R. G. BOSCOVICH AND THE MEASUREMENT OF THE REFRACTIVE QUALITY OF LENSES

Edoardo Proverbio
Istituto di Astronomia e Fisica Superiore
University of Cagliari (Italy)

1. The problem of correcting the chromatic aberration

1.1. It is known that the discovery of the different refrangibility of light rays making up white light led Newton to the hypothesis that the refraction of light rays was always accompanied by the phenomenon of light dispersion. From a well-known experiment Newton deduced the theorem according to which "The Excesses of the Sines of Refraction of several sorts of Rays above their common Sine of Incidence when the Refractions are made out of divers denser Mediums immediately into one and the same rarer Medium, suppose of Air, are to one another in a given Proportion" (1).

In other words (see Figures 1 and 2), having measured the refractive quality (qualitas refractiva) of a substance with respect to the air, that is to say, the relation

$$m = \sin i / \sin r,$$

between the sine of the angle of incidence i (sinus incidentiae) and the sine of the refracted angle r (angulus refractus) for the limit values of the spectrum of sunlight, red (r) and violet (v), and having thus determined the value

$$dm = m_v - m_r$$

of the dispersive force or quality of the substance itself (vis dispersiva or qualitas distractiva), the relation: $dm / (m - 1)$, which represents the so-called dispersive power of a given substance, was

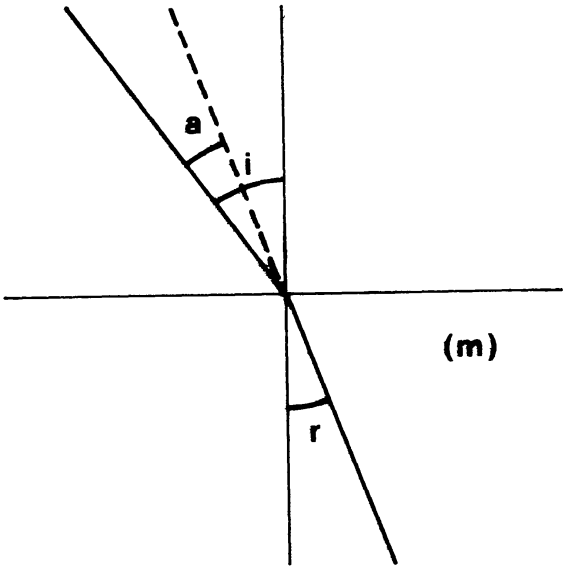

Fig. 1. Angulus refractus r and angulus refractionis a following the nomenclature introduced by Boscovich. The ratio m = sin i/sin r gives the qualitas refractiva of the medium (1).

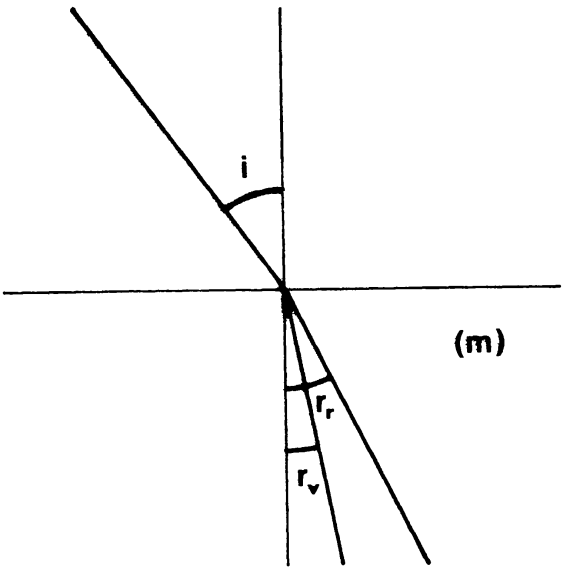

Fig. 2. The Vis dispersiva or qualitas distractiva of the medium (1) is given by the difference $dm = m_v - m_r$ between the angulus refractus of the violet (v) and the red (r) ray of light.

considered by Newton to be a kind of natural constant, to which he experimentally assigned a value between 1/27 and 1/28.

Newton had arrived at this consideration after observing "that when Light goes out of Air through several contiguous refracting Mediums as through Water and Glass; and thence goes out again into Air, whether the refracting Superficies be parallel or inclin'd to one another, that Light as often as by contrary Refractions 'tis so corrected, that it emergeth in Lines parallel to those in which it was incident, continues ever after to be white." (2).

These conclusions discouraged Newton (3), as well as just about all other practical and theoretical opticians almost to the middle of the 18th century, from attempting to correct the effects of chromatic aberration in lenses and telescopic dioptric systems.

It is just as well known that following a first work by Leonhard Euler (4), and, in particular, a subsequent important observation made by the Swedish mathematician S. Klingenstierna (5), who questioned Newton's experimental measurement of the dispersive force of transparent substances, the English optician John Dollond was induced to verify Newton's famous experiment.

At the beginning of 1757, Dollond constructed a water prism according to instructions supplied by Newton (6). It was made up of two hinged plane-parallel sheets of glass filled with water inside of which he placed a glass prism (Fig. 3). By widening the angle of the water prism until the emerging rays became parallel to the incidental ones Dollond realized that the objects observed did not appear in their natural colours, as Newton had predicted, but were still greatly affected by chromatic aberration. He further observed that the cor-

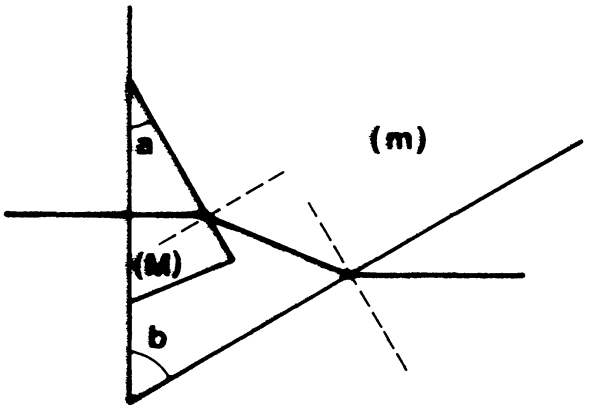

Fig. 3. Sketch of the water prism utilized by John Dollond (1757) for the verification of Newton's esperiment on the refraction.

