Preface

An instrument can change the world and compel us to rethink our place in the universe. The telescope did just this, but only when it was used by Galileo, whose eye was prepared to see new things and whose hand was able to depict what he saw. It was not only because Galileo was a gifted and persistent observer, but also because he was an exceptional draughtsman that he was able to discover what others had failed to see or lacked the ability to record. The telescope, invented around 1590 in Italy, was a crude device that enlarged an object four or five times and was little more than a plaything. Galileo saw its potential. He also had the good fortune of having access to the best lenses in Europe, those that were made on the island of Murano near Venice, until the present day the capital of glasswork. Without Galileo's vision, it might have taken several years for the telescope to become an instrument capable of magnifying 20 times, as is required to see the features of the celestial bodies that he observed. Without the unknown and unsung craftsmen who made the lenses that he needed, Galileo would not have achieved lasting fame as the Columbus of a new heaven. With his new instrument, Galileo was able to make eight discoveries that were all confirmed except for the last, whose correct interpretation was beyond his ken. They are all familiar to us today, but let us rapidly run through them. First, Galileo saw that the Moon had mountains and valleys and, hence, that it resembled the earth. This was exciting news, because if the Moon was like the Earth, then it could be inhabited! Second, innumerable stars popped out of the sky, and untold worlds were suddenly and unexpectedly revealed. Third, the Milky Way, which looks like a whitish cloud when seen with the naked eye, showed itself to be a mass of starlets. Fourth, the faint luminosity, which is observed on the dark side of the Moon when its illuminated part is a thin crescent four or five days old, was correctly interpreted by Galileo as the reflection of sunlight bouncing off the surface of the Earth. The Moon has "earthshine" for the same reason that we have "moonlight," but the reflected light that reaches the Moon from the Earth is more powerful, because the Earth is four times as big as the Moon. The fifth discovery was even more spectacular, for Galileo became the first person since Antiquity to spot a new celestial body, and he detected not one but four that orbit around Jupiter. This was great news because it had not been anticipated, even in the wildest dreams of philosophers or astronomers. Furthermore, it enabled Galileo to name them after the Medici, the ruling family of Tuscany, where he was born and where he soon hoped to be recalled. Sixth, Galileo observed that Venus has phases, not unlike the Moon. This proved beyond doubt that Venus went around the sun, for otherwise the phases could not be seen from the Earth. Seventh, even the Sun revealed his secret features and Galileo witnessed, for the first time in human history, that it was covered with spots. The eighth, and the only problematic, of his celestial discoveries was what he called the "ears of Saturn," which he assumed were the visible parts of two satellites revolving around Jupiter. The disturbing fact was that the "ears" changed shape and disappeared at irregular times. Galileo was baffled and made no secret of his embarrassment. What he had seen were what we know as the rings of Saturn that are sometimes seen edgewise, when they are hard to detect, and sometimes slanted, when they can be identified with a good telescope, something that was only achieved by Christiaan Huygens many years later.

Our task was made easier by the availability of earlier translations, and we wish to express our gratitude to Edward Stafford Carlos, Stillman Drake, and Albert Van Helden, who published English translations.[1] We are particularly indebted to the French translations and the extended commentaries of Isabelle Pantin and Fernand Hallyn that both appeared in the same year.[2] Our debt to many other scholars will be apparent in the notes to the introduction and the translation, but we would like to mention how much we owe to the exciting discovery of a set of preparatory drawings that Galileo made of the Moon that were extensively discussed by Horst Bredekamp in his path-breaking book, *Galilei der Künstler*.[3] We wish to thank Richard Lan and Seyla Martayan for their gracious permission to reproduce one of these drawings on the cover of the book. We are deeply grateful to our Venetian friends Francesco Rizzoli, Gino Seguso and Romano Zen for their help in understanding how Galileo made his instrument and to what extent he was indebted to the unsung lens-makers of Murano. We also want to record the invaluable assistance of Evelyn Shea, whose suggestions helped us clarify a number of issues, and of our publisher, Neale W. Watson, whose patience we may have tried but whose generosity and insight were a constant stimulus.

