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*GALILEO IN THE HISTORY OF OPTICS**

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1. THE FEATURES OF GALILEO'S SCIENTIFIC ACTIVITY

PEOPLE often treat the history of science as a stepwise "one-dimensional" development of knowledge growing in complexity. This artificially neat scheme isolates science from living human society and individuals and from history in the broad sense, and it little resembles reality. It copies the internal logic of present-day scientific dogma as it has developed in time; this is its didactic justification and this is its fundamental error. As we know, the sequence of this logic seldom coincides with the complex zigzags of what has actually taken place.

In truth, the growth of science in recent times has been mainly progressive; the press and the perfection of communications make it possible to have full and timely access to the acquired knowledge, rather than to repeat what has already been done. However, even under contemporary conditions the course of science is not one-dimensional; it has "breadth," and shows branchings, zigzags, and loops. It is defined not only by its content and by, so to speak, the absolute value of the scientific discoveries, but also to a great degree by the coincidence of the discoveries with the current needs of modern society. One can recite a long sad list of remarkable scientific discoveries, both in antiquity and in recent time, that have remained as seeds without sprouting.

We must never lose sight of this complexity of development of scientific thought, especially with such unequalled figures in the history of natural science as Galileo. In the artificially cut-and-dried history of science, a stage of great importance is associated with Galileo, but it differs little in significance from that ascribed to the names of Kepler, Descartes, and Huygens. However, even during Galileo's lifetime, his image had acquired its uniqueness that has not been obliterated, but has become even more distinct after three centuries.

In the schematic history of science, Galileo's place, even at the heart of his activity in the development and confirmation of the heliocentric theory, seems smaller than that of Copernicus and Kepler. Galileo's physical and astronomical arguments in favor of the motion of the Earth are either not new, or erroneous, or not very substantial; Kepler's laws escaped his attention or remained outside his grasp, Galileo's theory of the tides is erroneous, and his notions about comets now seem archaic. Nevertheless, in the real history of science the great significance of Galileo in the victory of the heliocentric system of the universe is obvious, and his role cannot be compared with that of anyone else. The lively, full-blooded, and artistic argumentation and propaganda of the Dialog, which he wrote in his own language, his tragic struggle with the Jesuits and the Inquisition, his circular letters, with which Europe was engrossed, and finally, the new picture of Galileo's infinite heaven with the Sun rotating about its axis, with the mountainous Moon, with the Medicean moons of Jupiter, with the phases of Venus, and with the cloud of the Milky Way resolving into individual stars—these convinced the world, and compelled everyone, in spite of "common sense," to believe in the stationary Sun and in the complex motion of the Earth. Galileo had to an amazing degree the gift that we now call the "inculcation" of scientific truth. The truth became common property by virtue of its application to new arguments understandable to all, through active struggle for it, and through the dialectics of a genius. The significance of this "inculcation" in the progress of science is truly colossal. However, there is no mention of it in the abstract, schematic history.

Galileo's scientific heritage in the field of mechanics, the principle of relativity of motion, the law of inertia, and the theory of uniformly accelerated motion, might also seem pale from the standpoint of the simplified history of knowledge alongside the works of Newton and Huygens. Actually the Discorsi, with their breadth, their clear presentation of fundamental mechanical concepts, and their striking sound sensibility are related to the Principia as the root system is to the powerful trunk and the green treetop.

In the history of optics, Galileo is at best remembered up to the present for his telescope, and rarely for his microscope. This offhandness, however, is only another example of the crying disagreement between schoolbook history and the actual process of development. Throughout the time that optics has existed as a science, a time reckoned in millennia, it received the greatest stimulus to further theoretical and technical growth precisely from Galileo. The Sidereus Nuncius compelled the scientific world of the early 17th Century to busy itself with dioptric instruments, and with the grinding and polishing of

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*Originally published in the collected volume Galileo Galilei, M.–L., AN SSR, 1943, p. 5.

lenses. History found Descartes, Spinoza, Newton, kings and princes, abbots and monks, craftsmen, physicists, philosophers, and doctors busy at this sort of work. With unheard of speed, there grew in this soil the geometric optics of refractive media, the technology of handling glass, the art of constructing optical instruments, and the optical industry in the broad sense. With complete justification, one of the oldest optical factories in the world, a factory in Florence, is called the Officine Galilei. Besides, all of Newton's optics and Euler's optical researches arose from the attempt to perfect Galileo's tube. Before Galileo, optics was a widespread but purely scholastic undertaking, one of the parts of the quadrivium. Since Galileo turned his tube toward the starry heavens, it has become a fundamental part of physics and an important branch of technology. The image of Galileo separates ancient and medieval optics with their archaism, scholasticism, and closed character from a new, living, and active discipline.

This is why, in spite of the fact that Galileo's heritage of scientific articles and manuscripts contains not a single work especially devoted to optics, it is the duty of history to reconstruct as far as possible Galileo's activity and thought in the field of study of light. In its development, optics is so indebted to Galileo that modern researchers in optics have a quite obvious duty to reconstruct as fully as possible the work and thought of Galileo in the field of study of light. The material for this exists on individual pages of Galileo's works, especially in Il Saggiatore, and in Galileo's correspondence with his contemporaries, which has been collected in the National Edition of Galileo's works*, a publication worthy of imitation in all ways. All that I shall present below is a preliminary attempt along this line.

2. ANCIENT AND MEDIEVAL PRECURSORS OF GALILEO IN OPTICS

Galileo was preceded by at least two thousand years of existence of optics as a science. Euclid's treatise on optics was written no later than the 3rd Century B. C. Further, undoubtedly Euclid drew upon a fully-formed tradition in optics, and besides, on practice and everyday experience. For example, much unquestionable evidence from ancient authors has been preserved on means of collecting the sun's rays to set fires. Thus apparently, the sacred "pure" sacrificial fire has been obtained from time immemorial. Aristophanes mentions this way of starting fires in The Clouds as a phenomenon known to everyone as early as the 5th Century B. C. Pliny reports on the incendiary action of glass spheres. Seneca writes on the magnifying action of such a sphere when one looks through it at fine writing. Archimedes, Ptolemy, and indeed, apparently, all the ancient physicists in general were aware of the refraction of light. It was a truism that light rays and the phenomenon of reflection were rectilinear. The attention of observant people of antiquity, of course, did not overlook the remarkable facts of atmospheric optics, the rainbow, the halo, the dawn and sunset, and great dimensions of the Sun and Moon at the horizon, and the apparent changes of colors in nature, including even interference colors in thin films. However, this was the limit of the fundamental stock of information about light of the ancient physicist, at least in the more ancient periods.*

The attempt to make intelligible and to comprehend phenomena, which was organically inherent in the ancient philosopher and physicist, touched on light as well, of course. There have come down to us brief fragmentary accounts of highly varied speculations of the ancients on the nature of light.† We can classify them into six or seven large groups: 1) the theory of visual rays; 2) the atomistic theory of Democritus and Epicurus of the so-called reflections and aerial imprints; 3) Plato's theory of synaugia, i.e., the interaction of internal and external light, and of visual and external rays; 4) Aristotle's theory of the mediation of the transparent medium, which had certain features resembling modern wave conceptions; 5) the Stoic theory of aerial stress, which was a variant of the theory of visual rays (it was assumed here that not the visual rays themselves extend to objects, but only their action on the intervening air); 6) the theory of the Neo-Platonists of indirect psychic action at a distance.

This varied list is indicative of the instability and indefiniteness of the ancient physical theory of light. The known facts were so complex and qualitatively different that they gave little hindrance to the simultaneous existence of such contradictory opinions. Only the geometric properties of light could be applied for the construction of a fully concrete quantitative optics, based on the geometry of the ancients.

As is well known, the basis of the ancient geometric optics, in particular the optics of Euclid, was the doctrine of visual rays emerging from the eye. This viewpoint now seems curious and even absurd, disintegrating at the very first comparison with experi-

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*G. Galilei, Le Opere, Edizione Nazionale, Florence, 1890–1909, 20 volumes. In recent years, Galileo's works have begun to be reprinted. The National Edition will be cited below as Ed. Naz. for short.

*T. H. Martin, Sur des instruments d'optique faussement attribués aux anciens par quelques savants modernes (On Some Optical Instruments Falsely Attributed to the Ancients by Some Modern Scientists), Bolletino di bibliografia e di storia delle scienze matematiche e fisiche 4, 165 (1871). For a detailed, account of this memoir see A. N. Disney (Ed.), Origin and Development of the Microscope, 1928.

†A. E. Haas, Antike Lichttheorien (Ancient Theories of Light), Archiv für Geschichte der Philosophie 13, 345 (1907).

ment. However, in fact the theory of visual rays was not at all so elementarily illiterate and naive, and we might even remark that it was progressive for its time.

The possibility of obtaining real images using optical systems remained unknown to the ancients. They knew only images in the eye as obtained directly or by means of mirrors and transparent media. Aristotle had some knowledge of the structure of the eye, the media of the eye, and the optic nerve, but he did not understand their functions. When we produce a "virtual image" in a mirror (Fig. 1), we now are fully informed that in fact here a most ordinary real image is produced on the retina by the crystalline lens. However, Euclid did not at all know the fact or even the possibility of producing an objective image; information on the path of the rays into the eye ended upon entrance into the pupil BC. There was no doubt as to the path of the rays AB and AC, but no one knew nor suspected that AB and AC intersect at the retina. The image in the eye was interpreted on the basis of the only remaining similarity with the sense of touch. Just as the two hands in touching an object make it possible to localize it, the visual rays emerging from the eye and returning to the eye along their original path provide a representation of the shapes of objects. That is, they generate an image *in the brain.* We might mention that in modern physiological optics as well, spatial perception of depth by the two eyes is explained in essence, not optically, but by the mechanical rotation of the eyeball, which elicits a corresponding reaction in the brain. We cannot but acknowledge the ingenuity of this explanation, which made it possible to construct visual images without any information on what takes place in the eye. How otherwise could the Greek students of optics act in seeking a quantitative theory of mirror reflection? By accepting the existence of objective rays and the law of reflection, they were able to construct the rays correctly from A to B and C. However, they still didn't obtain thereby the position of the virtual reflected point, as determined in the diagram with the aid of the dotted lines. When we unhesitatingly draw such lines, then we also in essence are applying the concept of visual rays emerging from the eye. However, we know that these virtual rays are justified by the real image on the retina, which the ancients didn't suspect. The convenience of the concept of visual rays (especially in the absence of information on the path of the rays within the eye), even as an auxiliary, compelled people to use them during the era when no one doubted any longer that light proceeds from the source, rather than from the eye. In particular, Galileo also used the model of visual rays to solve optical problems. This is why the theory of visual rays was not at all a naive error; it was a hypothesis that permitted the ancients to create the geometric optics of reflecting surfaces with correct quantitative conclusions, in spite of the lack of knowledge about the eye.

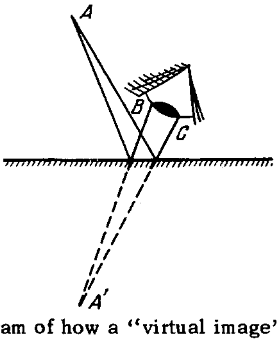

FIG. 1. Diagram of how a "virtual image" is obtained.

The hypotheses on which Euclid's *Optics* was based, e.g., "The figure enveloped by the rays is a conic solid with its vertex at the eye and with its base on the edges of the objects being seen; among these objects we can distinguish those to which rays extend; objects distinguished at a larger angle seem larger," etc., are quite understandable from the presented standpoint, and are necessary for the creation of geometric optics. Based on them, Euclid developed *modo geometrico* the catoptrics of plane and spherical mirrors, starting from the law of reflection.

We might note that while the problem of the virtual image was easily solved in the geometrical optics of the ancients on the basis of the visual-ray theory, the problem of the real focus of a curved mirror, which the ancients knew as the site of greatest burning power of the sun's rays when collected by the mirror, was difficult and paradoxical on the basis of the same theory, and was not always solved correctly.