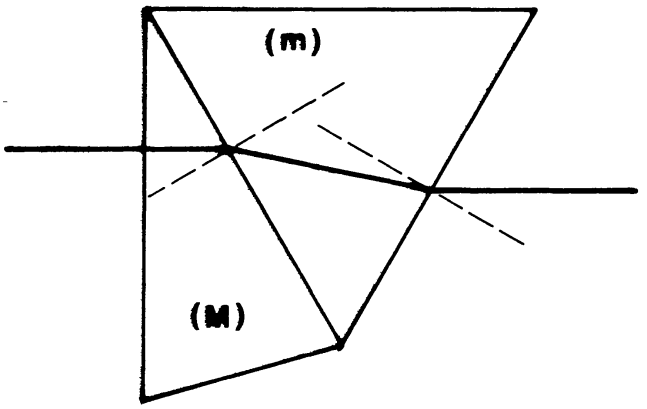

Fig. 4. Method of the "approached prism" utilised by Dollond and Clairaut for the correction of the divergency of the light.

rection of this aberration corresponded to a greater aperture of the water prism, in correspondence to which the emerging rays were no longer parallel to the incident rays (7).

1.2. This crucial experience led Dollond to believe that the divergency of the colours in the different substances was not proportional to refraction and that there was thus the possibility of setting up dioptric systems in which refraction was manifested in absence of effects caused by light dispersion.

Thus Dollond began searching for types of glass with different power of dispersion; and the discovery of the different dispersive properties of so-called Venetian glass and English crown glass with respect to English flint glass led him to the construction of the first achromatic objectives made up of a biconvex (crown) lens and a plane-concave (flint) lens (8).

The latter experiments were carried out using a technique different from the one used in the water prism experiment. As can be seen in Fig. 4, Dollond took a flint prism with an aperture of about 25 degrees and placed a certain number of crown glass prisms having a larger aperture against it and observed, "I got one, which was equal, with respect to the divergency of the light, to that in white flint: for when they were put together, so as to refract in contrary directione, the refracted light was interely free from coulers" (9).

The lack of a rigorous mathematical theory on chromatic and spherical aberration, which because of the decrease in the focal length and the rays of curvature of the surfaces of the objective lenses became more and more pronounced, still represented a considerable difficulty in the realization of achromatic and aplanatic (in the sense

of being free of spheric aberrations) objectives.

In 1761 and 1762, Clairaut's first important works appeared, in which he gave an account of the experiments on achromatic objectives he had carried out in 1756 and 1757, which confirmed Dollond's results. In these works he formulated a complete theory of achromatic objectives made up of one concave and one convex lens (10). In a subsequent work, which appeared in 1764, Clairaut attempted to elaborate a theory of extra-axial spheric aberrations (astigmatism, curvature and coma) for objectives made up of two and three lenses (11).

Almost at the same time, in 1761, Klingstierna made known his mathematical theory on achromatic and aplanatic dioptric systems which had been published in Swedish in 1760 (12).

On the basis of these works the calculation of the rays of curvature of the surfaces of achromatic objectives could be tackled with greater rigour. For an achromatic objective composed of two lenses, one biconvex and the other plane-concave, as was the one used in Clairaut's research, the focal distances f and f' of the lenses are expressed by relations:

$$(1) \qquad 1/f = (m - 1)(1/r_1 - 1/r_2),$$
$$1/f' = (m' - 1)(1/r'_1 - 1/r'_2),$$

where m, m' are the refractive indices, while r_1, r_2 and r'_1, r'_2 are the radii of curvature of the respective surfaces. By calling $F_r = (1/f_r + 1/f'_r)^{-1}$ and $F_v = (1/f_v + 1/f'_v)^{-1}$ the focal distance of the system made up of the two lenses with respect to the red (r) and violet (v) rays, placed at the extremities of the luminous spectrum, the system's condition of achromatism (at least for the two colours taken

into consideration), is expressed in the equality $F_r = F_v$, which leads to the fundamental equation

$$f/f' = -(m'_r - 1)/(m_r - 1)\ dm/dm', \qquad (2)$$

where $dm = m_v - m_r$, and $dm' = m'_v - m'_r$. This gives the ratio of the focal distances of the two lenses, on the basis of the values of the refractive qualities (refractive index) of the glass the two lenses are made of and the ratio of their respective distractive qualities.

2. Measurement of refractive and distractive qualities of lenses

2.1. The problem of arriving at a more accurate evaluation of the refractive and distractive qualities of lenses led opticians to introduce methods less qualitative than those used by Dollond in measuring these quantities. These methods, as has been said, were based on the observation of the reconstruction of the original colours of the objects observed through the system of prisms in Fig. 4.