INTRODUCTION

The Invention of the Telescope

At the end of September 1608, Hans Lipperhey, a spectacle-maker from the Dutch town of Middelburg, traveled to The Hague in order to present to Count Maurice of Nassau, the governor and commander-in-chief of the armed forces of the Low Countries, a device that he had discovered and that made things far away appear as being near. The instrument consisted of a tube with a concave lens at one end as eyepiece, and a convex lens at the other as object glass. News spread rapidly, and within a few days a publication provided an account of how people in The Hague were able to see the clock-tower in Delft some fifteen kilometers away and the windows of a church in Leyden that was almost twice as far.[4] The French Huguenot, Francesco Castrino, sent a copy to the Venetian friar Paolo Sarpi, who replied on 9 December 1608 that he had already been informed about this a month before.[5] Sarpi had been interested in optics in his youth but the news did not strike him as important, perhaps because the pamphlet said nothing about the construction of the instrument. This is confirmed by what he wrote to a French correspondent, Jérome Groslot de L'Ile, on 6 January 1609:

> I have had word of the new spectacles (the Italian reads "*L'avviso delli nuovi occhiali*," literally "News of the new spectacles") more than a month ago, and I believed it well enough not to seek further, for Socrates forbids us to speculate about experiments that we have not seen ourselves. When I was young, I thought of such a thing, and it occurred to me that a parabolically shaped lens (*occhial*) could produce such an effect. I had demonstrative arguments, but since these were abstract and did not take into account the fractiousness of matter, I sensed some difficulty. Hence I was not much inclined to the labor, which would have been very tiresome, and I neither confirmed nor refuted my idea by experiment. I do not know whether that artisan has hit upon my idea—if indeed the story has not been, as usual, swelled by report in the course of its journeys.[6]

On 16 March 1610, three days after the publication of the *Sidereal Message*, Sarpi wrote once more about the telescope, this time to Jacques Leschassier in Paris: "As you know, more than two years ago an instrument was discovered in Holland by whose means objects that are far away could be seen, which otherwise were not visible or could just barely be seen. Our Paduan Mathematician [Galileo] and others here, who are not ignorant about these matters, began to use it to look at the heavens and, in the light of experience, adapted and improved it."[7] Sarpi describes the instrument as about 4 Venetian feet in length with a concave eyepiece ground spherically to a radius of less than a finger's breadth, and an objective lense ground to a radius of 6 feet. Since the Venetian foot was 0.3477 centimeter, this means that the telescope was roughly 140 centimeters long.

Albert, the Archduke of Austria, who was also the ruler of the 10 loyal provinces of the Netherlands, acquired a telescope by March 1609. He showed it to Guido Bentivoglio, who had been Galileo's student in Padua, and was now papal nuncio to Brussels, and he immediately ordered one. On 2 April 1609, he shipped it to Cardinal Scipione Borghese, the nephew of Pope Paul V in Rome, and the instrument may have been shown to the astronomers of the Roman College, at the time the leading Jesuit University in Christendom. These included the Bavarian Christopher Clavius (who had helped Galileo get his first job at the University of Pisa as well as his second and better-paid one at the University of Padua), the Tyrolese Christopher Grienberger, the Brussels-born Odo van Maelcote, and the Italian Paolo Lembo. Before they had heard of his telescope, Lembo had already constructed one of his own with which he observed "not only the unevenness of the Moon, but also the stars in Pleiades, in Orion, and many other ones."[8] But Lembo had been unable to see the satellites of Jupiter until he improved his instrument after the publication of the *Sidereal Message*. The Jesuits were perfectly courteous, but Galileo was not universally liked, and many felt that he had overstated his claims. For instance, George Fugger, a member of the great banking family from Augsburg and the Imperial Ambassador to Venice, wrote on 16 April 1610 to Johann Kepler in Prague to explain why he had not "dared" send a copy of the *Sidereal Message* to the Emperor:

> Galileo is in the habit of preening himself with the feathers of others, which he picks up here and there like the crow in Aesop.[9] He would like to be considered as the inventor of that ingenious spyglass, despite the fact that a Dutchman, coming from France, brought it here first. It was shown to me and others,

> and when Galileo saw it he made copies and, what is easy, perhaps added some improvements to what had already been invented.[10]

The English Ambassador, Henry Wotton, was less prejudiced and more perceptive. He sent a copy of the *Sidereal Message* to King James I on the very day it appeared. "Now touching the occurrents of the present," he wrote,

