instrumentalism: the traditional, Aristotelian empiricism assumed by Galileo's Jesuit competitors, with its strict preference to the human sense,and he did not hesitate to challenge it directly and in detail.

According to Aristotle the initial state of cognition is perception; all that the intellect knows was previously in the senses.[64] This assumption, Kepler insists, does not agree well with astronomical practice; it does not seem that "the motions of the heaven come immediately into the perception of the eyes." The eye's physiology

---

[59] Pecham 1970, 121.

[60] Kepler 2000 [1604], 78.

[61] Kepler 2000 [1604], 184.

[62] For Kepler's mathematization of light cf. Gal and Chen-Morris 2005.

[63] We discuss in detail Kepler's transformation of optics from a teleological theory of human vision into a causal theory of the production of the images by light, as well as its far reaching epistemological ramifications, in Gal and Chen-Morris 2010 (in press).

[64] Aristotle 1984, *Posterior analytics*, II, 19, 100^{a}4–15, 165–166.

does not allow for such immediate perception: it is "attached to the posterior part of the head;" it has a spherical shape and it depends for its proper functioning on "the use of multiple refractions." There is no lack of evidence that the eye judges motion erroneously, especially motion of distant objects, and Kepler provides a handful.[65]

These shortcomings are unavoidable, Kepler claims, and in fact the eyes will fault even the most acute observer, such as Tycho Brahe. His own instrumental empiricism was much more radical in intellectual ambitions and commitments than that of his mentor in matters of astronomical observations, and Kepler did not shy away from the difference. Tycho utilized the *Camera Obscura* to observe solar eclipses, Kepler points out, under the assumption that the astronomer's eye remains the chief arbitrator and the instrument is but a prosthesis; a secondary aid to the sense of sight. Tycho thus "noticed that eclipses of the sun, whether the ray be allowed in through a notch or received by the eyes, always show the moon's diameter to be much less than it appears at oppositions." Trusting the accuracy of his visual perception, Tycho concluded that the real lunar diameter is smaller than was assumed. He was, however, wrong, because he did not take into account "the actual structure of the sense of sight" and its tendency to enlarge "the edges of luminous bodies, particularly in darkness." Kepler admonishes that the "astronomer should carefully take note of this … that unless he be endowed with the sharpest and most powerful sense of sight, he is not equal to measuring that moon's diameter at the full with the eyes without error." Therefore

> one has to distinguish carefully … between those things that happen to the sense of sight and those that happen when the consideration of the sense of sight is removed. For those things that happen to the sense of sight vary by individual cases, but those things that really happen are uniform within a single horizon. … Astronomers will now take note of this: that one must not trust the sense of sight… it cannot therefore be argued from this accident of the sense of sight to what happens outside the consideration of the sense of sight … For astronomers should not present anything other than those things that in actual fact occur. The sense of vision, however, we leave to the physicians to remedy.[66]

The remedy of astronomical observation and measurements is relegating the eyes in favor of an instrument. The careful application of the *Camera Obscura* allows "a most certain procedure for measuring the quantities of eclipses … If this device be correctly applied, the diameter of the moon appears decidedly greater than the amount that Tycho's table shows."[67]

In spite of his insistence that the application of instruments to astronomical investigation was the only way to avoid "the inadequacies of the eyes,"[68] Kepler was not promoting skepticism about the human senses. The purpose of his optics is to "subdue the hostile fortress of doubt,"[69] not to reinforce it, and much of

[65] Kepler 2000 [1604], 336.

[66] Kepler 2000 [1604], 298.

[67] Kepler 2000 [1604], 298.

[68] Kepler 2000 [1604], 57.

[69] Kepler 1937- [1604], 2:6.