Clairaut had already made use of the water prism but, in contrast to Dollond, he resorted to the direct observation of the Sun in a dark environment (13). Subsequently, seemingly in about 1757, he used a cylindrical prism functioning as a variable angle prism. By observing through this prism a sunray in direction A (see Fig. 5), corresponding to angle b of the prism having refractive index m, he was able to vary point A on the cylinder surface until the luminous ray emerging from the comparison prism having aperture a and refractive index M was in practice without any aberration (14). It can be observed that even this procedure used by Clairaut supplies only qualitative data and does not allow us to go back to the calculation of the refractive and distractive qualities of the prisms and lenses. Clairaut himself arrived at the determination of these quantities by resorting to a quan-

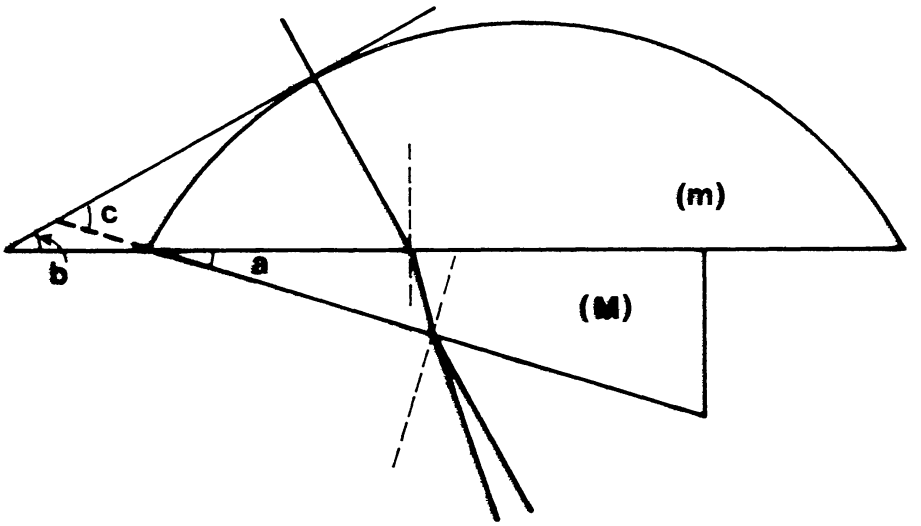

Fig. 5 The Clairaut's variable angle prism. Varying the position of the point A on the surface of the cilindrical prism the angle b could increase from zero to about 20-30 degrees.

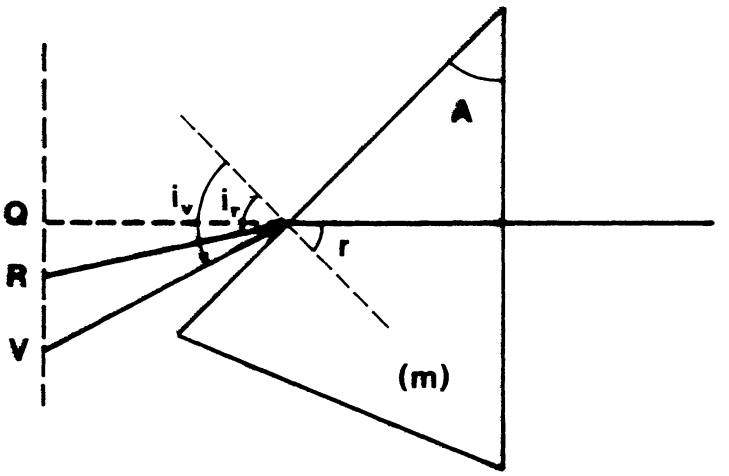

Fig. 6. The method based on the measurement of the dimension of the light spectrum RV made the refraction index determination easier. The methode was utilised by Clairaut and Boscovich.

titative method based on the measurement of the dimensions of a spectrum of sunlight produced by a small-aperture prism (14). By using a prism of this kind with a given aperture A we have, in fact, on observing Fig. 6, that since the refraction angle r = A, the mean refractive index m of the prism is:

$$m = \sin i / \sin A \tag{3}$$

Angle $i = A + \alpha$ can easily be calculated by determining angle α on the basis of the linear measurements of the distances of Q (site of incidence of the ray in absence of the prism on wall QV) from the mean position of spectrum RV and from the given prism. In the same way it is possible to determine the value of the refractive qualities m_r and m_v relative to the red (R) and violet (V) values of the spectrum by means of the relations

$$m_r = \sin i_r / \sin A, \quad m_v = \sin i_v / \sin A, \tag{4}$$

and thus it is just as easy to arrive at the calculation of the distractive quality $dm = m_v - m_r$, which, with good approximation, can be put equal to

$$dm = (i_v - i_r) \cos i / \sin A. \tag{5}$$

This was the state of the art as regards techniques for measuring the refractive and distractive qualities of glass when Boscovich, from August 1759 to May 1760, made his first journey to France and, later on, from May to December 1760, to England.

It is beyond any doubt that Boscovich, on this occasion, had the chance to learn directly from Clairaut and Dollond of the problems

connected with the construction of achromatic objectives and the techniques employed in determining the refractive qualities of lenses, although we still do not have any direct records of this fact.

On the other hand, Boscovich's interest in problems concerning optics and the construction of telescopic systems can be seen in his previous works. Already in 1739 he had published a dissertation on the use of the telescope in astronomy (15), and, in 1755, a more specific work on lenses and dioptric telescopes (16).

It is to be presumed that from the time of his journey to France and England Boscovich knew about Dollond's work published in 1758 and that presumably during his second sojourn in Vienna, from January to May 1763, on his return journey from Constantinopolis, he saw Clairaut's dissertations, published in 1761 and 1762 (17).

While in Rome, towards the end of 1763, he also came into contact with the work published by Klingenstierna in 1761, "che vidi costì alla sfuggita", as he wrote to his friend Giovanni Stefano Conti from Rome on 10th December 1763 (18).

2.2. Boscovich's interest in optics, and in particular in problems connected with the realization of the new achromatic objectives, is also demonstrated by the fact that this was the subject of his inaugural lecture (19) at Pavia at the beginning of May 1764, after being called to teach mathematics at that university (20).

Boscovich's contributions to research into theoretical and practical optics were many and of great originality, and their numbers increased and their content became more profound after his return from Vienna and starting from 1763.