> I send herewith unto his Majesty the strangest piece of news (as I may justly call it) that he hath ever yet received from any part of the world; which is the annexed book (come abroad this very day) of the Mathematical Professor at Padua, who by the help of an optical instrument (which both enlargeth and approximateth the object) invented first in Flanders, and bettered by himself, hath discovered four new planets rolling about the sphere of Jupiter, besides many other unknown fixed stars; likewise, the true cause of the *Via Lactea*, so long searched; and lastly, that the moon is not spherical, but endued with many prominences, and, which is of all the strangest, illuminated with the solar light by reflection from the body of the earth, as he seemeth to say. So as upon the whole subject he hath first overthrown all former astronomy–for we must have a new sphere to save the appearances–and next all astrology. For the virtue of these new planets must needs vary the judicial part,[11] and why may there not yet be more? These things I have been bold thus to discourse unto your Lordship, whereof here all corners are full. And the author runneth a fortune to be either exceeding famous or exceeding ridiculous. By the next ship your Lordship shall receive from me one of the above-mentioned instruments, as it is bettered by this man.[12]

We do not know how the King of England reacted to the news, but by then, albeit unknown to him, one of his subjects, Thomas Harriot, had already fitted a tube with two lenses and made the first known telescopic drawing of the lunar surface on 26 July 1609 (Figure 1). Harriot's rendering of the crescent phase, which shows an uneven terminator (the line separating the light from the dark side) is rather crude, and he does not seem to have grasped the similarities between the Earth and the Moon or, if he did, he did not comment on them. A year later, after seeing a copy of the *Sidereal Message*, his interest was rekindled and he made new drawings, this time with the topographical features that Galileo had revealed (Figure 2).[13] This raises the question of why Galileo saw what had escaped Harriot. The answer may lie in the field of possibilities that Galileo was willing to entertain, one of them being that the Moon is another Earth, an idea that had

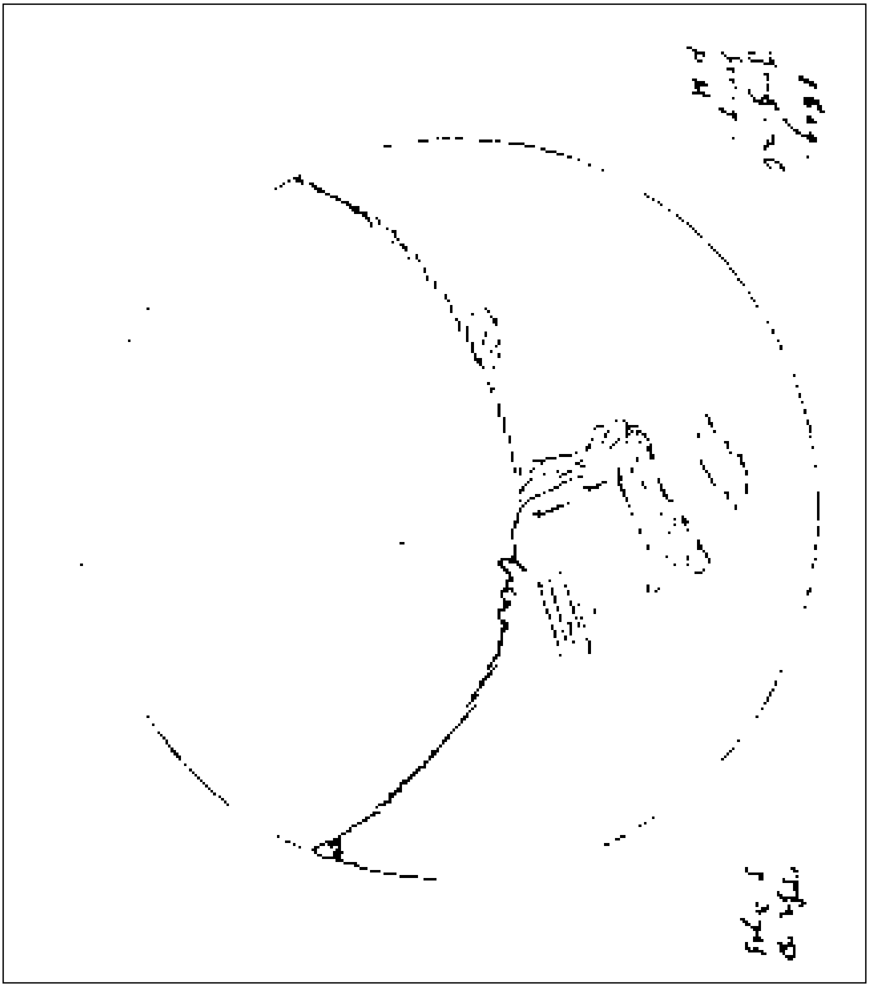

FIGURE 1 Harriot's drawing of 26 July 1609.