Ancient optics changed and evolved exceedingly slowly. The treatise of Ptolemy (2nd Century A. D.) was written four or five centuries after Euclid. However, the only essentially new feature of this work was a quantitative experiment, which was unusual for ancient physics. Ptolemy reported the angle of refraction of light upon passage from air into water, from air into glass, and from water into glass.

Angle of incidence	10°	20°	30°	40°	50°	60°	70°	80°
True angle of refraction	8°	15.5°	22.5°	28°	35°	40.5°	45°	50°
Angle of refraction according to Ptolemy	7.5°	15°	22°	29°	35°	40.5°	45°	47.5°

Ptolemy's numbers, as we see from the table, are amazingly accurate for his time. From these figures and from Ptolemy's entire treatise, we can make out the remarkable image of the physicist of the close of antiquity, who combined in himself mathematical knowledge, theoretical breadth, and the art of quantitative experimentation.

However, the centuries of the ancient dawn were followed by the many-century "zone of silence," a time when science, including optics, at best stood still; the noble role of the preservers of ancient science fell to the lot of the Arabs. However, undoubtedly this conservation was accompanied by a slow process of change and growth. Here a gradual radical change in the theoretical foundation was the most symptomatic feature. The idea of visual rays begins to give way to the concept of external illumination. We do not know exactly the reasons for this change, but we may suppose that the fundamental factors here were the anatomical information on the structure and functions of the eye obtained by the Arabic physicians. Arabic optics found its fullest expression in the famous treatise of Ibn al Haitam, or Alhazen (965-1039). Optics was not Alhazen's principal specialty; his biography* lists 25 works on the mathematical sciences and 44 on physics (in the Aristotelian sense) and on metaphysics. Hence we may assume that Alhazen's Opticae Thesaurus is not very individual, but probably rather is only a résumé of 10th Century learning.

Alhazen's treatise is divided into seven books, of which the first three are concerned with the problem of the eye and vision. Alhazen gave for the first time in the history of optics an anatomical description of the eye, and it was quite unquestionable to him that vision is caused by external rays entering the eye from objects. Here he assumed that the image is formed within the crystalline lens before it reaches the optic nerve. In line with the marked change from the original theoretical views, Alhazen puts much importance on the question of the real image formed by mirrors and refractive media. The last book of the treatise, which discusses the problems of refraction, is especially concrete and new; it contains problems involving refraction in transparent spheres. Indeed, we might speak here of the posing of problems rather than their solution; the problem of greatest practical importance involving the action of a transparent body bounded by two surfaces is not solved at all.

We must reckon again about a half a millenium from the era when the Opticae Thesaurus was written until we find anything that is not only new but also important in optical science. Indeed, we may note an indubitable revival of optics in the 13th Century on the basis of the memoirs that have been preserved. This is especially evidenced by the treatises of the Englishmen Roger Bacon (1214-1294) and John Peckham (1228-1291), and the Pole of Thüringen Vitello.

The optical parts of these books mainly paraphrase Euclid, Ptolemy, and Alhazen, sometimes literally, sometimes with variations. Following Plato's example and differing from Alhazen, Bacon tries to synthesize Euclid's visual rays and Alhazen's external light; he devotes much space to problems of refraction in lenses and mirrors, but without substantial progress. We may note only his complete clarity with regard to the location of the focus of a concave burning mirror. Bacon establishes the indefiniteness of the focus for a deep spherical reflector and its unambiguity for a parabolic mirror. In the trilogy that Bacon wrote at the request of Pope Clement IV (Opus Majus, Opus Minus, and Opus Tertium), many pages are taken up with optical themes. Here we find places from which we can infer that Bacon knew certain forms of the telescope, microscope, and camera obscura. However, such lines probably actually express only guesses and scientific fantasies, to which the fascinating Doctor Mirabilis was not averse; along with his optical theorems, for example, he had recounted to the reader information on flying dragons and their caverns.

A genuine unquestionable achievement of the 13th Century was the invention of eyeglasses in Italy and the gradual spread of their use. Several quite clear pieces of evidence of the appearance of eyeglasses in Italy at the end of the 13th Century have been preserved. A wealth of documentary data shows that the invention took hold and attracted attention to itself. It is remarkable and very sad as well that the learned opticians of the 13th Century, who wrote much about refractive media, were apparently not involved in the invention of eyeglasses. A gravestone in the church Santa Maria Maggiore in Florence ascribes their invention to the Florentine Salvino degli Armati, who died in 1317, but there are certain signs of the existence of eyeglasses even in the middle of the 13th Century. It is plausible to assume that both positive and negative eyeglasses were invented in the process of the work of the Italian glass masters, who were known throughout the world for their art of grinding and polishing. The fabrication of colorless and colored glass into spherical shapes, convex and concave, in various artistic wares was no rarity. In testing the quality of a work, the master inevitably raised the article to his eye. Under these conditions, granted enough sagacity and powers of observation, the invention of eyeglass lenses in the glass workshops became quite natural. Further, even conscious inventiveness was expressed in the combination of two lenses to make eyeglasses.

The scientists in optics in the 13th Century, Bacon, Vitello, and Peckham, not only did not aid in the invention of eyeglasses, but they simply didn't know of their existence. Further, it was not a question of trifles, but of the most remarkable result in optics for many centuries of its existence, not only in the practical sense, but also with regard to theoretical perspectives. If the true inventor of eyeglasses were to become known, undoubtedly his name would occupy one of the most honored places in the history of the science of light. Unfortunately, the anonymity of the

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*E. Wiedemann, Ibn al Haitam, ein arabischer Gelehrter (Ibn al Haitam, an Arabic Scholar) "Festschrift für J. Rosenthal" 149, 1906, Leipzig; A. N. Disney, loc. cit.

invention has caused the oblivion of the very fact of the invention. Do many people, with the exception of scientists in optics and oculists, know the period in which eyeglasses were created, and their significance in the history of optics? The history of the logical scheme rather than the living process, just like the history of scientists rather than of science, finds itself in a difficult position as to the problem of the invention of eyeglasses.

3. ITALIAN PRECURSORS OF GALILEO IN THE 16TH CENTURY

Eyeglasses did not become the basis of further growth in optics, in spite of all the wonder they held for mankind in the 14th and 15th Centuries and their practical importance. The books of Alhazen, Vitello, and Bacon rested in peace in the monastery and university libraries; in the universities one read the optical courses as part of the quadrivium, prominent people corrected their vision in old age with eyeglasses, but optical science in the 14th and 15th Centuries stood still, except for perspective, which was of value only for artists. Only at the turn of the 16th Century do we finally observe a marked advance in the person of the genius Leonardo da Vinci (1452-1519).

A great number of Leonardo's notes and drawings on problems of optics, vision, and the anatomy of the eye have been preserved. With full justice we can consider him to be an optical scientist who knew the fundamental optical treatises of his time, and as an amazing observer and experimenter. To a certain degree we can even consider Leonardo's art works to be an expression of his optical concepts and knowledge. We know of several attempts to analyze Leonardo's optics, but none of them give a true picture of the great place that this science took in his life and creation. Certain of these attempts are simply random collections of raw material*, in others the tendency dominates to prove that almost every thought of Leonardo was not his own, but borrowed from somewhere†; there are also other attempts to ascribe to Leonardo's name almost all of the fundamental content of optics before him and after him.‡

The material collected in these works is very valuable, but in many cases the conclusions require reexamination. Leonardo is hardly mentioned in courses in the history of optics. The same reason is again at the bottom of it: he does not fit into the cut-and-dried scheme of the development of science. Leonardo either outstrips his period in an unusual way, or he lags, or he by-passes it, and what is most difficult, it is almost impossible to prove his influence on the further growth of science.

For Leonardo, light was a phenomenon that was absolutely external. Vision begins with the image at the back of the eye, just as happens in a camera obscura. The camera and the eye are objects of numerous considerations and experiments by Leonardo. Leonardo studied the eye anatomically and built a model of it, but a dead preparation having a crystalline lens that has almost become a sphere upon treatment does not permit one to understand the actual path of the rays. The correct solution of the problem is especially hindered by the inverted image of objects that one obtains in a camera. Erroneously assuming that the image in the eye must be upright, Leonardo makes the rays within the eye intersect twice (cf. Fig. 2).

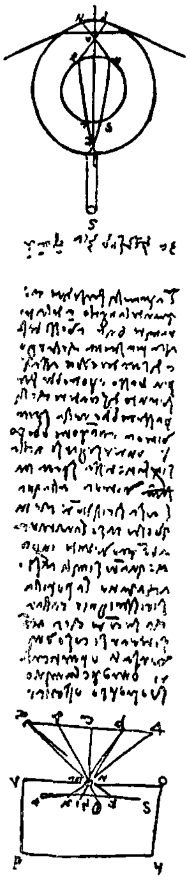

FIG. 2. From the manuscripts of Leonardo da Vinci. The path of the rays in the camera obscura and in the eye according to Leonardo.

On the basis of certain remarks and drawings in Leonardo's manuscripts, the hypothesis has been advanced that he had a wave view of the nature of light. This is hardly likely. Leonardo actually knew from observations and experiments with liquids about the properties and peculiarities of wave motion much more clearly and concretely than any of his contem-

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*E. g., E. MacCurdy, The Notebooks of Leonardo da Vinci, Vol. I, 1938.

†O. Werner, Zur Physik Leonardo da Vincis (On Leonardo da Vinci's Physics), Dissertation, Erlangen, 1909.

‡Domenico Argentieri, L'optica di Leonardo (Leonardo's Optics) (collected volume L. da Vinci, Edizione curata della mostra di L. da Vinci in Milano, 1939, p. 405).

poraries or even the physicists of the 17th and early 18th Centuries (including Hooke and Huygens). He took up the combination of oscillations when waves from two sources meet, and he noted and quite correctly described the change in the shape of a wave from a stone cast into a moving current of water.

FIG. 3. Combination and distortion of waves in a moving current according to Leonardo.

That is, he was one step from discovering Doppler's phenomenon (Fig. 3). Leonardo knew certain diffraction phenomena, he applied the concept of waves to the propagation of sound, etc. From the modern standpoint, the transition from here to the wave theory of light is very probable, but there are no definite signs of this in Leonardo's manuscripts. We should emphasize in general the traits of Leonardo's scientific genius. He was an amazing observer for accuracy, attention, and ability to note essentials, he was a master of quantitative experimentation, but he did not have the gift of abstraction which is necessary to a theoretician. Abstraction was replaced by concrete artistic perception; instead of generalization and abstraction, analogy and metaphor prevailed with Leonardo. Thus the most valuable things in his scientific heritage are his observations and experimentation. His notes on atmospheric and physiological optics are still of considerable direct, rather than only historical interest. On the other hand, Leonardo is the undisputed founder of photometry as an exact science of measurement. His diagrams and explanations of them (Fig. 4) leave no doubt of the fact that Leonardo experimented with a photometric apparatus of the Rumford type.