Ad Vitellionem is dedicated to accounting for the reliability of the retinal image. Galileo, unperturbed by Kepler's careful optical and epistemological deliberations, is significantly more extreme in his stand for the instrument: *the eye* mediates and distorts; the instrument provides the standard of trustworthy perception against which the eye is to be judged. In a sense, Galileo re-introduces the distinction between direct and mediated vision that Kepler labored to abolish, reversing the epistemological order between eye and instrument. The two ways of observation, he argues during the controversy over the comets, provide data of entirely different value, not to be conflated or compared, and his adversary Grassi is fundamentally wrong to submit the telescope to the same analysis as ocular vision:

> Your error lies in comparing the star taken together with its irradiation when seen with the naked eye to the body of the star alone when seen with the telescope and distinguished from the irradiated regions.[70]

If Kepler was keen to hold the skeptical ramifications of his optics at bay, Galileo is unhesitant: his endorsement of the instrument comes at the expense and with the explicit distrust in the eye. The human organ is not merely weak but a positive source of various deceptions, which he makes a point to enumerate:

> There is another illumination here, made by refraction in the moist surface of the eye, and by this, the real object appears to us to be surrounded by a luminous circle … there is a third vivid splendor here, almost as bright as that of the original light itself; this is produced by reflection of the primary rays in the moisture at the edges of the eyelids, and it extends over the convexity of the pupil … this radiant crown [is] a sensation of the eye … it does not depend upon the illumination of the surrounding area.[71]

Like Kepler, Galileo thrusts the eye into the outside world. From a veridical conduit of knowledge it becomes part of a causal process of material nature, producing phenomena to be studied and explained physically. And while the eye mediates, adds spurious and distorting brilliance, the telescope is not only a reliable source, but the standard against which to judge the observation made through the eye and the means by which to remove the errors it introduces:

> Fancy to yourself some definite size for [a] wig, and in the center of this imagine a very tiny luminous body. The shape of this will be lost, being crowned by excessively long hair … the telescope, by enlarging the star but not the wig, makes the tiny disc which originally was imperceptible … so that its shape may be well distinguished. [72]

[70] Galilei 1623, 326.

[71] Galilei 1623, 319–320.

[72] Galilei 1623, 322–323. "Figuratevi una determinate grandezza d'una capellatura; nel mezo della quale se voi intenderete essere un piccolissimo corpo luminoso, perderà la sua figura, coronato di troppo lunghi crini … il telescopio, accrescendo la stella ma non la chioma, fa che, dove prima il piccolissimo disco tra sì ampio fulgore era impercettibile … si può distinguere ed assai ben figurare." Galilei 1890–1909; 6 360–361.

6 The Eye of the Mind

The metaphor of the "wig" – this paradigm of artificiality – to denote the eye-added splendor stresses Galileo's deliberate inversion of natural and artificial, direct and mediated. Galileo encapsulates his argument for this inversion of epistemological roles and standing in his most famous phrase of the "Assayer:"

> Philosophy is written in this grand book – I mean the universe … in the language of mathematics.[73]

The eye had always been, and for Grassi, Scheiner, and Agvilonius still was, the divinely assigned instrument of visual knowledge. This is nicely and simply put by Scheiner in his *Oculus* published in 1619, with no immediate reference to any of the controversies: "in order to see, the eye of the animal fulfils the duty it was ordained by God, grasping the presence of visible things."[74] For Kepler and Galileo, the eye loses this independent "duty" and becomes part of the "things." It introduces error because it is immersed in the confusing nature to be observed and its passions and affects are causally-bound physical phenomena.

The telescope, on the other hand, is not bound to the physical world. It is mathematical *in essence*, argues Galileo; it is fully captured by the mathematical laws governing the shape and relative placing of its lenses; "the convex lens unites the rays, the concave glass expands them and forms an inverted cone." [75] The asymptotic diminution of the angle of vision to the eye, with which Grassi accounted for the apparent lack of magnification, is thus of no significance. Magnification is strictly a mathematical relation, and the telescope always magnifies, whether the eye is capable of perceiving it or not. In a pedantic mood, Galileo even insists that changing the mutual position of the lenses results in having a completely different instrument:

> [Sarsi] says that a telescope which is now long and now short may be called the same instrument though differently applied … Our case is just the reverse, for the use of the telescope is always the same … while the instrument itself is diversified by its alteration in one essential respect, which is the interval between its lenses.[76]

---

[73] Galilei 1623, 183–184.