been discussed in ancient Greece and Rome. In a famous dialogue, *Concerning the Face Which Appears in the Disk of the Moon*, Plutarch (c. 46–120 A.D.) has one of the speakers declare that "the Moon is very uneven and rugged," and that "just as our Earth has deep and great gulfs . . . so on the Moon there are depths and hollows."[14] When Camillo Gloriosi, who was to succeed Galileo as Professor of Mathematics at the University of Padua, was asked his opinion of the *Sidereal Message* by one of the founding members of the Academy of the Lynxes, he replied that what Galileo wrote about the Moon was "old stuff that has been attributed to the Pythagoreans. There is an ample discussion

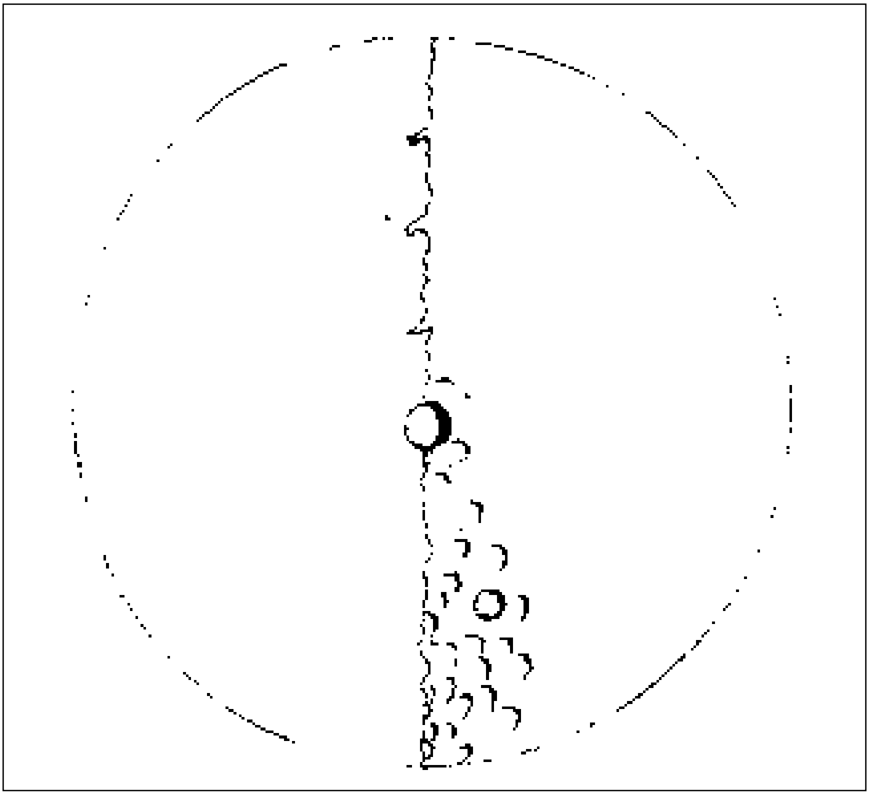

FIGURE 2 Harriot's drawing made a year later (17 July 1610).

on the subject in a booklet by Plutarch."[15] Galileo's achievement is also linked to his exceptional gifts as a draughtsman, as has recently been shown by Horst Bredekamp.[16]

Galileo and Venice

Galileo does not say when he started showing off his nine-power telescope, but the Venetian patrician and future Doge, Antonio Priuli, kept a diary in which he records that on 21 August 1609 Galileo invited him and a number of prominent persons to ascend the famous Campanile in Saint Marc's Square to have a look through his new instrument.[17] They were able to see people getting in and out of gondolas on the island of Murano, and to clearly distinguish the bell-tower and the façade of the church of Saint Giustina in Padua, some 25 kilometers away.[18] Priuli describes the length of the tube as "about 3.5 quarters" of the Venetian *braccio*, which was 68.3 centimeters for wool and 63.8 for silk.[19] If we take the higher value, this means that the telescope was approximately 60 centimeters long, considerably less than the 140 centimeters that Sarpi mentioned in his letter to Leschassier of 16 March 1610 that was quoted above. The reason is that the telescope that Priuli was shown magnified about nine times, much less than the one that Sarpi described. Priuli gives the width across as that of the coin called the *scudo*, which was just a little over 4 centimeters.