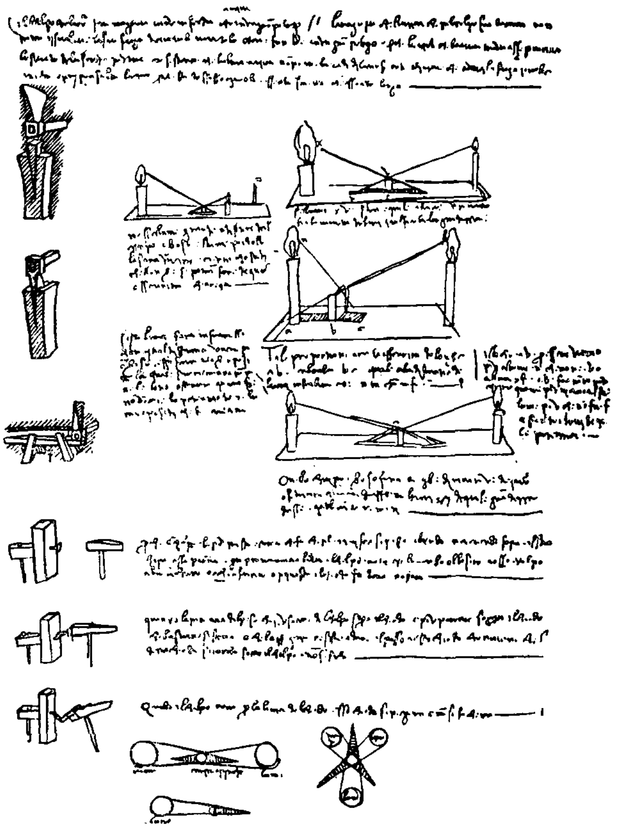

FIG. 4. Photometric notes and diagrams of Leonardo.

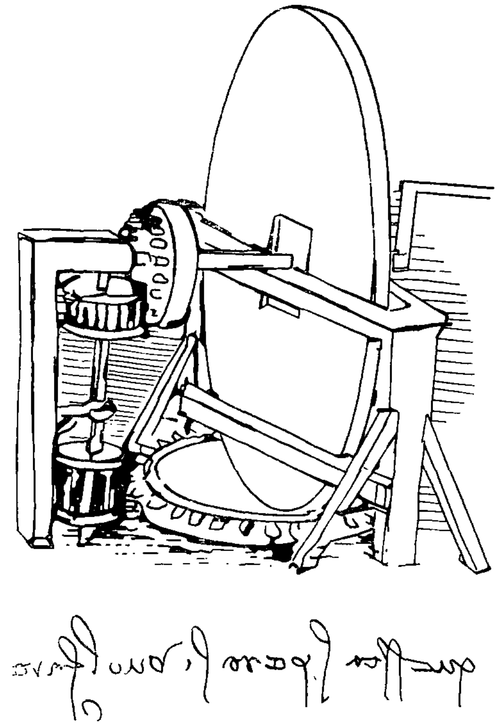

FIG. 5. Leonardo's machine for grinding concave mirrors.

Mirrors and lenses, of course, became the object of intense attention of the artist. His manuscripts contain many diagrams in which caustic curves are determined graphically, and he gave an experimental

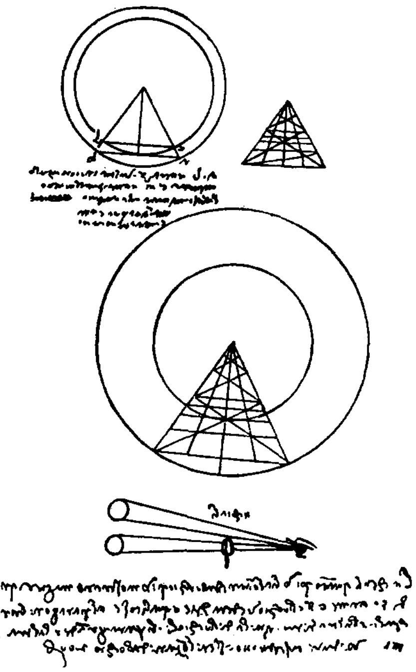

FIG. 6. Leonardo's single-lens telescope.

method of determining aberrations recalling certain forms of modern aberrometers. Leonardo built or at least made drawings of apparatus for grinding of concave mirrors (Fig. 5) and discussed the production of eyeglass lenses. Undoubtedly, Leonardo not only dreamed of telescopic devices, but actually made them. In Codex A (folio 12) we find the following lines, illustrated by a diagram (cf. Fig. 6): "The farther you remove the glass from the eye, the greater it shows objects to fifty-year-old eyes; if for comparison one of the eyes looks through an eyeglass, and the other not, then for the one the object seems large, and for the other small; however, to do this, the objects seen must be 200 feet away from the eye." Leonardo reports here a reproducible observation not known to all, but exceedingly simple, of the considerable magnifications that one can get by looking with the naked eye at the real image of a distant object produced by a convex lens when the focal length of the lens is greater than the distance of best vision. Donjon and Couder* point out that with a lens of focal length 12 meters, a normal observer will get a fifty-power magnification, and a nearsighted observer even greater. It is curious to read in these authors' excellent book some lines indicating how poorly known everything that Leonardo did is even today: They write, "If the application of such a simple apparatus had preceded the tube with two lenses, its inventor would deserve to be called a precursor, but in fact this did not happen." Leonardo's note that we have cited fully evidently shows that in fact "this did happen."

Recently D. Argentieri* has published a proof that Leonardo also created the two-lens systems of Galileo's telescope. In Codex F, folio 25 (Fig. 7) in the middle of the page is sketched a rectangular frame on a stand. Within the frame is the legend: "Ochiale di cristallo grosso da'lati un'oncia d'un oncia" (Eyeglass of thickness at the edges one inch of an inch, i.e. $\frac{1}{12}\cdot\frac{1}{12}=\frac{1}{144}$ foot). Further on he writes in explication, "Questo ochiale di cristallo debbe essere netto di machie e molto chiaro e da'lati debbe essere grosso un'oncia d'un oncia civè $\frac{1}{144}$ di braccio e sia sottile in mezo" (This eyeglass must be free from spots and very clear, on the edges it must be of thickness one inch of an inch, i.e., $^1/_{144}$ foot, and thin in the middle). Undoubtedly this refers to a concave negative lens. Further on, the text indicates that Leonardo is describing a magnifying optical system; he writes, "la lettera comune in instanpa parrà di scatola da spetiali" (the ordinary printed letter will appear like a letter on a drug box). One cannot obtain magnification with a negative lens; hence Argentieri considers that there must be also a positive lens in the system. Further on, Leonardo writes that "per fuori" (outside, i.e., for observation

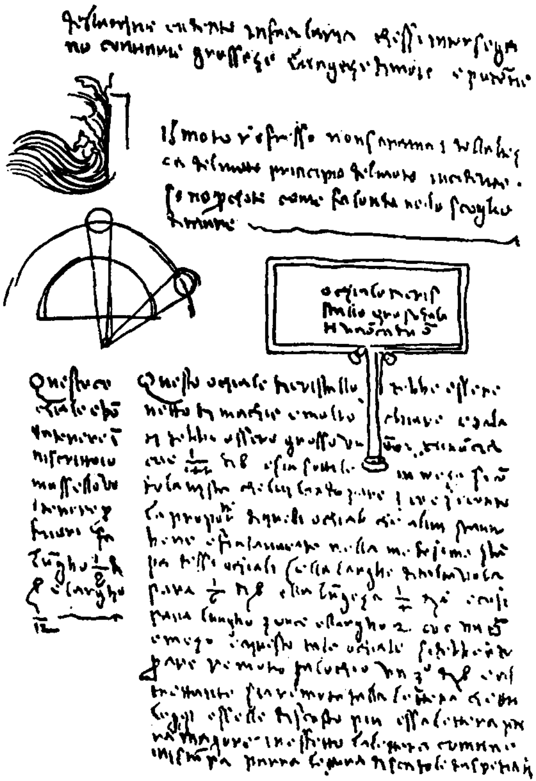

FIG. 7. A page from Codex F, folio 25, with a description of Leonardo's telescope (according to Argentieri). Copied in a mirror.

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*A. Donjon and A. Couder, Lunettes et telescopes, 1935, pp. 1, 581.

*D. Argentieri, loc. cit.

at a distance) the system must have a length of $\frac{1}{8}$ foot, but "bono da tenere in iscrittoio" (to be convenient for a writing table, i.e., for observation of nearby objects) it will be of length $\frac{1}{4}$ foot. If the interpretation of Leonardo's words is correct, the noted characteristics coincide with the properties of the Galilean telescope. In Argentieri's opinion, the diagram at the right of folio 25 of Codex F (cf. Fig. 7) depicts a lead form (calotta) for grinding of both convex and concave lenses, while the frame is the picture of a tube, at the ends of which there must be a convex and a concave lens. On the basis of various considerations, Argentieri completely reconstructed this telescope of Leonardo's, and demonstrated the reconstruction at the Vincian Exhibition in Milan in 1939.

It is difficult to rebut these proofs, and thus there are grounds to add Leonardo to the list of direct precursors of Galileo. Of course, Leonardo had positive and negative lenses at his disposal, and it is not very amazing that this restless, many-sided experimenter and observer found by chance Galileo's system in 1508-1509, i.e., 100 years before Galileo.

However, Leonardo himself never collected together all of his optical discoveries, thoughts, experiments, and observations, interspersed with extracts from books that he had read, nor have the historians done this. Leonardo's optical notes remained, insofar as we know, without effect on the development of the science of light. The fate was about the same of the optical researches of another remarkable scientist in optics of the 16th Century, the abbot Francesco Maurolico (1494-1575). Maurolico's thoughts, which were collected in his works under the jesting title of Photismi de Lumine*, written in 1567, were first published only in 1611, or shortly after Galileo's astronomical discoveries. Here the publisher C. Clavius points out in the preface that the occasion for publishing the book was precisely the "new and amazing discovery of the optical tube, which has aroused great expectations in all minds." Maurolico's treatise, which was written in a concise and clear form, is distinguished from the works of his precursors by its exceeding clarity, simplicity, and scientific frankness. Its introductory parts give a series of photometric theorems, which we can consider to be the first attempt at theoretical photometry. Further on, there follow catoptric theorems dealing with planar and spherical mirrors. The second part of the book discusses problems of refraction at planar surfaces and within spheres, the theory of the rainbow, the eye, and both positive and negative eyeglasses. Essentially new material is contained in the pages concerned with photometric laws, the eye, and eyeglasses. Apparently, Maurolico was the first to understand correctly how eyeglasses work, in spite of the fact that even he could not correctly portray the path of the rays in a lens and in the eye and did not know the law of refraction. On this he frankly writes, "In a medium bounded by a convex surface forming part of a smaller sphere, the refracted rays will converge more quickly, i.e., at a shorter distance; on the other hand, in a transparent medium bounded by concave surfaces of smaller spheres, the refracted rays will diverge. This is all that I can say in brief." Maurolico finishes his book with 24 "problems" recalling the famous Problems at the end of Newton's Optics. Among these problems, the second is as follows: "Why is optical theory so difficult? Isn't it because it requires both physical and mathematical reasoning, and thus is what they call a mixed science [mixta scientia]?"

Maurolico's treatise is by nature the complete opposite of the disorder and impressionism of Leonardo's notes. Perhaps if it had been written at the right time, the Photismi would have been of great didactic importance and might have helped in the development of optics. Actually, it saw the light after the great breakthrough brought by Galileo, and only a certain part of it retained its importance even later (in particular the pages on photometry).

A third remarkable figure among the Italian precursors of Galileo in the 16th Century in the field of optics was the Neapolitan Gióvan Battista de la Porta (1535-1615). His sphere of activity was unusually varied: an alchemist occupied throughout his life with the search for the philosopher's stone, a palmist, a prophet, a poet who wrote about thirteen tragedies and comedies, a mathematician who tried to solve the squaring of the circle, and besides, a skillful experimental physicist, especially in optics, and one of the most prominent members of the Accademia dei Lincei.* De la Porta presented his optical ideas and discoveries in the first and second editions of the Magia Naturalis sive de Miraculis rerum (1558 and 1589), which was very popular in his time, and in De refractione optices (1593). Magia Naturalis was called by this name not only in the figurative sense, but to the author the transition from "natural magic" to supernatural seemed conceivable and possible. Thus the optical experiments described by de la Porta are also reported as something miraculous. Such was the "great secret of nature" of the camera obscura (with a lens in the aperture, in distinction to Leonardo's camera) and a way of obtaining an image with a hidden mirror, etc.