[74] Scheiner 1619, 2.

[75] Galilei 1623, 209. Antoni Malet writes: "In our understanding of them, telescopes always work by producing geometrical optical images, real or virtual, regardless of whether or not any observer is peering through them. From our theoretical point of view, it does not matter whether an eye, or a screen, or just empty space gets the light rays coming out of the ocular lens, because the telescope *always* produces one geometrical image. However, in Kepler's time, and up to the last decades of the seventeenth century, when somebody looked through a telescope, it was not understood to work by producing images similar to the pictures projected upon screens" (Malet 2005, 239). We differ from Malet in arguing that in spite of the absence of theoretical grounding, the independence of the geometrical image from the observer is exactly the position Galileo formulates and defends.

[76] Galileo 1623, 225.

This pedantry is not merely a rhetorical maneuver. As Sven Dupré has recently shown against what has been long assumed, Galileo did develop a mathematical understanding of the telescope.[77] This was based on contemporary optics, which owed as much to new lens and mirror grinding techniques as to traditional perspective theory, and it was not informed by Kepler's innovations, but it provided Galileo with the confidence to insist on the mathematical nature of his instrument. Being thoroughly mathematical, the telescope is not an extension of the eye but of reason. As was beautifully put by his fellow Lyncean Johann Faber, Galileo,

> with marvellous skill so fit spectacles to an aging world that with mind still sound but eyes dimmed and body weakened it might see through two glasses. [78]

In an important sense, we saw, Faber was missing Galileo's point: the telescope was *not* a pair of spectacles. But he did capture the dream of an instrument of mind, superior to the eye and answering directly to the laws of reason, which a few years earlier Kepler put into more careful, less exhilarating prose:

> Certainly, the mind itself, if it never had the use of an eye at all, would demand an eye for itself for the comprehension of things outside it, and would lay down laws of its structure which were drawn from itself (if in fact it were pure and sound and without hindrance, that is, if it were only what it is).[79]

In Kepler's terms, Galileo could have said that the telescope is the sense organ that reason *would have* had. For this reason he finds it is very important to stress that in contrast to its Dutch predecessor, his telescope was "discovered by the way of reason." "The original contraption was accidentally discovered by a "simple maker of ordinary spectacles" (he does not honor Hans Lipperhey by name) who "in casually handling pieces of glass of various sorts happened to look through two at once, one convex and the other concave, and placed at different distances from the eye." His instrument, on the other hand, followed a "reasoning" which he cursorily recounts, allegedly to "render less incredulous those people who, like Sarsi, may wish to diminish whatever praise there is in it that belongs to me."[80] One can easily identify with Grassi's astonishment at the ingratitude of the one he dubbed "the Lynx," but it was less important for Galileo to gather supporters than to clarify that his instrument was no pair of spectacles (and he, of course, no "simple maker"). It does not assist the eye; it is an extension of reason, an embodied mathematical entity, and it can allow reason an unmediated approach to reality because *reality* is mathematical, "written in this grand book … the universe … in the language of mathematics."

---

[77] Dupré 2005. See also Zik and Van Helden 2003.

[78] Faber in Galileo 1623, 154. "[An], velut in vetulo languentes corpore ocelli, Mente tamen valida, per duo vitra vident, Forte senescenti tu sic OCULARIA mundo Aptasti, mirae dexteritatis opus?" Faber in Galilei 1890–1909, 6: 205.

[79] Kepler 1937– [1619], 6: 304.

[80] Galilei 1623, 212–213.