Antonio Priuli was an influential person who had helped Galileo over the years. In 1599 when he was Podestà (the Venetian-appointed Governor of Padua), he had approved Galileo's confirmation as Professor of Mathematics with a salary increase that practically doubled his annual income, which rose from 180 to 320 florins.[20] In 1602 and again in 1608, Priuli and two colleagues, who were the Overseers of the University of Padua, granted Galileo a full-year advance on his salary.[21] Fortune smiled even more decisively on Galileo at the end of August 1609. The chairmanship of the Venetian Senate rotated on a weekly basis, and it so happened that it was Priuli's turn. This enabled him to arrange for Galileo to come to the Ducal Palace on 24 August 1609 to present his instrument to Doge Leonardo Donato. The accompanying letter, in Galileo's own handwriting, effectively gave the Venetian Republic the right to patent the device or keep it a secret should they so choose. He writes in the third person, as was the custom, and he addresses the Doge by his official title, "Serenity":

> Your humble servant, Galileo Galilei, who is assiduous in doing all in his power not only to fulfill his obligations as Professor of Mathematics at the University of Padua but also in trying to render some great service to your Serenity, now presents himself before you with a new kind of spyglass (*occhiale*) that is the outcome of profound speculation about the nature of perspective. It brings objects so close to the eye and shows them so large and so distinct that what is nine miles away seems to be only one mile off. This can be of inestimable advantage in any naval or terrestrial undertaking. At sea it becomes possible to distinguish the rig and sails of enemy boats at a much greater distance than usual. Why, we may discover them more than two hours before they discover us! Knowing the number and the kind of ships, and being able to assess their strength, we can prepare ourselves for pursuit, engagement or flight. Likewise from some elevated position on shore, we can see where, inside the walls, the enemy has taken cover or shelter. In open country, we can see and distinguish, to our great advantage, their movements and preparations, as well as many other things that will be obvious to any

> competent person. Therefore, since this instrument is very useful and worthy of being offered to your Serenity, I want to present it to you that you may decide, as may seem fit to your wise counsel, whether to make or not make more of them.
>
> The said Galileo presents this instrument to your Serenity, out of deep affection, as one of the fruits of the science that he has been teaching for over 17 years at the University of Padua, and in the hope of soon offering still better ones if it pleases God Almighty and your Serenity that he may pass the rest of his life in the service of your Serenity before whom he humbly bows and for whom he prays that the Divine Majesty may grant him perfect happiness.[22]

On the next day, Priuli had a motion voted by the Senate in which it was stipulated that Galileo was to be given tenure for life and his salary increased to one thousand florins per year. Both measures were exceptional. Although appointments at the University of Padua were renewable, that was usually for a period of no more than six years. Life-tenure was exceedingly rare and was conferred to professors who were so famous that the University feared they might leave to go elsewhere. Girolamo Fabrizio d'Acquapendente, the Professor of Medicine and Galileo's personal physician, was given this honor, but the famous Philosopher, Cesare Cremonini, who was the highest-paid professor of the University, was not. The salary increase that Galileo received was also exceptional since it rose from 520 florins, an already high salary, to 1000 florins, the highest ever paid to a professor of mathematics. But there were clouds in the sky. The motion stipulated that the increase was to take place only at the end of his current contract, which had another year to run and, more surprisingly, that Galileo was never to receive any further raise. Also when the ballots were cast, the outcome was not unanimous. Of the 139 patricians present, 98 voted in favor of the motion, 11 against, and 30 abstained.[23]

The reason is to be found in the stir that was created in the Council when someone said that the telescope was not invented by Galileo but by someone in Flanders. Worse still, the instrument was on sale, at a very cheap price, just outside the Doge Palace in St. Marc's Square.[24] Giovanni Bartoli, the secretary to the Florentine Ambassador to Venice, had already found that out a few days earlier. On 22 August 1609, the day after Galileo had climbed the Campanile of San Marco with his influential friends, Bartoli had written to Belisario Vinta, the Secretary of State of Tuscany, that the instrument could be purchased in France and elsewhere for a few pennies.[25] On 29 August, he wrote again to say that he had heard that a foreigner had come to