The chapter on refraction gave some indications of the combined action of a convex and a concave lens, very unclear, but in which we can assume a system like Galileo's. On June 27, 1586, de la Porta wrote

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*Cf. the English translation The Photismi de Lumine of Maurolycus, translated by H. Crew, 1940. The quotations are cited according to this translation.

*Cf. F. Fiorentino, Gióvan Battista de la Porta (Studi e ritratti); also A. N. Disney, loc. cit.

to Cardinal d'Este, "I shall bring a book that I began more than thirty years ago, Magnalia naturae. In it I have disclosed all the secrets, selected and tested by all the sciences, i.e., the most subtle things, on which all science is toiling: how in optics to make a mirror that sets fires a mile away; how to make another mirror with which you can communicate with someone a thousand miles away by using the moon at night; how to make eyeglasses showing a person several thousand miles away, and other amazing things." It is difficult to separate truth from fantasy with the fascinating author of this letter; even when he speaks of facts, it is in an extremely exaggerated form.

In distinction from the Magia Naturalis, the De refractione is written in a quiet scientific style, and is distinguished by clarity and conciseness. Besides, it does not contain anything great and fundamentally new in comparison with his precursors. In the preface to the eighth book, de la Porta states that he had been able to see the tiniest objects a great distance away; however, the report was not followed by proofs and explanations.

After receiving word of Galileo's telescope, on August 28, 1609 de la Porta wrote to Prince Federico Cesi at the Accademia dei Lincei in Rome:* ". . . I know the secret of the seeing tube; it is a trifle [coglionaria] taken from the 9th book of my De refractione,† and I assure you that if Your Excellency should wish to make it, you will be truly satisfied. This tube is made of silvered tin [di stango d'argento], of length one cubit [palmo] ad, of diameter three inches; at the beginning a there is a convex eyeglass; there is another tube four inches long fitting into the first one, with a concave glass fastened at the end b, as in the first tube. If you look only through the first tube, you can see distant and near objects, but since the view is not upright [non si fa nel catheto], objects seem obscure and indistinct. However, if you put inside the other tube with the concave glass, which has the opposite effect, then objects can be seen clearly and directly. Here the second tube must fit into the first as in a trombone for adjustment to the eye of the viewer." The letter was accompanied by a drawing. One can assume that de la Porta didn't yet know with assurance the design of Galileo's telescope at the moment he wrote the letter to Cesi, and hence the fully clear description of the instrument on August 28, 1609 shows that de la Porta actually was one of the independent inventors of the telescope having a concave ocular. This is plausible if we bear in mind de la Porta's experimental ingenuity and his hints in Magia and in De refractione; of course, from the standpoint of juridical priority, a post factum letter does not have the force of proof. In any case, the Accademia dei Lincei, in which de la Porta was one of the most eminent figures, accepted his priority, and the general secretary of the Academy, Giovanni Fabro (Johann Faber of Bemberg) honored de la Porta with the following verses, which were rather tactlessly inserted into the first academic edition of Il Saggiatore:*

PORTA tenet primas, habes, GERMANE, secundas
Sunt, GALILAEE, tuus tertia regna labor.
Sidera sed quantum Terris caelestia distant
Ante alios tantum Tu, GALILAEE, nites.

(Porta was first, the German [an artisan from Middelburg] second, and your regal work, Galileo, was third. But you, Galileo, studied first among the others how far the stars are from the Earth).

De la Porta planned to publish a book on the telescope which, he thought, should correct numerous errors; in the summer of 1612 he wrote to the same Cesi, "All the books on the telescope that you have sent me are lifeless and contain errors, as the authors do not know optics. As soon as my hands are free of the tragedy of Ulysses that I am writing for a nobleman, I shall proceed to it, print it with many excellent experiments, and publish it in a book, which, if it had appeared earlier, would have prevented so many absurdities from having been written."†

However, the book was never published, and we know only that de la Porta worked on it during the last days of his life. It is evident from his words, as de la Porta was complaining, that the book on the telescope was killing him, for this was the most difficult and obscure thing of all that he had begun. The knowledge and discoveries of Leonardo, Maurolico, and de la Porta give a picture of only the very peaks of 16th Century optics. Much of what they knew hadn't reached, and never did reach, the wider circles of professionals, and remained without effect on the development of science. However, certain new results in good time became the inheritance of scientific thought, and were thoroughly recognized.

First of all, the camera obscura, which was a center of interest to Leonardo, Maurolico, and de la Porta, became of great importance. With the aid of this generally accessible instrument, everyone understood at last what real optical images of objects were, and they convinced themselves of their existence. Prior to the camera, images were known only in the eye and in pictures drawn by the hand of man. The camera decisively separated light from vision; this is its theoretical and perceptual role in history. Since the discovery of the camera, the problem of the structure of the eye, which had occupied the central spot in optics up to then, was transformed into a special

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*Ed. Naz., Vol. X, p. 252.

†The editor of Ed. Naz. points out that there is nothing in the ninth nor the eighth book of De refractione that is described further in de la Porta's letter.

*Ed. Naz., Vol. VI, p. 205.

†F. Fiorentino, op. cit., p. 279.

problem, mainly physiological and medical. In the 16th Century, strictly speaking, optics (in the exact sense of the word, the science of vision) ceased to be such, and changed into the science of light.

Catoptrics, the study of reflection, changed little during that time, having become a typically scholastic discipline. It was bound to physics by only a few threads, and remained primarily a field for purely geometric exercises. The only problem of catoptrics that aroused lively interest remained that of focusing mirrors; both Leonardo and de la Porta worked on it diligently in the vain hope of realizing the ancient and medieval legends associated with the name of Archimedes.

Dioptrics (refractive glasses) was a novelty, and was extremely interesting to the optical scientists of the 16th Century. However, we should be astonished at the sparsity of their results: a number of qualitative theorems, fruitless attempts to analyze the very complex case of image formation by a complete sphere, and complete inability to solve problems for the case of greatest practical importance of spherical lenses. De la Porta's dying complaint on the extreme difficulty and obscurity of the problems of the telescope is indicative in this regard. This state of affairs is usually explained by the lack of knowledge of the law of refraction in the 16th Century. Still, the modern student in the junior classes quantitatively solves problems on the construction of images in lens systems without using the law of refraction, but replacing it with a simple proportionality for small angles of incidence and refraction! The entire secret consists in the rational limitation of the problem to what we now call the paraxial rays and the Gaussian region. Like Alhazen and Bacon, the optical scientists of the 16th Century tried to solve the general case of the dioptric action of a sphere, and had to give up in the face of actual tremendous difficulties of the problem. Finally, only Kepler was able, after Galileo's discoveries, to eliminate this hypnosis over the generality of the problem of the sphere and to create the first quantitative dioptrics for a system of thin spherical lenses, based on an approximate law of refraction that is practically valid for small angles. Here we encounter again the fantastic zigzags of the actual history of science, in confutation of the artificial scheme.

Before Kepler, dioptrics, being hypnotized by the general problem of refraction by a sphere, could develop successfully only in the empirical way, as actually occurred, as we have seen.

In connection with the notorious disputes over the priority of discovery of the telescope, which haven't ceased even now, much interesting material has been discovered characterizing the state of dioptrics in the 16th Century, not in the high learned circles, but among the craftsmen, monks, and amateurs, who got convex and concave eyeglasses from the market. These people also experimented, sometimes successfully.

In the commentaries to Aristotle's Meteors,* published in 1646 in Rome, the mathematician Nicolaus Cabeus tells, for example, that he knew in Modena of an old Jesuit monk who, for twenty years before Galileo's discovery used the same optical system to read "the time" during his church service. He would press a concave lens to his eye, and hold a convex one in his other hand. Thus he could read the finest print at the other end of his cell. The monk did not concern himself with optics, and was not interested in the reasons for such an improvement in vision, but found the system by chance by combining eyeglasses, and did not consider it an important matter.

In the words of the son of one of the "inventors" of the telescope, his father Z. Jansen (1588-1632) made the first telescope in 1604 according to the model of some Italian, on which was written "anno 1590." It is usually considered that this "model" was de la Porta's tube. This is doubtful, since de la Porta himself never referred to the preparation of a model, let alone one in someone else's hands. However, in any case, some Italian in 1590 built a telescope, and it began to be passed from hand to hand as a secret which above all they wanted to sell for good money for military needs. The history of the so-called "invention" of the telescope† is thus a tangled knot of various dark machinations, not so much by the opticians, as by the dealers and rogues (e.g., it is known that Z. Jansen was accused of being a counterfeiter). This story has little relation to optics in general and to Galileo's optics in particular. The only important point is that at the beginning of the 17th Century the importance of optical tubes for navigation and military affairs gradually became clear to military and government people (e.g., the circle of Henry IV).

4. GALILEO'S PERSPICILLUM

Galileo was 45 years old when he built his optical tube and his attention was attracted to optics. In spite of the great variety of his knowledge and interests, Galileo's thought up to 1609 tended preferentially toward the field of mechanics, engineering, and astronomy; insofar as we know, he was not even once involved with optics‡ (unless one refers to problems of painting involving optics). However, as early as 1610 in a letter to the minister of the Florentine Duke

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*A. N. Disney, op. cit., p. 123. Also Gasparis Schotti, Magia universalis naturae et artes, 1658, p. 42.

†Cf. A. Donjon and A. Couder, op. cit., pp. 583–614; L. Bell, The Telescope, pp. 1–9, 1922; R. S. Clay, The History of the Microscope, 1932, pp. 6–8.

‡In the words of Galileo's first biographer, Viviani, Galileo often said that in his youth he was ready to devote himself completely to painting (Ed. Naz., Vol. XIX, p. 602).

Vinta* he reports that, among other matters, he was preparing treatises on optics and on the theory of colors. These treatises were never published and probably were never written; in his letter he was speaking of projects. However, Galileo undoubtedly at this time had already thought many times about light, and had observed and experimented. We shall become acquainted with these ideas and experiments below, but first of all, let us reconstruct the story of Galileo's building of his tube† on the basis of two of his stories in the Sidereus Nuncius in 1610 and in Il Saggiatore in 1623. These stories supplement one another, and give the full true story of the matter, as corroborated by auxiliary documents.

In Sidereus Nuncius, Galileo writes,‡ "Ten months ago the rumor came to our ears that some Belgian had built a telescope with the aid of which visible objects at a distance from the eye become clearly distinguishable, as though they were near. Experiments with this amazing instrument were reported; some confirmed them, others denied them. Several days later this was confirmed in a letter by the French nobleman Giacobo Baldovero** from Paris. And this was the reason for my turning to the search for the basis and means for the invention of a similar instrument. Shortly after this, relying on the theory of refraction, I acquired a grasp of the subject, and first prepared a lead tube, on the ends of which I put two eyeglasses [perspicilla]. Both were flat on one side, and on the other side one glass was convex spherical, and the other concave. Putting my eye to the concave glass, I saw objects rather large and near; namely, they seemed three times nearer and ten times larger than when seen with the naked eye. After this, I developed a more precise tube, which showed objects magnified more than sixty times. After this, sparing no effort nor means, I succeeded in building for myself an instrument so excellent that objects seemed on looking through it almost a thousand times larger and more than thirty times nearer than when looking with the aid of one's natural powers. It would be quite superfluous to give an account of how convenient such instruments are, both on land and on sea. However, relinquishing terrestrial matters, I turned to heavenly ones."