In this new research into optics we can identify four distinct subjects:
(i) theoretical and practical research for the purpose of constructing objectives, eyepieces and telescopic systems made up of two or more lenses;
(ii) the study and realization of procedures for the measurement of the refractive and distractive qualities of lenses;
(iii) attempts, made together with his friend and collaborator Giovanni Stefano Conti, to produce new qualities of crystals for lenses, especially of flint glass;
(iv) the realization of the objective micrometer and other accessories for measurements and optical observations.

Historically speaking, it is difficult to separate the different moments of Boscovich's activities in the field of optics, as well as in other fields, among other things because these activities are at times closely interconnected and interdependent. However, to try to describe the overall contribution that Boscovich made to the study of optics in the 18th century through an analysis of his entire range of activities appears to be quite arduous.

It must also be said that his contributions to theoretical and practical optics have not as yet been fully explored and evaluated. A first analysis of Boscovich's works in optics was made by V. Drorak in 1887 (21).

Closer to us in time, Stanko Hondl (22) and Branimir Markovic (23) examined some of Boscovich's specific findings in the field of instrumental optics. His activity concerning certain problems in experimental optics has been the subject of recent research by August Ziggelaar (24). Although these works can claim the merit of having

analysed Boscovich's several contributions to optics, a whole series of questions remains to be investigated in greater detail. These questions are bound up with the origin and the motives that led Boscovich to apply himself to certain areas of research, and thus to problems regarding priority in certain discoveries or inventions. Questions concerning the events that influenced the evolution of ideas of Boscovich's theoretical and practical scientific production with regard to determined subjects of his research in optics are also involved.

2.3. As has been said, the problem of measuring the refractive and distractive qualities of lenses became the subject of special interest following Dollond's experiments with crown and flint crystals in 1757 (25), and the construction of the first achromatic objectives.

The contacts that Boscovich had, presumably with Clairaut and Dollond himself during his visit to France and England in 1759 and 1760, concerning the new achromatic objectives, have already been mentioned.

It must also be presumed that Boscovich had been led to interest himself seriously in the problem of achromatic objectives, also in connection with the close epistolary relations that were going on with Giovan Stefano Conti (26) which had begun at the end of 1756 (27), after his first stay at Lucca in May and June and from August to October of the same year, following his appointment to represent the Republic of Lucca in its dispute with the Grand Duchy of Tuscany over Lake Bientina.

In a letter from Conti to Boscovich dated 15 June 1761, the former mentioned for the first time the use he had made of a telescope he

had copied from a Dollondian telescope (28) for the observation of a passage of Venus across the Sun on 6 June 1761. It appears that Boscovich was surprised by this announcement and, on responding to Conti on the 28th of the same month of June, he observed that in his opinion the telescope "copied" from Dollond, "sarebbe stato via via buono, se fosse veramente il suo, perché cotesta imitazione, che ella dice, non la credo giusta nell'essenziale" (29).

On the other hand, it is known that Conti was especially interested in the construction of achromatic telescopes (30), and his interest in the construction of these objectives seems to have originated following the news he had received from Abbot Narducci (31), concerning the presumed Dollond telescope he had spoken about in his letter to Boscovich dated 15 June 1761 (32).

Conti's interest in the construction of achromatic objectives was quite tenacious right from the very beginning, and it is without doubt that he intended to speak to Boscovich about this already at the time of Conti's invitation to the latter to be his guest at Lucca for a certain period of time even before Boscovich's journey to Constantinopolis, when in June of 1761 Boscovich was still in Venice (33). For the moment, however, this invitation led to nothing.

But when Boscovich returned from Constantinopolis and sojourned in Vienna, where he arrived on 30 December 1762 (34) and remained until May 1763, it was he himself, it appears, who brought up the idea of a stay in Lucca as Conti's guest (35). In Vienna Boscovich had already begun writing the first dissertation on Dollondian telescopes (36) that towards the end of the same year he sent to the Accademia di Bologna (37), of which he had been a member since 1746, and which was published in the "Commentarii" of 1767 (38).

In this "dissertation", of which, as Boscovich stated with excessive modesty, "tutte le cose essenziali sono di Clairaut" (39), and whose geometric demonstrations Boscovich had previously communicated to Clairaut himself (40), for the first time we find the description of the water prism known as the vitrometro (vitrometrum), whose construction was carried out under Boscovich's supervision for the purpose of measuring and comparing with sufficient accuracy the refractive and dispersive qualities of prisms and lenses (41).

The knowledge of these quantities was, and is in fact, at the basis of the theories on achromatic and aplanatic objectives, and it allowed the determination, on knowing the curvatures of one or more lenses, the determination of those of the others, as can easily be seen on considering relations (1) and (2) given previously. And Boscovich pointed out on different occasions the necessity of determining with the greatest precision the values of the refractive qualities m and M of crown and flint lenses, and the ratio dm/dM of their distractive qualities in order to construct these objectives (42).

The "vitrometro" that Boscovich designed for this purpose in the first months of 1763 was no different, in its operating principle, from the water prism Dollond, and presumably Clairaut, had used. The important difference was in the fact that with this device the refractive qualities of glass prisms could be measured with greater accuracy. Fig. 7 reproduces the instrument illustrated by Boscovich in "De recentibus compertis" (43).