Venice with "the secret" (the word often used to indicate a hidden or concealed process),

> and having been told, I do not know by whom (some say Fra Paolo [Sarpi], theologian of the Servites),[26] that if he was asking 1000 *zecchini* he would do no business here, he went away without making any further attempts. Then Fra Paolo, being a friend of Galileo, told him about the secret, which he had seen, and they say that Galileo, applying his knowledge, and examining another similar instrument of inferior quality that came from France, tackled the problem and found the secret.[27]

As we have seen, this is the version that the Ambassador George Fugger had sent to Prague. By the end of September, the instrument had become so common that "every lens-maker," according to Bartoli, claimed to have invented the telescope and had some on sale. Why a Frenchman was offering them for as little as 2 *zecchini*, although better ones cost six times as much for the lenses alone if they were made of glass from Murano. Bartoli examined one that had been purchased for 3 *zecchini*, but he found it difficult to use because he could not hold it steadily and the field of vision was too narrow. The "secret," he declared, "is in the quality of the lenses and the way they are placed in the tube."[28] Granduke Cosimo II was all for buying a telescope from the Frenchman. Bartoli tried to dissuade him, but was nonetheless ordered to purchase one. He did as he was told and sent the cheap instrument to Florence at the end of October. But he first had a look through it and found it much inferior to those that Galileo made.[29] A couple of weeks later, Bartoli used stronger language and called the Frenchman's instrument "an hoax (*burla*) and no better than those made by common lens-makers."[30]

Galileo's Italian Forerunners

That the telescope was made by a Dutchman and that Galileo produced an improved version is out of the question. But who had the idea of the telescope in the first place? Here the story becomes more complicated but also more interesting.[31] As soon as Hans Lipperhey applied for a patent for his device, two other Dutch spectacle-makers claimed it as their own. One was Jacob Metius of Alkmar, the other Zacharias Jansen, who had a shop in Middelburg, the same town as Lipperhey. How Jansen came to make his instrument is known from an entry in the diary of Isaac Beeckman, who learned the technique of lens-grinding from Jansen's son. He writes, "Johannes, son of Zacharias, says that his father made here in the year 1604 the first telescope (*verrekijcker* in Dutch) after an Italian one, on which was written *anno 1[5]90*."[32] That a telescope should have been made in Italy so many years before being produced in The Netherlands was not generally known. In the summer of 1609, before Galileo had presented his telescope to the Doge, Prince Federico Cesi wrote from Rome to the person most likely to be informed, the Neapolitan polymath Giovanni Battista della Porta, who replied that the alleged "secret" was culled from one of his own books.[33] He dismissed it with a vulgar Italian word for "balls" (*coglionaria*), but the sketch that he enclosed (see Figure 3) shows that he knew what he was talking about. Unfortunately for him, he had not realized its potential and considered it a mere toy.

Kepler knew about della Porta's invention and when he wrote to congratulate Galileo on his celestial discoveries, he pointed that out.[34] What had struck Kepler was the very close parallel between what Galileo said about the construction of the telescope and what della Porta had written.[35] Members of the Lyncean Academy, to which both Galileo and della Porta belonged, took della Porta's claim for granted.[36] Galileo himself was singularly quiet about it.

A would-be forerunner was Galileo's old friend from Florence, Raffaello Gualterotti, who wrote in 1610 to recall that he had made a telescope 12 years earlier, but had not thought that it made things big enough to be of any astronomical significance.[37] If Gualterotti had a telescope by 1598, it probably did not magnify more than three or four times, and was indeed of limited interest. Another person who claimed to have worked out the properties of the telescope is Antonio de Dominis, who later became a bishop and is notorious for having left the Roman Church to join the Anglican Communion only to recant, return to Rome, and be thrown into prison where he died in 1624. Before becoming Archbishop of Spalato, de Dominis had been a Jesuit and had taught science at their College in Padua where he may have met Galileo in 1592. When the *Sidereal Message* appeared in 1610,

FIGURE 3 Sketch of a telescope by G. B. della Porta.