Galileo's second story is less well known and more detailed:***

"I long ago wrote in my Avviso Sidereo to what extent I took part in the invention of that instrument and whether with justice I could call this taking part. I described how in Venice, where I was then, the news arrived that a Dutchman had presented to Signor Count Maurizio an optical tube in which distant objects were as perfectly visible as if they were quite close. Nothing more was added in this report. Learning of this, I returned to Padua, where I was living then, and began to think about this problem. I solved it on the very first night after my return, and on the next day prepared the instrument on which I reported to the very same friends in Venice with whom I had discussed this matter on the previous day. I then immediately took up the building of another more perfected instrument, which I brought six days later to Venice. Here almost all the higher nobility of this republic looked through it with great amazement incessantly for more than a month, of which I became exceedingly weary. Finally, on the advice of some enthusiastic patron of mine, I presented the instruments to the Doge at the plenary session of the Council. How it was valued and with what enthusiasm it was accepted is evidenced by the letters of the Doge, which I still have with me. The magnanimity of this most brilliant prince was expressed in rewarding me for the invention that I presented by a life appointment to my chair at the University of Padua with a doubling of my salary as compared with what I had had earlier, which meant three times as great as for any of my predecessors. These events, Signor Sarsi*, didn't take place in the woods nor in the desert, they took place in Venice, and if you had happened to be there at those times, you would not have taken me to be its mere godfather. By the grace of God, most of the gentlemen are still alive, and know everything very well, and they can tell you everything even better.

But perhaps someone will say that it is a great aid in the discovery and solution of any problem to know somehow at the beginning that the conclusion is correct and to be assured of not seeking the impossible. Hence, they say, the knowledge and the indubitability of the fact that the optical tube had already been made helped me so much that without this I wouldn't have found anything. I shall answer this in two ways [distinguendo]. I shall say that the aid rendered me by the news aroused in me the desire to exert my thoughts, and that, perhaps, otherwise I never would have begun to think of the tube; however, I don't think that news of this sort could have any other effect on the invention. Besides, I assure you that it is a much harder thing to find the solution of a stated and named problem than to find the solution of a problem that hasn't been thought of or named, for here chance plays a great role; in the other case, everything is the result of thinking. Now we assuredly know that

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*Ed. Naz., Vol. X, p. 352.

†In the Sidereus Nuncius, Galileo calls the tube a perspicillum, which was translated in Russian books of the 18th Century by the word "perspektiva." In Italian Galileo called his tube "ochiale", i. e., "eyeglass." The word "telescope" was coined by Demisiani, a member of the Accademia dei Lincei, and "microscope" by the general secretary of this academy, J. Faber. Galileo denoted the microscope by the diminutive of ochiale, i. e., ochialino (little eyeglass).

‡Ed. Naz., Vol. III, Part 1, p. 60.

**Jaques Baldouère.

***Ed. Naz., Vol. VI, p. 257 et seq.

*The Jesuit Grassi, to whose objections Il Saggiatore is a reply.

the Dutchman, the first inventor of the telescope, was a simple maker of ordinary glasses. By chance, in examining glasses of different sorts, he looked through two glasses at once, one convex and the other concave, while they were at different distances from the eyes. Thus he saw and observed the effect that one obtains here, and thus discovered the instrument. However, I, motivated by the said report, found the instrument by thinking, and insofar as this thinking was very simple, I wish to report it to Your Most Excellent Worship, so that you can tell of it when the opportunity offers itself, and with your knowledge can make speak those who might have tried along with Sarsi to belittle my services, such as they may be.

My idea was this: this device consists either of one glass or of more than one. It can't consist of only one. The shape of a glass is either convex, i.e., thicker in the middle than at the edge, or concave, i.e., thinner in the middle, or it is bounded by parallel surfaces; such a glass does not change visible objects at all by magnifying or diminishing them, a concave lens diminishes them, while a convex lens magnifies them considerably, and shows them as very indistinct and distorted. Thus one glass is not enough to get the effect. I went then to two glasses, and knowing that a glass with parallel surfaces doesn't change anything, as I have said, I concluded that the effect also cannot take place when it is combined with either of the two others. Thus I wanted to find what happens on combining the two others, i.e., a convex and a concave one, and I saw that here I got what I was seeking. This is the way that my discovery happened, and here I got no help from the opinion that I had heard that the conclusion is valid. But if Sarsi or others suppose that the certainty of the conclusion greatly simplifies the finding of a way to realize the effect, let them read the story of how Archytas discovered the dove in flight, or Archimedes the mirror that sets fires at great distances, and other amazing machines, based on what others had said on the lighting of the eternal fire and on hundreds of other amazing things. Thinking this over, to their great glory they could easily and advantageously invent the devices, or at least, when this didn't succeed, find other benefits. Thus it becomes clearer that the help that might arise from a prior knowledge of the reality of an effect is actually much smaller than they think.''

Galileo's two stories answer many questions that we should ask on the invention of the telescope. First of all, Galileo's degree of independence in this invention is clear. There are no grounds for doubting the truth of Galileo's story; he was the same sort of independent inventor of the optical tube as were many other pretenders to this title, some of whom have been cited above. Galileo does not deny the stimulating effect on his invention of the news of the existence of a finished tube without any details of its construction; further, he was correct in that it was perhaps easier and more probable in his time to invent the telescope by chance than to construct it intentionally. The trend of Galileo's thoughts and work is clear. As is evident from the second story, he knew of the telescopic action of a single lens, which even Leonardo knew, but the information on the ''Dutch'' tube clearly surpassed what one could achieve with a single lens. Therefore Galileo asks the question of the action of a system of lenses, experiments with two lenses, a convex and a concave one, and thus finds the system being sought. Why didn't Galileo try a system of two convex lenses?* Possibly it was because, starting with his logical system, he immediately began with as general a case as possible. Further, Galileo's stories imply that he had no new theoretical concepts on the action of spherical lenses beyond what Leonardo, Maurolico, and de la Porta knew. His distinction from his precursors consisted primarily in Galileo's lively, clear, and broad understanding of the possibilities of the new instrument for navigation, military affairs, and astronomy. For Leonardo and de la Porta, the viewing tube was one of the foci of ''natural magic,'' like the camera obscura and the ''magic'' mirrors. Galileo relates, in full accord with actuality, with what unheard-of speed he could find the principle of the tube from one hint, perfect it, raising the magnification to very large values, and without delay realize its fundamental applications. These features of Galileo's discovery render it incomparable in value with the discoveries of Leonardo and de la Porta, that took place unnoted, not only by their contemporaries, but also in essence by the authors themselves.

Let us suppose for a minute that it had occurred to no one before Galileo to combine a concave and a convex lens, and that also priority for this system was added to his other merits. It would seem that this priority would prove to be only a ''drop in the ocean'' in comparison with the amount that Galileo actually did for optics. However, it is precisely the lack of priority in discovering the telescope that serves as grounds for modern historians of optics simply to exclude Galileo from its history. Hoppe in his History of Optics limits his remarks with respect to Galileo to the crude joke that there was no fee for constructing the telescope: ''The fee was in quite a different field,'' writes Hoppe, ''and yet was quite a proper one, for the Council of Doges raised Galileo's salary threefold on August 25, 1609 as a reward.''

Science is created by people, and there have been and will be disputes over priority. However, priority is fundamentally a juridical concept, and disputes over it in most cases are insignificant in a scientific evalua-

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*In the manuscript of Sidereus Nuncius in a diagram drawn by Galileo of the path of the rays in the tube, a system is actually illustrated having two convex lenses (Ed. Naz., Vol. III, Part 1), i. e., Kepler's system.

tion of the activity of a scientist, and even less important in the development of science. The time is long since due for us to understand that the probability of priority in a scientific discovery ceteris paribus is on the average inversely proportional to the number of persons concerned with the given problem at the same time. In Euclid's time, this probability was approximately unity, but now in many cases it is very small. As is well known, today even the most subtle and unexpected discoveries often have been made simultaneously by many persons and in different countries. Discoveries must above all be associated with the names of the persons who most clearly and fully understood their significance and accomplished most of all toward their development and furtherance. From this standpoint, of course, the first telescope must justly be called that of Galileo.

5. GALILEO'S MICROSCOPES

In his home in Padua Galileo built a shop for *founders, carpenters, and turners.** This probably explains the speed with which he prepared the first specimens of the telescope. We can with good reason also assume that an optical shop was gradually being built in the Florentine home of the Lincean academician; these were the original Officine Galilei. This was required by the incessant orders for telescopes from all the ends of Europe, and also by the optical tribute that Galileo often had to make to notable secular and ecclesiastic personages. Galileo's correspondence is full of letters containing requests to send a telescope or to thank him for a telescope received.† Sometimes he sent only lenses, though the clients insisted on the whole instrument. Then Galileo had to allude to the great length of the tube and the difficulty of sending it.‡

Few traces have come down to the present of this first production of optical goods. Two of Galileo's telescopes (Fig. 8) are kept in Florence in the Museum of the History of Science.** In the center of the stand supporting the tubes is the broken objective of a third tube. The length of the larger tube is 122 cm and the width of the aperture is 44 mm. The length of the other one is 93 cm and the aperture is 14 mm. The tubes are made of paper. The title page of Il Saggiatore (1623) shows two crossed extensible tubes (Fig. 9 shows a magnified photograph of this detail of the engraving) and a lens on a stand. Apparently we have here the first picture of Galileo's extensible tube.*

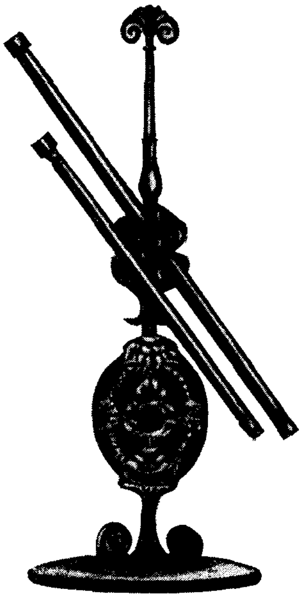

FIG. 8. Two of Galileo's telescopes from the collection of the History of Science in Florence.

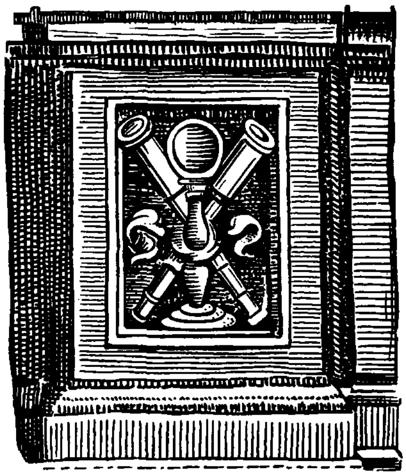

FIG. 9. A detail from the title page of Il Saggiatore (1623) with a picture of two crossed adjustable telescopes.

Galileo found it necessary to be able to change the tube length, and not only for adjustment to one's eye and for portability. Apparently, by manipulating convex and concave lenses Galileo noted as early as 1609-1610 that when he changed the distance between the lenses he could see in magnified form not only distant objects, but also near ones. In other words, the same system of a convex and a concave lens can produce a telescope or a microscope upon variation of the distance between the lenses. In Il Saggiatore

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*Ed. Naz., Vol. XIX, p. 130 et seq.

†Cf. Ed. Naz., Vol. XIII.

‡E. g., E. Wiedemann, Studien zur Geschichte Galileis, Stzb. d. phys. med. Sozietät in Erlangen 36, 273 (1904).

**This poorly-known museum contains a remarkable collection of Italian physical and chemical apparatus, in particular, the heritage of the Accademia del Cimento. Unfortunately, the magnificent collection of historical apparatus is being kept with insufficient care. This, at least, was the condition of the museum in 1935.

*The engraved portrait of Galileo affixed to the Descriptions and Proofs Concerning the Sunspots (1613) is surrounded by a frame with the figure of an angel looking through a telescope of an improbable shape (Fig. 10, p. 605).