It appears that Boscovich, at the time of the writing of this work, entertained the idea of determining, which he later did, the refractive quality (M), that is, the refractive index of flint or crown

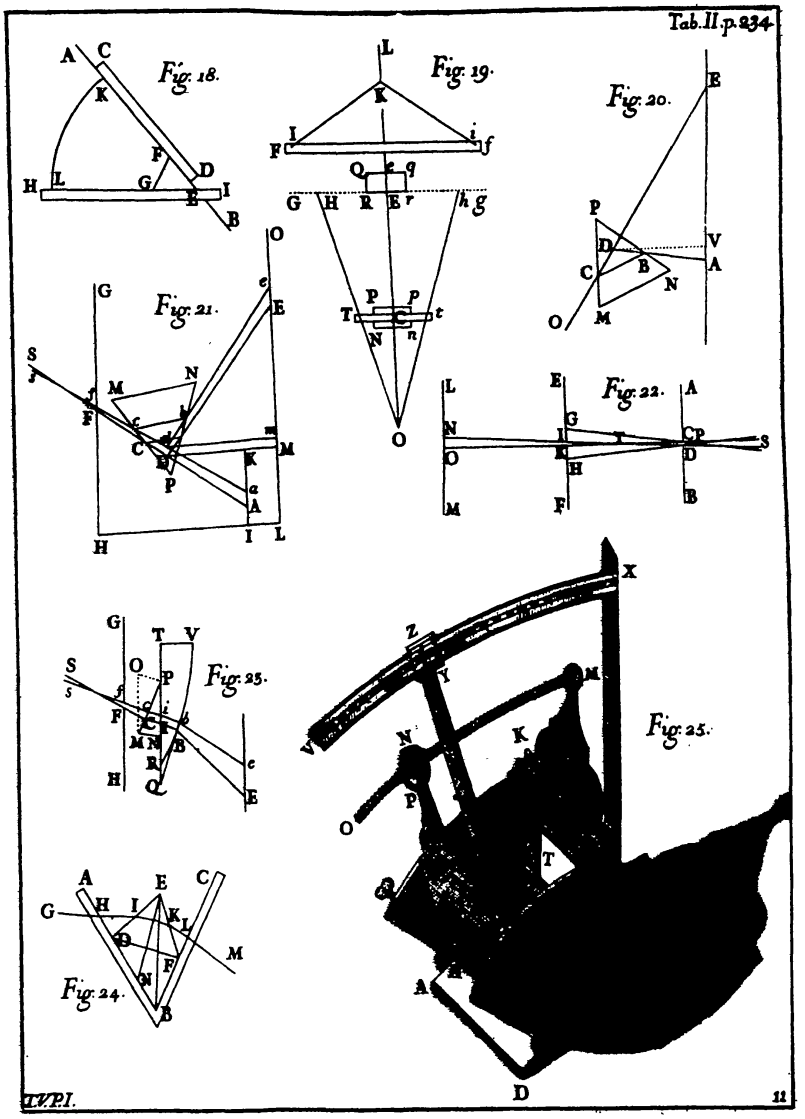

Fig. 7. Drawing of the vitrometrum conceived (beginning 1763) and utilised (June - July 1763) by Boscovich for the measurement of the refraction index of crown and flint glasses. The measurement of the angle of the moving wall RQ as regards the vertical fixed wall KLBC was given by the readind of the index Z.

glass prisms by immerging these prisms in the vitrometer, placing the base on the same horizontal plane as the water prism, as can be seen in Fig. 8.

At the beginning, since he was still in Vienna, he resorted to observations based on the method of measuring the solar spectrum, which had also been used by Clairaut (44). Boscovich was able to use both the vitrometer and the solar spectrum observations only after deciding, following an exchange of letters with Giovan Stefano Conti, to stay with his friend in Lucca (46), a stay that lasted from about the last ten days of June to the beginning of July of 1763 (47).

It is impossible to establish precisely when this first vitrometer was built, as Boscovich himself stated, by Giovan Stefano Conti and Abbot Niccolao Narducci, Conti's friend and close collaborator (48). On the other hand, since the "machinetta" was really used, as can be seen from a letter Boscovich wrote Conti in August 1763, in which Boscovich sent his friend the first results of calculations of measurements of the refractive and distractive qualities made during his stay at Lucca with the "spectrum" and the water "machinetta", it is to be presumed that it was constructed either during Boscovich's stay at Lucca or, more probably, just before this sojourn (49).

At least up to the end of 1763 the reduction calculations of the measurements of refractive and distractive qualities of prisms, carried out by Boscovich with the vitrometer, the rectilinear prism starting from the determination of the "spectrum" and, later on, with Clairaut's composite prism (the prism with a variable angle shown in Fig. 5), were based on the theory Boscovich himself had developed in "De recentibus compertis". As is the case with all his geometric theories, this one appears quite simple and elegant (50).

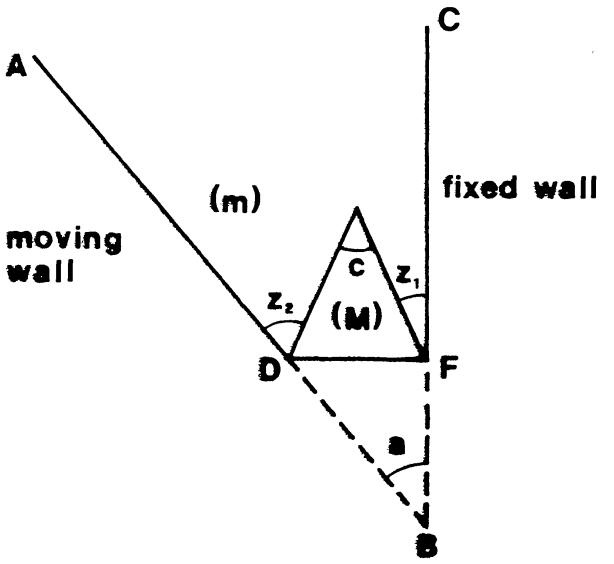

Fig. 8. Method used by Boscovich (until the summer 1764) for the determination of the refraction index with the first vitrometer.