This is the import of the celebrated idiom on the mathematical language of nature: to re-construct observed reality so it can be approached by reason, through the instrument. It is not an ontological justification for mathematical theorizing but for radical instrumental empiricism; nature is written in a language legible *only* through the instrument. The telescope does not mediate – it reveals the real makeup of nature; shapes, figures, quantities – directly to Reason. *The senses* mediate, creating appearances which are not proper representations of the "external bodies:"

> I do not believe that for exciting in us tastes, odors and sounds there are required in external bodies anything but sizes, shapes, numbers, and slow or fast movements; and I think that if ears, tongues, and noses were taken away, shapes and numbers and motions would remain, but not odors or tastes or sounds. These, I believe, are nothing but names, apart from the living animal just as tickling and titillation are nothing but names when armpits and the skin around the nose are upset.[81]

"Sizes, shapes, numbers, and slow or fast movements;" nature is comprised of elements the instrument makes apparent, but the senses mask by with "tastes, odors and sound … tickling and titillation." And what is true for noses and armpits is just as true for the eye:

> I believe that vision, the sense which is eminent above all others, is related to light, but in that ratio of excellence which exists between the finite and the infinite, the temporal and the instantaneous, the quantity and the indivisible; between darkness and light.[82]

7 Conclusion: The Price

Some 50 years later, Robert Hooke, the seventeenth century's most definitive beneficiary from and prominent follower of the legacy of radical instrumental empiricism, would give the conquest of the artificial over the natural a religious aura. In terms of "observations" and the capacity to "behold the works of nature" through the senses, Mankind is essentially inferior to "Beasts:"

> As for the actions of our *Senses*, we cannot but observe them to be in many particulars much outdone by those of other Creatures, and when at best, to be far short of the perfection they seem capable of.[83]

This 'shortness of perfection" is our own doing, but deliverance is also within our grasp:

> By the addition of such *artificial Instruments* and *methods*, there may be, in some manner, a reparation made for the mischiefs, and imperfection, mankind has drawn upon it self, by negligence, and intemperance, and a wilful and superstitious deserting the Prescripts and Rules of Nature, whereby every man, both from a deriv'd corruption, innate and born with

[81] Galilei 1623, 311.

[82] Galilei 1623, 311–312.

[83] Hooke 1665, xvii–xviii.

> him, and from his breeding and converse with men, is very subject to slip into all sorts of errors.[84]

Hooke may be overstated, but he is completely sincere. It is appropriate to discuss instruments in terms of fall and redemption, “the only way which now remains for us to recover some degree of those former perfections” (Hooke 1665, xvii), because they represent the one divine advantage that humans enjoy over beasts:

> It is the great prerogative of Mankind above other Creatures, that we are not only able to *behold* the works of Nature, or barely to *sustein* our lives by them, but we have also the power of *considering, comparing, altering, assisting, and improving* them to various uses. And as this is the peculiar priviledge of humane Nature in general, so is it capable of being so far advanced by the helps of Art, and Experience, as to make some Men excel others in their Observations, and Deductions, almost as much as they do Beasts.[85]

For Hooke, the arguments that have turned proper observation to the work of the mind rather than the senses have become almost a commonplace. He ignores, or suppresses, the great tensions and anxieties with which these arguments came. Such indifference was not an option for Galileo and Kepler. Hooke can marvel at “Telescopes or Microscopes producing new Worlds and Terra-Incognita’s to our view” (Hooke 1665, xxxii), but Galileo, anxious to defend the mathematical rapport by which he legitimized the inversion of epistemological standings, finds himself defending the simplicity of its revelation. Gone are the marvels and wonders of the *Sidereus Nuncius*; radical instrumentalism requires the bare bones representation of the heavens as the “triangles, circles and other geometrical figures” of Fig. 3. And Hooke can simply complain that “the eye cannot distinguish a smaller object then [*sic*.] appears within the angle of half a minute,”[86] but Kepler has to admit that vision, as a whole, has become a complete mystery:

> How this image or picture is joined together with the visual spirits that reside in the retina and in the nerve, and whether it is arraigned within by the spirits into the caverns of the cerebrum to the tribunal of the soul or of the visual faculty; whether the visual faculty, like a magistrate, given by the soul, descending from the headquarters of the cerebrum outside to the visual nerve itself and the retina, as to lower courts, might go forth to meet this image – this, I say, I leave to the natural philosophers to argue about.[87]

The mediation of light justified radical instrumentalism. It supported and explained the marvellous achievements of the *camera obscura*, the telescope and later the microscope, and provided a most convincing account of the function of the eye itself. But it came at a most difficult price, a bewilderment that would haunt the New Science: how is it that we see at all?

[84] Hooke 1665, xvii.

[85] Hooke 1665, xvii.

[86] Hooke 1674, 8.

[87] Kepler 2000 [1604], 180.

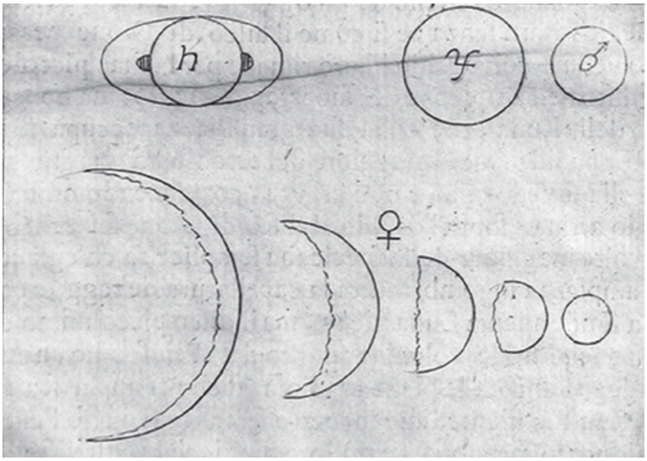

Fig. 3 The planets according to Galileo's "Assayer"

References

Alberti, Leon Battista. 1972. *On Painting and on Sculpture: The Latin Texts of De Pictura and De Statua*, trans and eds, introduction and notes by C. Grayson. London: Phaidon.

Alpers, Svetlana. 1983. *The Art of Describing: Dutch Art in the Seventeenth Century*. Chicago: University of Chicago Press.

Aristotle. 1984. Problems; posterior analytics. In *The Complete Works of Aristotle*, ed. Jonathan Barnes. Princeton: Princeton University Press.

Agvilonius, Franciscus. 1613. *Opticorum libri sex philosophis iuxta ac mathematicis utiles*. Antwerp: Plantin Press, widow and sons of J. Moretus.

Bacon, Roger. 1983. Roger Bacon's natural philosophy: a critical edition. Incl. *De multiplicatione specierum* and *De speculis comburentibus,* trans. and ed. David C. Lindberg. Oxford: Oxford University Press.

Baldini, Ugo. 1992. *Legem impone subactis: Studi su filosofia e scienza dei gesuiti in Italia, 1540–1632*. Rome: Bulzon.

Biagioli, Mario. 2006. *Galileo's Instruments of Credit: Telescopes, Images, Secrecy*. Chicago: The University of Chicago Press.

Blackwell, Richard. 1992. *Galileo, Bellarmine, and the Bible.* Notre Dame: University of Notre Dame Press.

Cassirer, Ernst. 1942. The Influence of language upon the development of scientific thought. *The Journal of Philosophy* 39,12: 309–327.

Crombie, Alistair C. 1953. *Robert Grosseteste and the Origins of Experimental Science 1100–1700*. Oxford: Clarendon.

Dear, Peter. 1995 *Discipline & Experience: the Mathematical Way in the Scientific Revolution*. Chicago: University of Chicago Press.

Denery II, Dallas G. 2005. *Seeing and Being Seen in the Later Medieval World: Optics, Theology and Religious Life*. Cambridge: Cambridge University Press.