Galileo wrote with regard to the problem of magnifying objects at various distances:[*] "If one approaches to quite small distances, to four paces, to two, to one, and one-half, the image becomes blurred and dark, and the telescope must be lengthened for distinct and clear observation. This lengthening corresponds to a greater magnification. Here the magnification depends only on the lengthening of the tube, rather than on the closeness of the object." This conclusion of Galileo's agrees with the formula for the magnification in a system consisting of a convex and a concave lens as applied to observe very close objects, i.e., as a microscope:

$$\Gamma = \frac{25\,(d - F - f)}{Ff}\,;$$

Γ is the magnification, i.e., the ratio of the angle over which the image is visible in the microscope to the angle subtended by the object at the "distance of best vision," which is about 25 cm; d is the distance between the lenses; and F and f are the focal lengths of the objective and the ocular.

Galileo possessed this information on the properties of a system consisting of a concave and a convex lens long before he wrote *Il Saggiatore*. The Scotsman John Wedderburn[†] in 1610 wrote the following: "Several days ago I heard that the author himself [Galileo] reported to His Most Excellent Signor Cremona various things, and among others, how with the aid of his telescope [ex perspicillo] he could beautifully distinguish the organs of motion and sensation of tiny animals." The National Library in Paris contains the manuscripts of the diary of Jean Tarde of a journey to Italy.[‡] During November and December of 1614 he wrote the following:

"I asked him [Galileo] about the refractions and the method of working the glass in such a way that objects are magnified and brought closer in the desired ratio. He answered me thereupon that this science is not yet well enough known, and that in this matter he couldn't point out anyone of the practising optical scientists [qui traitent la perspective] except Johann Kepler, the Imperial mathematician, who had recently written a book, which however was so obscure that it seems that the author himself doesn't understand it. Of the entire conversation I have used only two theorems of importance in this question. The first consists in the fact that the greater the circle that the convex lens forms a part of, and the smaller the circle for the concave lens, the farther one can see. The second one says that a telescope tube for looking at stars is no longer than two feet, but in order to see very close objects that can't be distinguished owing to their smallness, the tube must be as long as two or three *brasses*.[*] He told me that through the long tube flies seemed as large as a lamb, and that they are covered with wool and have very sharp claws by means of which they hold on and walk on glass, sticking the points of their claws into the pores of the glass."

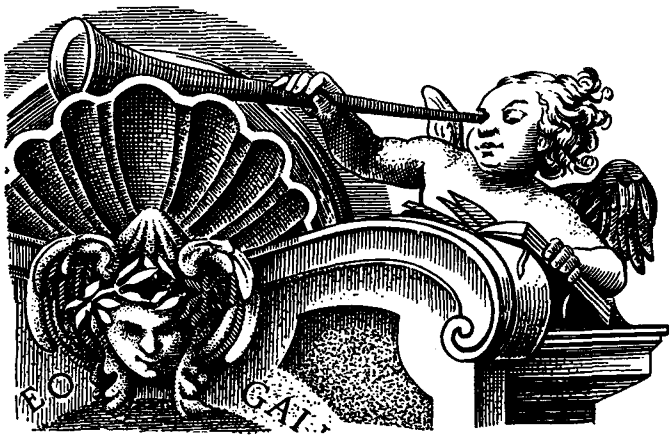

FIG. 10. A detail from the frame of the engraved portrait of Galileo affixed to the *Descriptions and Proofs Concerning the Sunspots* (1613), with the picture of a telescope.

Further information on Galileo's microscope appears only after ten years. On May 11, 1624, Faber wrote to Federico Cesi:[†]

"Yesterday I met our Signor Galileo, who is living near the Church of the Magdalene. He gave a very excellent microscope [ochialino] to Signor Cardinal Zoller for the Duke of Bavaria. I myself saw a fly that Signor Galileo showed me. I was amazed, and told Signor Galileo that he is the new creator, since he makes things appear that were not known to have been created."

On September 5 of the same year, Bartolomeo Imperiale sent his thanks from Genoa to Galileo for an instrument that he had received,[‡] "which is a perfection, like all of your inventions." It is clear from the following text that he is referring to a microscope for observing small insects.

On September 23, 1624, Galileo sent a microscope to Federico Cesi with the following covering letter.[**]

"I am sending Your Excellency a microscope [ochialino] for observation of tiny objects at close range. I hope that you too will find great pleasure in it, as I have. I am late in sending it to you, since earlier I was not able to bring it to perfection owing to the difficulties of proper working of the glasses. The object is fastened to a mobile ring at the bottom; in order to see everything, you must move it, since the eye can see only a small part. The distance between the lens and the object must be very small, and

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[*] Ed. Naz., Vol. VI, Part 1, p. 265.

[†] Ed. Naz., Vol. III, Part 1, p. 158.

[‡] Ed. Naz., Vol. XIX, p. 589.

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[*] The *brasse* is approximately 1.62 meters.

[†] Ed. Naz., Vol. XIII, p. 177.

[‡] Ed. Naz., Vol. XIII, p. 201.

[**] Ed. Naz., Vol. XIII, p. 208.

hence in viewing objects showing relief, one must have the possibility of bringing the lens closer and moving it depending on which part one is looking at. Thus the little tube [il cannoncino] is made movable on its base [nel suo piede] or guide [guida], as one would like to call it. You should use the instrument in the clear, transparent air, and better in the direct sun so that the object will be well illuminated. I have observed very many tiny animals [animalucci] with endless delight. . . On the whole, here you can ceaselessly contemplate the grandeur of nature, how finely it operates, and with what untold care."

On October 4, 1624,* B. Imperiale again shares with Galileo the results of his microscopic observations, and also discusses on the basis of de la Porta's remarks in Sec. 11 of the 17th book of Magia the possibility and advantages of using lenses with parabolic surfaces.

On October 25, 1624, Bartolomeo Balba notifies Galileo that he is expecting receipt from him of a small tube (il piccolo ochiale) that he had promised.†

On comparing the cited documents, we easily note that in 1610-1614 and in 1624, they refer to two completely different designs of the microscope. At first, by using the same lenses as for a telescope, Galileo transformed the system into a microscope by lengthening it to the dimensions of seven feet (by increasing d in the cited formula). However, in 1624 Galileo probably built a completely new instrument with very small focal lengths of the lenses, owing to which the tube was extremely shortened and acquired its modern shape. Hence is derived the diminutive name of ochialino (little tube) or il piccolo ochiale, as Balba expressed it. The first seven-foot variant of the microscope, on the contrary, should have been called in Italian ochialone (big tube).

In the Museum of the History of Science in Florence there are two microscopes without lenses, ascribed to Galileo since the time of the Accademia del Cimento (Fig. 11). This attribution is general regarded skeptically,‡ mainly for reasons of the high degree of perfection of the mechanical part of the preserved microscopes. The letter to Cesi cited above evidently shows that the microscopes coming from Galileo's shop in 1624 already had a complex and subtle design with a movable stage and a "micrometric" arrangement. Hence the question of the attribution of the Florentine microscopes would deserve a further, more attentive study. Undoubtedly, the microscope was invented and built independently of Galileo at the same time (1608-1620) in Holland** (Lippershey, Mezius, Gans, and Zacharias Jansen) and in England (Drebbel, 1621). However, there is no question of Galileo's independence in this discovery as well, of his ability to carry it through in essence and in design, and finally, of his actual promotion of the new instrument for the sake of biology. The series of letters cited above demonstrates this sufficiently, and though Galileo himself never reported on his new instrument in printed form, however, a book by Francesco Stelluti* on bees was published as early as 1625 in Rome; here the author "microscopio observavit," i.e., he reported on anatomical observations made with Galileo's microscope. Just as Sidereus Nuncius was the first publication on astronomical observations with the telescope, Stelluti's Apiarium began an endless series of publications on microscopic discoveries.

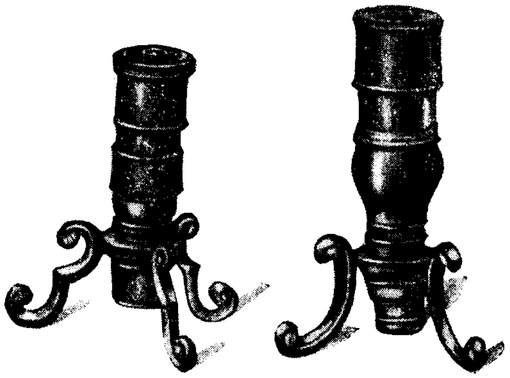

FIG. 11. Two microscopes without lenses from the collection of the Accademia del Cimento, ascribed to Galileo.

6. GALILEO'S GEOMETRIC OPTICS

Galileo's theoretical scope in geometric optics differed little from the knowledge of his contemporaries (except Kepler). This is eloquently told by Galileo's story of the invention of the telescope and his conversation with Tarde in 1614, as given above. Traces have been preserved of Galileo's involvement with the quantitative relations in reflection from spherical mirrors† in the form of a large drawing that presents nothing new. The path of the rays in systems containing lenses theoretically was guessed at only qualitatively, and lens optics remained for Galileo a purely experimental science with the most general, but nevertheless incontestable geometric postulates. This appeared especially expressively in his polemic with the Jesuit Orazio Grassi on the nature of comets. Galileo at first appeared under the cloak of his friend and student Mario Giuducci, who gave a speech in 1619 in the Florentine Academy.‡

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*Ed. Naz., Vol. XIII, p. 212.

†Ed. Naz., Vol. XIII, p. 218.

‡A. N. Disney, op. cit., p. 107.

**Cf., e. g., A. N. Disney, po. cit., p. 89 et seq.

*Apiarium ex frontispiciis naturalis theatri principis. Federici Caesii Lyncei, S. Angeli et S. Pauli Principisi, Marchionis montis Coeli ii, Baronis Romani depromptum, quo universa mellificum familia ab suis prae-generibus derivata, in suas species ac differentias distributa in physicum conspectum adducitur. Franciscus Stellatus Lynceus Fabrianensis microscopio observavit. Romae superiorum permissa, anno 1625.

†Ed. Naz., Vol. III, Part 2.

‡Ed. Naz., Vol. VI, p. 43.

The basic part of this speech was written by Galileo or expresses his thoughts. After another of Grassi's polemic works had appeared, published under the pseudonym of Sarsi, Galileo wrote Il Saggiatore (1623), where he attacked Grassi with renewed vigor.

One of Grassi's arguments against Galileo was the fact that the telescope is ineffective in forming images of the fixed stars. In the telescope not only did they not seem larger, but even smaller than when seen with the naked eye. Hence Grassi drew the fantastic conclusion that the telescope magnifies only at relatively short distances, and magnification ceases for distant objects. The fact cited by Grassi was incomprehensible not only for the optical scientists of the 17th Century: as we know now, it has remained forever unattainable from the standpoint of geometric optics. Here the optical scientists of the 17th Century came up against a manifestation of the wave nature of light. Galileo was not disconcerted by the force of the argument, but skillfully skirted the fundamental point, i.e., the fact, and smashed to smithereens all of Grassi's own fantasies. Let us give Galileo's argumentation in Il Saggiatore:* "The telescope permits one to see what was not visible," Galileo presents Grassi's opinion, "not in one, but in two ways. The first consists in presenting objects to the eye at a larger angle, so that they seem larger, and the second in the condensation of the rays and images [specie], so that they act more strongly. Since one of these ways is enough to manifest that which had not been perceived, then shouldn't we conclude from it that only one of the ways is acting? These are his [Sarsi's] exact words, of which I would not say that I could penetrate to their inner meaning... The presentation of objects at a larger angle, whereby they seem larger, seems to be an action opposite to the condensation of rays and images. Since if the rays bear images, isn't it easy to understand how they are condensed and at the same time form a larger angle? [According to Sarsi] when we look through the telescope, e.g., at the Moon, and it grows in dimensions, this results from an increase in the angle; however, when we look at the stars, the angle doesn't increase, but the rays are condensed. I, though, can say in all truth that for the infinite, or better, extremely great number of times that I have looked through this instrument, I have never noted any distinction in its action. On the contrary, I assume that it always acts in the same way, and suppose that Sarsi does not think otherwise. And if that is so, then both operations, the increase in the angle and the condensation of the rays, always take place together, and Sarsi's objection completely loses weight... Assuming that in part I understand Sarsi's intentions, who, if I am not in error, wishes the reader to believe something that he himself doesn't believe at all, i.e., the point that the visibility of stars that were previously invisible arises from the condensation of the rays, rather than from increase in the angle... He didn't wish to express himself openly on other ideas of Signor Mario, but remained silent, in particular, on the point that the distances between stars are magnified in the same ratio as are objects here below; these distances should not increase at all, since they are as far away as the stars themselves."