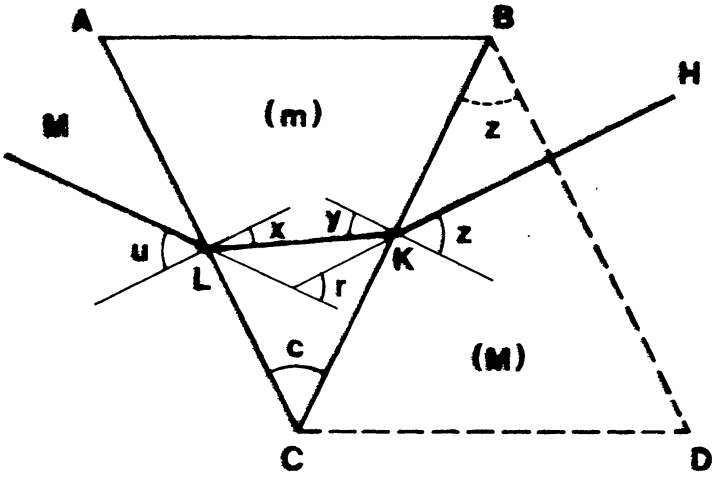

Fig. 9. The fondation of the Boscovich's theory for the determination of the refraction index (first half 1763), based on the condition $u\_ = \underline{z}$, will be then called "method of minimum deviation".

From prism ABC in Fig. 9, for value m of the refractive quality, he immediately arrived at

$$\sin u / \sin x = \sin z / \sin y = m$$

since x + y = c, and u + z = c + r. Boscovich observed, however, that by varying the angle of incidence z until the angle of refraction r, which can be found from directions HK and LM projected onto a wall perpendicular to base AB of the prism, is at a minimum, one has x = y, and u = z. In these conditions x = y = c/2, and the refractive index can be written

$$m = \sin (c + r)/2 : \sin c/2,$$

and is therefore determined, knowing angle c of the prism and having measured the minimum angle of refraction r.

It must be underlined that this formula is still in use today for the approximate measurement of the refractive index of transparent substances, and is known as the minimum deviation method.

The distractive quality dm of a crystal is then easily obtained, having from the previous equation

$$dm = [\cos (c + r)/2 : \sin c / 2]dr/2$$

where $dr = r_v - r_m$, is given by the difference between the minimum refractive angle with respect to violet (v) and red rays (r) of the spectrum.

By determining value dM of the distractive quality of another prism having angle z and refractive quality M, we have immediately the value of the relation

$$dM/dm = [\cos (z + r)/2 : \sin z/2][\sin c/2 : \cos (c + r)/2]dR/dr.$$

Boscovich then observed that by using prisms for which angles c and r are small, the previous equations reduce to the elementary expressions

$$m = 1+r/c, \quad dm = dr/c.$$

He then applied the above relations both to observations made with the vitrometer and with Clairaut's curvilinear prism. In both cases, with the hypothesis that the water prism or the curvilinear prism correct the refraction of the comparison prism, and in this circumstance having dR = dr, one obtains:

$$dM / dm = c/z.$$

However, in the case of the vitrometer, on observing Fig. 8, and finding that

$$a + z = c_1 + c_2,$$

the above equation assumes the form

$$dM/dm = c_1/z + c_2/z = (a + z)/z = 1 + a/z.$$

At this point, it is interesting to observe that the use of the new vitrometer, about which we shall speak later on, and the reduction

formulas for the refractive and distractive qualities of prisms and lenses, which Boscovich made known only much later with the publication of his greatest work (51) in 1785, differ substantially from those given above.

2.4. It has already been said that during his stay in Lucca Boscovich made use of his first vitrometer and the rectilinear prism for measuring the refractive and distractive qualities of prisms, but it is not completely certain whether or not he used Clairaut's curvilinear prism (52). He referred to the latter in a letter to Conti dated 6 August 1763 (53), and Boscovich surely used it towards the end of December of that year after receiving one of them that had probably been built by Conti himself following Boscovich's instructions (54). This prism was apparently cylindrical like the one used by Clairaut, despite the difficulties Conti met with in the working of cylindrical prisms, and it had a mounting, which Boscovich did not describe, provided with a micrometer (55).

But already in the summer of 1763 Boscovich asked Conti to construct a second vitrometer (56), and this was delivered the following September. However, it was defective in the reading device because of the incorrect division of the scale on the circular band for reading the prism's angle of aperture. This scale also had a parallax defect (57). It was on this occasion that for the first time Boscovich mentioned to Conti the idea of constructing a "specchietto di metallo", provided with "due movimenti su due assi", so as to direct, in the course of observations, the sun's rays along a fixed direction in order to avoid having to move the vitrometer or the prisms continually (58). This is the famous eliostato (shown in Fig. 12) which Boscovich probably realized in December of the same year (59) and which he later used in his solar observations with the vitrometer and other instru-

ments.

That the second vitrometer Conti and Narducci built had not been properly made was confirmed by Conti himself, who in a letter to Boscovich dated 24 September stated, "I difetti dello strumentino li conoscevo ancor io". In the autumn of 1763, the situation regarding the "vitrometer" was such that Boscovich, perhaps becoming assailed by doubts, on several occasions expressed his greater trust in observations carried out with the use of the curvilinear prism (60). Clairaut too was rather sceptical about the use of the water vitrometer, not so much because of the defects found by Boscovich, but because of the fact that on the basis of his experience with a "prisme à cherniere", built in Paris, "les couleurs subsistoient toujour quelqu'inclinaison que l'on donnat au Prisme d'eau" (61). This problem, as Clairaut pointed out in the same letter to Boscovich dated 15 January 1764, was, however, "moins marquèe" when using the curvilinear prism (62).

All these facts led Boscovich to try to improve the performance of the curvilinear prism. A first improvement was made at the beginning of January 1764, when Boscovich himself thought up a more accurate criterion to follow in defining and fixing on the curvilinear prism the point at which the tangent is parallel to the base of the prism, which corresponds to an angle of amplitude zero of the prism itself (63).