Descartes, René. 1998. *The World and Other Writing,* ed. and trans. Stephen Gaukroger. Cambridge: Cambridge University Press.

Drake, Stillman and O'Malley, C.D. (eds. and trans.). 1960. *The Controversy on the Comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler.* Philadelphia: University of Pennsylvania Press.

Dupré, Sven. 2003. Galileo's telescope and celestial light. *Journal for the History of Astronomy* 34, 4: 369–399.

Dupré, Sven. 2005. Ausonio's mirrors and Galileo's lenses: the telescope and sixteenth-century practical optical knowledge. *Galilaeana: Journal of Galilean Studies* 2: 145–180.

Feldhay, Rivka. 2000. Mathematical entities in scientific discourse: Paulus Gulding and his *Dissertatio de Motu Terrae*. In *Biographies of Scientific Objects*, ed. Lorraine Daston. Chicago: University of Chicago Press.

Gal, Ofer and Chen-Morris, Raz. 2005. The archaeology of the inverse square law part I: Metaphysical images and mathematical practices. *History of Science* 43.4: 391–414.

Gal, Ofer and Chen-Morris, Raz. 2010 (in press). Baroque optics and the disappearance of the observer: From Kepler's optics to Descartes' doubt. *Journal of the History of Ideas*.

Galilei, Galileo. 1623. *Il Saggiatore (The Assayer)*. Rome: Giacomo Mascardi. In *The Controversy on the comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler*, Drake and O'Malley, eds. 1960. And trans. Stillman Drake and C.D. O'Malley. Philadelphia: University of Pennsylvania Press.

Galilei, Galileo. 1890–1909. *Le Opere di Galileo Galilei* (20 vols) 1890–1909, ed. Favaro, A. Florence: Barbera.

Galilei, Galileo. 1989 (1610). *Sidereus Nuncius, or, The Sidereal Messenger*, ed. and trans. Albert Van Helden. Chicago: University of Chicago Press.

Grassi, Horatio. 1619. *Tribus Cometis Anni M. DC. XVIII. Disputatio Astronomica*. Rome: Iacobi Mascardi. In *The Controversy on the comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler,* Drake and O'Malley, eds. 1960. And trans. Stillman Drake and C.D. O'Malley. Philadelphia: University of Pennsylvania Press.

Grosseteste, Robert. 1912. De lineis angulis et figuris. In *Die Philosophischen Werke des Robert Grosseteste, Bischofs von Lincoln*, ed. Ludwig Baur. Beiträge zur Geschichte der Philosophie des Mittelalters. Münster i. W.: Aschendorff.

Guiducci, Mario. 1619. *Discorso Delle Comete*. Firenze: Pietro Cecconcelli. In *The Controversy on the comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler,* 1960, eds. and trans. Stillman Drake and C.D. O'Malley. Philadelphia: University of Pennsylvania Press.

Hamburger, Jeffrey F. 2000. Seeing and believing: the suspicion of sight and the authentication of vision in late medieval art. In *Imagination und Wirklichkeit: Zum Verhältnis von mentalen und realen Bildern in der Kunst der Frühen Neuzeit,* eds. Alessandro Nova and Klaus Krüger, 47–69. Mainz: Von Zabern.

Hooke, Robert. 1665. *Micrographia*. London: John Martin.

Hooke, Robert. 1674. *Animadversions on the ...* Machina Coelestis *of ... Johannes Hevelius.* London: John Martin.

Kepler, Johannes. 1937. *Gesammelte Werke* 1571–1630, eds. Walther von Dyck and Max Caspar München: C. H. Beck.

Kepler, Johannes. 1965 [1610]. *Kepler's Conversation with Galileo's Sidereal Messenger*, trans. Edward Rosen. New York: Johnson Reprint Corp.

Kepler, Johannes. 2000 [1604]. *Optics: Paralipomena to Witelo and the Optical Part of Astronomy*, trans. William H. Donahue. Santa Fe, NM: Green Lion Press.