Further on,* Galileo writes, "It is true, Signor Sarsi, that a lens, i.e., a convex glass, collects the rays and thus multiplies the light and favors your conclusion. But what have you done with the concave glass, which counteracts the lens in the most important place, since it is near the eye, into which the final rays pass. It is the final judge and summation [Saldo] of everything. Whereas the convex lens collects the rays, don't you know that the concave glass spreads them, forming an inverse cone? If you had tried to catch the rays passing through both glasses of the telescope in the same way that one observes the rays refracted by a single lens, you would have noted that at the place where the rays had combined to a single point, now they continue to diverge more and more to infinity, or better, to a vast distance... How could such rays in a telescope provide an increase in the illumination along with magnification?"

In a postscript to the text of Mario Giuducci's speech, Galileo notes:† "But why are other arguments and experiments necessary in an attempt to convince one of a point whose truth is evident from the singular and very simple postulate of optical science that the visual rays [raggi visivi] always propagate along straight lines and never along curves. From this premise, the conclusion immediately follows that visible objects at any distance, when seen by the same telescope, are always magnified in the same ratio."

Galileo explained the apparent decrease in the dimensions of stars when one goes from naked-eye to telescopic observation by the idea that the "glow" or "rays" is removed from the star. In Galileo's opinion, this property of having "rays" arises from the eye itself, from the ocular fluids, and the eyelashes.

In the heated argument with Grassi, we become witnesses of a complex scientific situation. Galileo strictly followed the concepts of geometric optics and handled his opponent with ease, but still we have to acknowledge that a considerable fraction of the truth is hidden in the ideas of the learned Jesuit, though they are ridiculous at first glance. If we translate, or better, interpret Grassi's ideas into modern physical language, then they say approximately the following: the telescope magnifies the image and also increases the light flux incident on the eye; when objects are at relatively short distances, geometric optics is fully

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*Ed. Naz., Vol. VI, p. 43.

*Ed. Naz., Vol. VI, p. 255.

†Ed. Naz., Vol. VI, p. 107.

applicable, and one obtains the normal magnification; when objects are at very great distances (beyond the resolving power of the instrument), one sees only a formless (diffraction) trace of the object, and the telescope helps us to discern it only because it collects more energy into the eye. In this translation, Grassi's idea is correct. Nevertheless, it is clear that a victory by Grassi at the beginning of the 17th Century would have hindered optics, and conversely, Galileo's strictly geometric position was progressive. Even almost 100 years later, Newton's Optics cautiously evaded Grassi's objection; this was also historically expedient.

The doubts raised by Grassi did not vanish completely, in spite of the brilliance and power of the argumentation in Il Saggiatore. A letter has been preserved from Galileo to an unknown person from Arcetri of January 15, 1639, i.e., almost 20 years after his polemic with Grassi. Galileo, who had become almost blind, dictated the following:*

"Regarding the fact that the fixed stars show no magnification in the telescope, I have already written and published many years ago. I explained at length that the telescope magnifies the planets and the fixed stars in the same ratio, and very clearly interpreted why it seems that the fixed stars do not get magnified, but sometimes are even made smaller. If you will be so kind as to look over my Il Saggiatore, you will find there a very detailed treatment of this matter. I see in the vast remoteness of the fixed stars an argument in favor of their extreme smallness, rather than of the idea that they are not magnified much. In this book I show that they are hundreds and thousands of times smaller than has been supposed. I myself, not long before I lost my sight, found a very precise way to measure their diameters. According to this method, they turned out to be much, much smaller than I myself had originally stated."

The "very precise" way of measuring the diameters of stars that Galileo mentioned has been preserved in a note by a certain Arrighetti.† It consists, in modern terms, of the following. Let there be a thin opaque rectangular screen with sharp edges (Fig. 12, left) of width l, placed in the field of view of the telescope. Let us note with the aid of a pendulum the moment of occultation t_0 of a star being hidden by the screen, and the moment t_1 of appearance of the light of the star after it has moved across the width of the entire screen. Now let the screen be doubled in width to $2l$, and the moments of beginning of occultation and of appearance of light be t_0 and t_2, respectively (Fig. 12, right). Let us denote the diameter of the star as d. If we assume that the star moves with constant velocity, we find

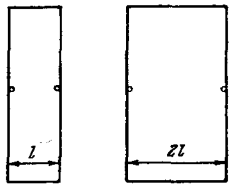

FIG. 12. Galileo's method for measuring the diameters of stars.

$$\frac{t_2-t_0}{t_1-t_0}\,\frac{2l-2d}{l-2d}=r,$$

whence

$$d=\frac{(r-2)\,l}{2\,(r-1)}\,.$$

If the width of the screen in the second case is nl, then

$$d=\frac{l}{2}\,\frac{(r-n)}{(r-1)}\,.$$

Galileo's elegant method is based on complete trust in geometric optics. Unfortunately, the nature of light here again manifests itself in diffraction, and the method in its simplest form can give only an upper limit for the diameter of the star.*

7. THE PROBLEM OF THE NATURE AND VELOCITY OF LIGHT IN GALILEO'S OPTICS

With Galileo, the formalism of geometric optics corresponded to a rather definite concept on the nature of light, which he expressed in Il Saggiatore and much later in the Discorsi. For Galileo, the visual sensations and their external cause, that is, light, were sharply and clearly distinct: "I do not think," he discusses in Il Saggiatore,† "that the excitation in us of tastes, odors, and sounds in the external world requires anything other than magnitudes, patterns, multitudes, and motions, slow or fast. I assume that if you take away the ears, tongue, and nose, everything will remain patterns, numbers, and motion, but there will no longer be odors, tastes, and sounds, which outside of living substances remain only words, just as tickling remains just a word if you take the brush or hair away from your nose. And just as the four discussed senses correspond to four elements, vision, the most important sense of all, corresponds to light, but with the same proportion of excellence that the infinite has over the finite, that the instantaneous has over that which takes time, that quantity has over the indivisible [tra l'quanto e l'indivisibile], and that light has over darkness. I know only extremely little about this sense and its causes. How-

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*Ed. Naz., Vol. XVIII.

†Ed. Naz., Vol. VIII, p. 462.

*Galileo's method can be applied in principle to determine stellar diameters if one performs a precise photometric measurement until the onset of occultation and after the appearance of light. In this case the theory of diffraction permits one in principle to determine the diameter of the star from the photometric data.

†Ed. Naz., Vol. VI, p. 350.

ever, to explain this very little, or better, to sketch it on paper, I would require much time, and hence I remain silent." However, Galileo sufficiently concretizes his thinking further on. For him, as for many of the physicists of the 16th and 17th Centuries, light was related to fire. Fire itself has a discrete structure: "Heat, which we shall call by the general word fire, is a multitude of tiny particles which have certain shapes and move with certain velocities.* . . .As long as they remain small particles [quanti], in spite of subdivision and disintegration, their motion takes time [é temporaneo], and their action is only thermal. However, if one goes beyond this to the extreme, highest subdivision into atoms that are really indivisible, then light is created, having instantaneous [instantanea] motion, or as we might say, expansion or diffusion. Light is powerful (I don't know whether it is permissible to express it thus) in its fineness, rarefaction, insubstantiality [immaterialitá], or in some other property differing from those named, giving it the ability to fill vast spaces."

Thus, in the period when he wrote Il Saggiatore, light seemed to Galileo to be an infinitely swift flow of the ultimate indivisibles into which matter can be subdivided by heat or mechanical means. This corresponded to Galileo's general mechanical and atomistic picture of the world. Later the idea was spelled out in detail, and instantaneous propagation of the atoms of light was replaced by propagation at finite speed, and Galileo tried experimentally to determine the speed of light. This is recounted in several brilliant pages of the Discorsi (1638).† Three of the discussants of the Discorsi are debating the question of the infinite and the finite, and go on to the subdivision of matter, and unexpectedly stumble across a fundamental problem of optics. Salviati, through whom Galileo himself speaks, remarks that "gold and silver are brought into a finer state of subdivision by aqua regia than by the sharpest file, which leaves them still in the form of powders; however, they become liquids and melt only when the indivisible particles of the fire or the sun's rays dissolve and disintegrate them, as I imagine, into their original indivisible and infinitely small parts." We see that Salviati repeats the ideas of Il Saggiatore.

Sagredo, Galileo's alter ego, points out further on, "I have observed several times with amazement what you just mentioned in passing with regard to the sunlight. I saw how they could melt lead instantaneously with a concave mirror of about three palms diameter; hence I concluded that if the mirror were very large, well polished, and of parabolic form, in a very short time it would melt all the other metals... Must we suppose that the action of the sun's rays, and such a powerful action besides, occurs without the participation of motion, or rather with the participation of motion, but a very rapid one?" Salviati agrees with this, and the dialog goes on to another interesting theme. The same Sagredo raises a new question, "But of what nature and what degree of rapidity must this motion of light be? Must we consider it to be instantaneous, or to take time, like all other motions? Couldn't we convince ourselves by experiment as to what it actually is?" On this theme Simplicio makes a worldly observation: "Everyday experience," he interrupts, "shows that the propagation of light takes place instantaneously. If you observe artillery action from a great distance, the light from the fire of the shots is impressed on our eye without any loss of time, in distinction from the sound, which reaches our ear after an appreciable interval of time." Sagredo interrupts this trivial reply, "Why, Signor Simplicio, from this generally known experience I can draw no other conclusion than that the sound reaches our hearing after longer intervals of time than the light; however, this does not convince me at all that the propagation of light occurs instantaneously, rather than taking a certain, though small, time. I derive no more than that from another observation, which one may express thus: "As soon as the Sun rises to the horizon, its brilliance immediately reaches our eyes." In fact, who can prove to me that its rays hadn't appeared at the horizon before they reached our eyes?" After this, Salviati goes on to a "concrete proposal": "The lack of cogency of these and other similar observations has forced me to think of some way of ascertaining without error whether illumination, i.e., the propagation of light, takes place truly instantaneously, since the rather rapid propagation of sound already compels us to assume that the propagation of light must be exceedingly swift. The experiment that I have devised consists in the following." Then follows the description of Galileo's well-known experiment with two experimenters with lighted lanterns which they can cover and uncover at will, signaling to each other at great distances. This experiment comprises in principle the system of all direct measurements of the speed of light that have been made up to the present. On hearing the description of the system of the experiment, Sagredo remarks, "This experiment seems to me to be as reliable as it is ingenious. But tell me, what was its result?" Salviati's answer gives some information on Galileo's actual experiments: "I was able," he said, "to carry it out only at a short distance, less than a mile, and hence I couldn't convince myself whether the appearance of the light at the other end actually took place immediately." Then follows the conclusion, which was wrong, as we know, but was interesting for his time. "If it [the appearance of the

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*Ed. Naz., Vol. VI, pp. 350-352.

†The references hereinafter are taken from the Russian translation by A. N. Dolgov, G. Galileĭ, Besedy i matematicheskie dokazatel'stva i pr. (G. Galileo, Discourses and Mathematical Proofs, etc.), 1934, p. 110 et seq.

light] doesn't take place immediately," Sagredo adds, "then in any case it occurs with extreme rapidity, almost instantaneously; I can compare it with the movement of the light in lightning that we see in the clouds from distances of eight to ten miles. Here we discern the very source and the beginning and end of the light at certain places in the cloud, although the propagation of the light to all of the surroundings follows immediately. This seems to me to prove that the phenomenon takes a time, though a small one, since if the light of the lightning had arisen at once in all parts, rather than gradually, then I suppose that we couldn't distinguish its source, the center of its radiation, and its branches." Sagredo-Galileo here takes the speed of propagation of an electric discharge to be the speed of light. Besides, he apparently has in mind also the propagation of the light coming to the eye from the edge of the cloud, as compared with the direct light of the lightning. However, this delay is beyond the limits of simple observations, since it is measured at most in ten-thousandths of a second.