For the same reason Boscovich insisted on several different occasions that Conti should begin work on a good curvilinear prism (64). Conti was, however, in difficulty because, as has been said, the realization of cylindrical prisms, ground on a base of marble patinas, as were those used by Conti himself, did not give satisfactory results (65). Only on 23 April 1764 could Conti write to Boscovich: "Io sono

intorno a suoi curvilinei e al suo specchio. I primi sono fatti. Aveva ragione grandissima lei quando diceva di non essere contento di quel curvilineo che ha. Ho trovati irregolarissimi quelli che avevo, ed o accomodati per mandare a lei. Non le dirò certo che siano perfetti, ma molto migliori sicuro di quello che ha" (66). In the same letter Conti mentioned a brilliant idea he had had. It was the realization of a simple plane-convex lens from which a spheric semi-segment with two symmetrical bases at the centre was to be obtained. In this way, Conti stated, "lei potrà contare di avere...un prisma veramente buono (67).

It is not clear whether or not Conti ever built these prisms having a spheric segment. The new variable prisms he mentioned in his letter of 23 April, which he was about to build and which Boscovich was to call spheric prisms, appear in fact to be prisms composed of simple spheric caps, much easier to make than the cylindrical prisms (68).

In any case, at the beginning of May, just a few days after his arrival in Pavia, Boscovich revealed that he was anxious to have these new curvilinear prisms, even though he pointed out that the theory of these variable prisms would be more complicated (69). The new spheric prisms were ready by the middle of May. One was of glass of Bohemia (a kind of crown glass) and the other was of flint glass (70), and after a fortnight, at the beginning of June, they were in Boscovich's possession (71).

According to Father Luigi Lagrange, superintendent of the Brera Observatory in Milan (72), and to Conti himeslf (73), Boscovich was on the point of building a third vitrometer that he was planning to use in Milan, where he intended to go after the closing of the academic

year at Pavia (74). We do not know who actually built this new water prism, which Boscovich later gave to the Duke of York, brother of the King of England, on the occasion of the Duke's visit to Boscovich in July of 1763 (75). This same vitrometer was sent back to Boscovich in June of the following year together with a Short telescope with an objective micrometer as a gift from the Duke to the astronomer from Dubrovnik. In the accompanying letter written by the Duke's secretary, a Mr Blair, there is a list of defects that had been found on using the vitrometer, and priority in the construction of this device was claimed by a certain Mr Hoave who, according to Blair, had built one in 1761 (75).

In July of 1764 Boscovich still did not have a really reliable instrument for measuring the refractive and distractive qualities of prisms and lenses. Although the apparent precision of his measurements can be evaluated as being on the order of a minute of an arc, in reality, because of systematic errors deriving from inaccuracy in the construction of the instruments and the reading procedures (77), the values he calculated could have differed widely from the effective ones.

In a letter he wrote Conti from Milan, dated 21 July, Boscovich himself admitted that "Fin ora avevo supposto i suoi prismi esattamente sferici e il parallelismo esattamente in cima. Ho pigliato al compasso la distanza dalla cima fino al punto in cui il raggio usciva, e tra qualche imperfezione della figura sferica, per cui la corda non dà l'angolo, parte per l'incertezza del suo semidiametro esatto, per cui data la corda resta incerto il numero de' gradi, i risultati venivano vari" (78).

If we add to the defects pointed out by Boscovich others such as

"la grande incertezza dell'immagine, che il prisma sferico forma, per cui non si può accertare bene, dove i colori si estinguano, o quasi estinguano" (79), it is easy to understand Boscovich's dissatisfaction with his work and the negative effects that a poor knowledge of the values of the refractive and distractive qualities of glass had on the construction of telescopic objectives, which was, after all, the final goal of Boscovich and his collaborators in Lucca.

Things were no better with the use of the vitrometer, and Boscovich confessed in the same letter to Conti: "Il mio Vitrometro sarà ottimo, se io sciolgo un problema che non trovo ancora la via di sciogliere" (80).

2.5. It is at this point that the astronomer from Dubrovnik came to know of a method for the measurement of the refractive quality of lenses introduced by a Franciscan father, the Marseillais optician Father Abat.

In the cited letter of 21 July 1764, Boscovich illustrated to Conti the operating principle of this new kind of curvilinear prism with a variable angle. In reality, it was a combination of two lenses (see Fig. 10), one plane-convex (P) and the other plane-concave (Q) with the same curvature. If the lenses fit together perfectly the two plane surfaces of the lenses in position AB form a null angle. On rotating the mobile lens (P) about the common centre C of an angle b till reaching the configuration A'B', the plane surfaces of the two lenses come instead to form the same angle b, which thus represents the (variable) prism angle constituted by the whole of the two lenses.

Boscovich immediately understood that this variable prism might

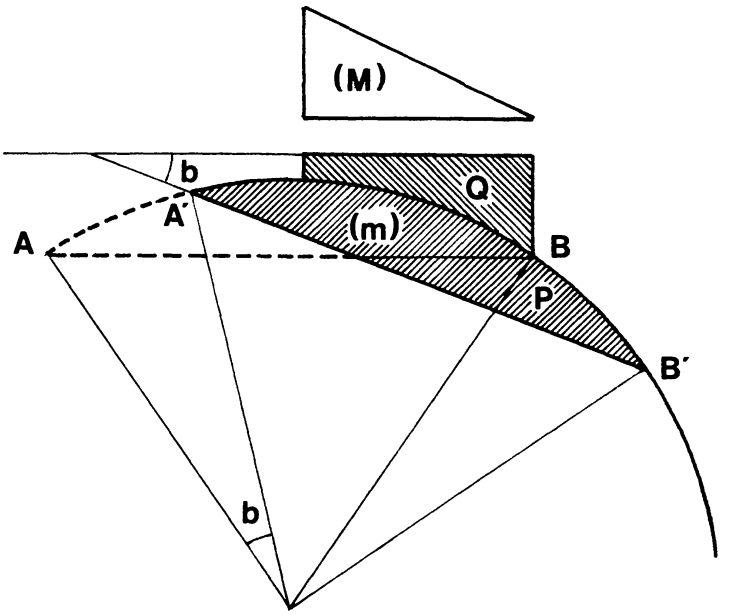

Fig. 10. Principles of operation of the new moving prism conceived by the optician P. Abat. The spread b of the prism is obtained by rotating the convex lens P as regards the fixed concave lens Q.