de Dominis decided to make his own contribution known, and it is worth mentioning that he gave his book to Galileo's own publisher, Tommaso Baglioni. Equally interesting is the fact that the work was edited by Giovanni Bartoli, the secretary of the Florentine Ambassador to Venice, who knew Galileo and kept Belisario Vinta informed about telescopes on sale in Venice.[38]

The Elusive Laws of Optics

In his letter of presentation of his telescope to the Doge of Venice on 24 August 1609, Galileo had claimed that his invention was the outcome of his knowledge of perspective,[39] and he repeated this in a letter to his brother-in-law a few days later.[40] Almost a year later, writing to his Roman friend, Piero Dini, Galileo added that "the construction of the spyglass depends on knowledge of refraction, which is a part of mathematics."[41] But Galileo did not have a clear idea of *refraction*, which he sometimes used as a synonym of *reflection*, as he seems to be doing here. No "knowledge of refraction" is involved in the account that he gives in the *Sidereal Message* of his almost feverish procedure. Several years later in his *Essayer*, Galileo prides himself on not having proceeded like the Dutchman who, while handling pieces of glass of various kinds, chanced to look through two at once, one convex and the other concave, and stumbled on the fact that objects were magnified. Here is Galileo's description of what he claimed was his more scientific approach:

> The device requires either a single piece of glass or more than one. Now it cannot consist of one only, because the shape can only be convex (that is, thicker in the middle than at the edges), concave (that is, thinner in the middle), or flat (namely with parallel surfaces). But the last kind does not alter visible objects by enlarging or reducing them. The concave diminishes them, and the convex, while it does indeed increase them, shows them very indistinctly and confusedly. Therefore, one glass alone is not enough to produce the effect. I then considered taking two, and knowing, as I have mentioned, that a glass with flat parallel surfaces alters nothing, I concluded that the effect could not be achieved by combining it with either of the other two. Therefore, I limited my experiments to combining the convex and the concave, and in this way I found what I was seeking.[42]

Galileo was both influenced and hampered by the traditional description of how light rays travel. Since the optical work of Kepler and Descartes, we are all familiar today with the correct theory, which is that of *intromission*, meaning that vision is caused by rays of light entering the pupil, whereas the rival theory of *extromission*, which accounted for vision by rays streaming from our eyes, was more commonly accepted in Galileo's day. Whether the rays originate from the object or from the eye, the geometrical description of the situation is the same because the direction of the rays does not alter the way they are traced. We still speak of "eye contact," of hard stares, and of gazing as looking outward. In the *Sidereal Message*, Galileo considers the rays as being carried from the eye to the object when lenses are placed between the eye and what is being observed, and in a letter to the Jesuit Christopher Grienberger, he writes, "our visual rays leave our eye as from the vertex [of a triangle] and stretch out spherically until they reach the perimeter of the Moon."[43] Galileo took little interest in the work of Kepler, who had broken with the traditional view and explained vision as the action of rays coming from the object and impinging upon a passive retina.[44] Galileo told a French visitor in November 1614 that the problem of grinding lenses according to a given magnification was unsolved, and that Kepler's book about it was "so obscure that it would seem that the author did not understand it himself."[45] This is a curious statement since the *Dioptrice*, unlike other works by Kepler, is remarkably straightforward.

Without understanding refraction, Galileo was unable to determine the focal length of lenses. He was also unable to explain how rays of light were bent when they passed through the atmosphere. Kepler and the Jesuit Christoph Scheiner had recognized that the Sun appears elliptical near the horizon because of refraction, but as late as 1623, Galileo dismissed their work as trivial and a waste of time.[46] It was only several years later, when he dictated a work on *Astronomical Operations* in 1637, that he faced up to the problem but without success.[47] In order to understand what Galileo achieved and what he missed, we shall briefly discuss the type of telescope that he used.

The Galilean Telescope

A lens is a thin piece of glass that has one or both of its faces appropriately curved so that the light entering it from one side can form an image of the object on the other side. It was known to the Greeks, who called it a lens because of its similarity to a lentil seed. Lenses are of two main types, convex and concave. The former, which is always thicker in the middle than at the edge, causes light to converge (see Figure 4); the latter is thinner in the middle than at the edge and causes light to diverge (see Figure 5).