The dialog on the speed and nature of light is interrupted by the frightened cry of the realist Salviati, "But into what a shoreless ocean we have gotten ourselves without noticing it! We are floating amid the void, the infinity, small indivisible particles, instantaneous motion, and thousands of other things, and in no way can we put in to shore!"

In the given remarkable excerpt from the Discorsi, especial attention is due to Sagredo's idea that the fact of ignition by the sun's rays implies the enormous speed of the atoms of light. In an unclear form Sagredo-Galileo is applying here the law of conservation of energy. If the atoms of light are small (i.e., their mass is small), then to explain the enormous energy manifested in ignition, we must assume that the velocity of these atoms is extremely large.

This is the extent of Galileo's statements on the nature of light that have come down to us. We may suppose that they were not fully defined. In Galileo's correspondence one finds lines indicating that he hadn't always nor fully put away even the archaic visual rays into the archives of history. The real-life, rather than the literary, Sagredo reports the following in a letter to Galileo on July 7, 1612*: "As for what you write to me on the visual rays and on images [Spetie], I can't begin to judge how they differ, since I don't believe that visual rays exist, and don't understand why they are necessary to vision." From the following text we can gather that the visual rays came up in connection with the old question of the inversion of the image on the retina of the eye. Another of Galileo's correspondents, D. Antonini, writes on July 21, 1612 from Brussels: "With regard to the ideas which Your Worship expresses on the image, which is inverted on paper but not in the eye, I assume that this doesn't imply a difference in the rays producing the image from those giving rise to vision. And above all, I don't agree that the image that is inverted on paper isn't also inverted in the eye." Even in his old age, in 1640, Galileo used the concept of visual rays. In the rough drafts of Letters to Prince Leopold of Tuscany* he remarks, "Liceti confuses the disappearance of the illuminating rays with the disappearance of the visual rays."

This does not imply that Galileo adhered to the ancient theory of visual rays, but in solving practical problems he used the customary conceptions of Euclidean optics as an auxiliary tool.

8. OBSERVATIONS IN THE FIELD OF PHYSICAL OPTICS

There are scattered through the pages of Il Saggiatore and Galileo's correspondence, in almost the same disorder as in Leonardo's manuscripts, notes and observations on physical optics revealing Galileo's sharp powers of observation and vast scope. Here are some lines on the regular reflection from matte surfaces in Il Saggiatore†, of quite modern content: "As for the necessity of polishing, I assure you that even without it you can get reflected images that are complete and distinct. If Your Most Excellent Worship will take a rock or a piece of wood that is not so lustrous as to give an image directly, and put them at an angle to the eye, as people do when they want to test for flatness and straightness, then you will see distinctly the images of objects situated at the other end. The distinctness is such that if you hold a book in this way, you can read it with ease." After this follow observations on the reflection from a heated wall and on the mirage.

Here is a description of some simple experiments with a prism and the observation of diffraction:‡ "If you hold to your eyes a triangular glass prism, all objects are colored with rainbow colors... Don't we see a similar play of various colors on the feathers of many birds when they are illuminated by the sun? More than that. I shall report to Sarsi something possibly new to him, if in general one can tell him anything new. Let him take any suitable substance, wood, rock, or metal, and look at them most attentively in the sunlight. He will see all the colors distributed among tiny particles, and if he uses a telescope set up for examination of very near objects,** he will see what I am talking about."

Phosphorescence phenomena were apparently unusually interesting to Galileo. Let us take up in more

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*Ed. Naz., Vol. XI, p. 355.

*Ed. Naz., Vol. VIII, p. 549.

†Ed. Naz. Vol. VI, p. 291.

‡Ed. Naz., Vol. VI, p. 290.

**Obviously he is referring to the first variant of Galileo's microscope (cf. Sec. 5).

detail this poorly-known episode in Galileo's scientific work.

In 1604, the alchemist Vincenzio Casciarolo discovered the amazing property of certain barites found on Mount Paderno in Bologna to phosphoresce after exposure to the sun. Casciarolo told of his discovery to the learned Bolognese. Apparently Galileo learned from the Bolognese mathematician Giovanni Antonio Magine of the Bolognese "luminiferous" stone. In any case, in 1611, at a time that he was in Rome at a meeting, perhaps of the Accademia dei Lincei, where the nature of light was being discussed, Galileo demonstrated the Bolognese stone.* If we recall Galileo's atomistic views on the nature of light, we can understand what a great importance he might put on the prolonged radiation of the stone. For the modern physicist, light exists only in the dynamic moving state; stationary, quiescent light is unthinkable. For the atomist of the 17th Century, conversely, particles of light could have any state of motion from a stationary one to enormous velocities. Therefore phosphorescence, naturally, was interpreted as the stopping of the atoms of light and their gradual liberation. While according to the Russian riddle, light is "what you can't hide or shut up in a box," in Galileo's eyes the Bolognese stone could be precisely such a box.

Galileo's demonstration in Rome apparently was very significant in spreading information about phosphorescence and in arousing especial interest in it. On October 21, Federico Cesi wrote to Galileo:† "Signor La Galla has written about light in connection with the stones that you showed. The problem is difficult, and it is always exceedingly hard to find the cause without departing from the old-fashioned opinions." On August 4, 1612, Sagredo writes to Galileo‡ with regard to the Bolognese stone: "The box** has become a most precious object to me, but I have no desire to enter into speculations on the reason for such an amazing effect." On May 9, 1613, Sagredo informs Galileo*** : "The stones that Your Worship sent in a box seem not to absorb light any more; I would like to know, are they natural or artificial?" On May 24, 1613, G. Bardi appeals to Galileo on the same matter:**** "My patron asked me to find out from Your Worship about the stones that flashed for you when touched or rubbed, do they lose their light where they are touched?" Federico Cesi in a letter of May 30, 1613 thanks him for sending a box containing the stones.***** We see that Galileo's boxes containing the Bolognese stones became just as fashionable a thing as his telescope, and we can assume that Galileo's Florentine shop prepared these boxes, along with telescopes and microscopes.

His interest in phosphorescence did not cease for many years. On August 29, 1626, Galileo made this request to Cesare Marsili in Bologna:* "I assume that Your Worship has heard of the stones which after heating absorb light and hold it for a short time; these stones come from a place not very far from Bologna. If you have no knowledge of them, I shall send you samples [la mostra] of the stones and also the name of the place where they are found. I would like to receive these stones, since their action, to my way of thinking, is one of the greatest wonders of nature." C. Marsili answered Galileo very quickly, in four days, "I have tried to have them supply me with the stones that you ask about. I shall have them not before Monday. An artist who knows them has promised to go to get them Sunday morning before dawn, since only at this time can one recognize them. They will bring me the best and all that they find. Indeed, they are not interested in them in Bologna [non se ne fa caso], but since there are other stones at this site that are valued in Venice and other places, they take all the stones. I don't know the name of the stone, but the mountain is called Paderno. I remember that I saw the phenomenon that Your Worship writes about 15—20 years ago. They write to me that they have also seen the water or elixir from this stone, from which hairs fall out. If you will send the samples, we will be surer to pick out the good ones. The person who promised to search them out for me knows how to fire them and pack them in a box."

The letters cited here indicate Galileo's concern with phosphorescence over a period of 15 years. Unfortunately, practically no traces have been preserved of the results of Galileo's work and his views on the nature of the phenomenon, except for the intriguing phrase cited above, that it is "one of the greatest wonders of nature." It is indubitable only that Galileo widely propagandized the Bolognese stone and interest in it.

At the end of his life, in 1640, the blind Galileo again happened to turn to the problem of the Bolognese stone in his last printed publication, the Letter to Prince Leopold of Tuscany,† which contains a critique of the new book of the Bolognese professor Fortunio Liceti, Litheosporus.‡ This book was the first monograph on phosphorescence. It provoked Galileo personally with its bold and fantastic hypothesis on the nature of the ashen light of the Moon. Liceti was

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*Ed. Naz., Vol. VIII, p. 467.

†Ed. Naz., Vol. XI, p. 223.

‡Ed. Naz., Vol. XI, p. 371.

**The box containing the Bolognese stones.

***Ed. Naz., Vol. XI, p. 505.

****Ed. Naz., Vol. XI, pp. 513, 515.

*****Ed. Naz., Vol. XIII, pp. 338, 340.

*Ibidem.

†Lettera a Principe Leopoldo di Toscana, Ed. Naz., Vol. VIII, p. 467.

‡Litheosporus, sive de lapide Bononiensi lucem in se conceptum... etc., 1640.

allured by the analogy of the weak glow occurring in the absence of direct sunlight falling on the Moon with the phosphorescence of the Bolognese stone.* Galileo was well acquainted with Liceti, and had corresponded with him for many years. Thus his objections have an externally respectful and good-tempered nature, but without losing their caustic essence: "Without entering an endless sea of problems that are insoluble to me, I would like to end with this," Galileo dictates, "but I still cannot remain silent on the truly ingenious comparison that the most learned Signor Liceti makes, I would say, with a light poetic joke, between the Moon and the luminiferous Bolognese stone. He assumes that the Moon, when immersed in the shadow of the Earth, maintains a weak light for some time, which it had absorbed from the Sun or from the surrounding air [etere]. This light disappears after a short stay in the darkness. In fact, I would admit such an idea if I hadn't been bothered by the difference in the way that the retained light is given off by the Moon and by the stone. The Moon, in moving away from the center of the shadow cone, begins to give out this retained light long before it leaves the shadow, and again begins to luxuriate in the strong light with which it had been illuminated before. This isn't the way that it happens with the stone; it is not enough in the absorption of light for it merely to approach this strong light; one must subject it to illumination for a considerable time, forcing it to absorb light, and then keep it for a short time in darkness."

The cited words of Galileo indicate his acquaintance with the kinetics of excitation and emission of the Bolognese stone, and we must deeply regret that it wasn't he who wrote the book on phosphorescence, rather than the Bolognese scholar Liceti, who barely moved this new field of knowledge ahead.

Probably, further historical study will uncover new things on Galileo's activity in optics. However, on the basis of the material already known and presented in part above, it is clear that Galileo was the most remarkable scientist in optics of his time. The many-sided nature of his activity and the forever to be remembered violence inflicted by the Papal Inquisition on the free science of Galileo prevented him from collecting together his experiments and ideas on light. Somewhere in Sidereus Nuncius he promised to publish the theory of the viewing tube;* in the letter to Vinta cited above he proposed to write treatises on light and colors. None of this took place.

From fragmentary evidence in others of Galileo's works and from his correspondence, we can fantasize on the content and characteristics of the unwritten Optics of Galileo. Of course, it would have been a book in no way resembling the treatises of Maurolico and Newton. Probably it would have had Galileo's favorite form of a dialog or conversation on optics with unstrained logic, artistic vividness, and a vast content in the field of experiment, observation, and scientific philosophy. Galileo wasn't able to write such a book, and much that he had done and found out in the physics of light remained without its proper influence on the further development of optics. We must regret this as an irretrievable loss.

Translated by M. V. King

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*Liceti's hypothesis, of course, cannot explain the major part of the ashen light of the Moon. However, the possibility is not excluded of a weak phosphorescence of the rocks occurring on the surface of the Moon. Owing to the low temperature, the luminescence should be very long-lived. The problem could be solved by a thorough spectral study of the ashen light.

*Ed. Naz., Vol. III, Part 1, p. 62.