Lattis, James. 1994. *Between Copernicus and Galileo*. Chicago: University of Chicago Press.

Lindberg, David C. 1976. *Theories of Vision from Al-Kindi to Kepler*. Chicago: University of Chicago Press.

Lindberg, David C. 1968. The theory of pinhole images from antiquity to the thirteenth century. *Archive for the History of Exact Sciences* 5: 154–176.

Lindberg, David C. 1969. The theory of pinhole images in the fourteenth century. *Archive for History of Exact Sciences* 6: 299–328.

Lindberg, David C. 1984. Optics in 16th century Italy. In *Novità Celsti e Crisi del Sapere*, ed. P. Galuzzi, 131–148. Firenze: Giunti Barbera.

Lindberg, David C. 1985. Laying the foundations of geometrical optics: Maurolico, Kepler, and the Medieval Tradition. In *The Discourse of Light from the Middle Ages to the Enlightenment*. Los Angeles: William Andrews Clark Memorial Library, UCLA 1–65.

Malet, Antoni. 2005. Early Conceptualizations of the telescope as an optical instrument. *Early Science and Medicine* 10, 2: 237–262.

Park, Katherine. 1998. Impressed images: reproducing wonders. In *Picturing Science and Producing Art*, eds. Caroline A. Jones and Peter Galison with Amy Slaton, 254–271. New York and London: Routledge.

Pecham, John. 1970. *John Pecham and the Science of Optics: Perspectiva Communis.* trans. and ed. David Lindberg. Madison: University of Wisconsin Press.

Sarsi Sigensano, Lothario. 1619. *Libra Astronomica ac Philosophica*. Perugia: Marci Naccarini. In *The Controversy on the comets of 1618: Galileo Galilei, Horatio Grassi, Mario Guiducci, Johann Kepler*, 1960, eds. and trans. Stillman Drake and C.D. O'Malley. Philadelphia: University of Pennsylvania Press.

Scheiner, Christoph. 1619. Reprinted 1652. *Oculus, hoc est, fundamentum opticum*. Innsbruck, London.

Shea, William R. 1972. *Galileo's Intellectual Revolution*. London: Macmillan. Sigensano, Lothario Sarsio. 1619. *Libra astronomica ac philosophica qva Galilaei Galilaei opiniones de cometis ... examinantur*. Perusiae: Marci Naccarini.

Smith, A. Mark. 1981. Getting the big picture in perspectivist optics. *Isis* 72, 568–589.

Spruit, Leen. 1994. *Species Intelligibilis: From Perception to Knowledge* (2 vols.) Leiden, New York, Köln: E.J. Brill.

Straker, Stephen. 1971. *Kepler's Optics.* Unpublished Dissertation. Indiana University.

Tachau, Katherine. 1982. The problem of the species in Medio at Oxford in the generation after Ockham. *Medieval Studies* 44, 394–443.

Tachau, Katherine. 1988. *Vision and Certitude in the Age of Ockham: Optics, Epistemology and the Foundations of Semantics, 1250–1345*. Leiden, New York, Köln: E. J. Brill.

Thro, E. Broydrick. 1996. Leonardo's early work on the pinhole camera: the astronomical heritage of Levi ben Gerson. *Achademia Leonardi Vinci* 9: 20–54.

Van Helden, Albert. 1974. The telescope in the seventeenth century. *Isis* 65.1.

Van Nouhuys, Tabitta. 1998. *The Age of Two-Faced Janus.* Leiden: Brill.

Zik, Yaakov and Giora Hon. 2007. Geometry of light and shadow: Francesco Maurolyco (1494–1575) and the pinhole Camera. In *Annals of Science* 64: 4, 549–578.

Zik, Yaakov and Albert van Helden. 2003. "Between Discovery and Disclosure." In Beretta, Marco et al., *Musa Musaei: Studies on Scientific Instruments and Collections in Honour of Mara Miniati*. Firenze: L. S. Olschki, 173–190.