A simple type of lens possesses two spherical surfaces. The centers of the sphere of which the surfaces are part are called the centers of curvature of the surfaces. The line joining the centers of curvature is called the principal axis of the lens. All rays parallel to the principal axis of a converging (convex) lens are refracted through a point F_1, called the principal focus. The distance CF_1 is called the focal length of the lens. Since light may come in from either side, a lens has two principal foci (F_1 and F_2), and F_1 and F_2 are equidistant from C. When a beam of light, parallel to the principal axis, falls on a diverging (concave) lens as in Figure 5, it is caused to diverge as though it were coming from the principal focus F_1. There is another principal focus, F_2, for the same reason as in the case of a converging lens, namely because light can enter from either side.

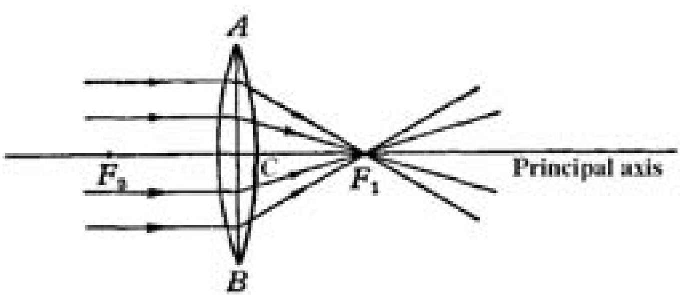

FIGURE 4 Converging Lens.

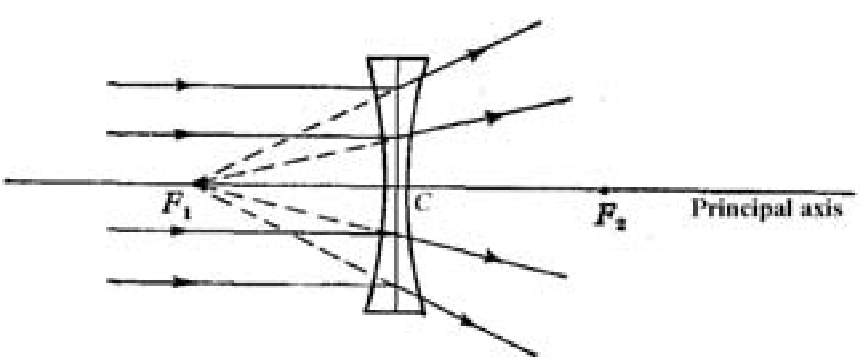

FIGURE 5 Diverging Lens.

In Figures 4 and 5, the rays have been drawn straight up to the line running through the center of the lens, and there made to bend suddenly. This is an oversimplification that is convenient for drawing the path of the beam of light, but the rays are actually bent on entering and leaving the lens.

The Image Formed by a Converging and a Diverging Lens

An image of a bright object such as a candle can be focused by means of a converging lens on a screen or a sheet of paper. It is possible to predict the size and the position of the image if the focal length of the lens and the distance of the object from the lens are known. This can be shown graphically by drawing two rays from the top of an object placed at AO (see Figure 6). One ray is drawn parallel to the principal axis and is refracted towards F_1 when it enters the lens. It passes through F_1 and continues on its way until it meets the other ray that goes through the center of the lens where it is not refracted but proceeds straight through.

A converging lens can form images of two types:

First type. If the object is at a greater distance from the lens than its focal length (i.e., if $OC > F_1C$), it forms an image (at I) that is real and inverted (Figure 6).

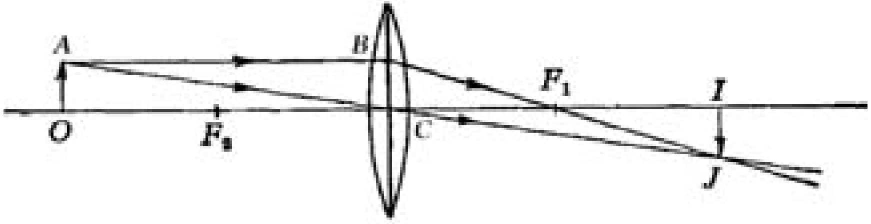

FIGURE 6 First Type of Image Formed by a Converging Lens.

Second type. If the object is at a shorter distance from the lens than its focal length (i.e., if $OC < F_1C$) as in Figure 7, the image (IJ) that is formed is erect and magnified but it is not real since the virtual rays forming it have no physical existence and are for this reason dotted in the figure.