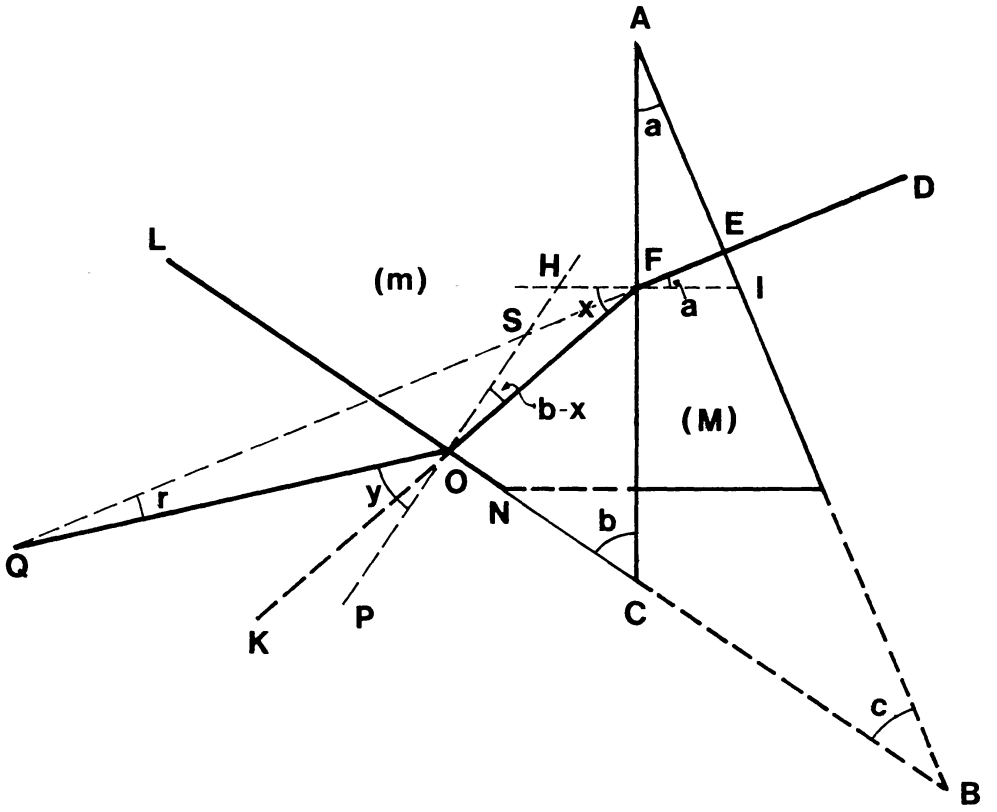

Fig. 11. Geometrical diagram of the new theory elaborated by Boscovich (september? 1764) for the determination of the refraction index applied to the new vitrometer and to the moving prism.

represent a method for measurement "incomparabilmente più accurato" than the previous ones, and asked Conti to make one, possibly cylindrical (81).

On 3 August Conti informed Boscovich that he had already begun work: the prism would be made of flint glass and would be spheric since it was so difficult for Conti to work Bohemian glass and realize an adequate cylindrical form (82). And on 8 August Conti wrote to Boscovich: "Non il prismetto, ma il prismone è fatto, e spedito in questo stesso giorno, etc." (83).

However, when on 14 August Boscovich received this new variable prism he was quite disappointed, since the material used by Conti was of very poor quality (84). The results were no better with a second variable prism that Boscovich had commissioned from a Milanese craftsman, "quando ho veduto", he wrote to Conti, "che Ella si era meritatamente straccata" (85).

This being the case, Boscovich had no choice but to ask Conti to make another variable prism, even with a small aperture (15 to 20 degrees), just so long as it had small rectilinear prisms in order to increase the overall aperture (86).

On 5 October Conti announced that he had finished two new variable prisms, one with flint glass, the other with glass of Bohemia (87), and finally, it appears, Boscovich's measurements of refractive and distractive qualities seemed to yield better results.

But despite the defects in the first variable prism, Boscovich had already, in a letter to Conti dated 26 September, just before leaving Milan on his way to Rimini, where he had been called "da quella

città per esaminare un progetto di un Ingegnere concernente il loro Porto" (88), after recommending that the rectilinear prisms to be used together with the variable prism be made of the same material, observed that "con questo Vitrometro (that is, with the new variable prism) a mille doppj migliore dell'altro ad acqua, la qualità rifrattiva della quale, e la sua diversione dello spettro è troppo diversa da quella delle altre sostanze, si fanno le osservazioni molto più facilmente, e più esatte, e col metodo, che ho al fine ideato, di cui abitualmente mi servo, avendo nel suo prisma trovato un sito, in cui l'immagine viene comunque netta, trovo in ogni osservazione con molta precisione i tre valori, di quali solo ho bisogno per calcolare la sfericità, e sono m, M, dM/dm." (89).

And in a subsequent letter from Rimini dated 13 October 1764, Boscovich reiterated to Conti that "per vari capi, che esporrò nell'altra dissertazione, deve essere incomparabilmente più opportuno all'intento questo (that is, the new variable prism) che il mio d'acqua". (90).

In this letter Boscovich referred to a second dissertation he had sent to the Istituto di Bologna at the beginning of February of the following year and published in the "Commentarii" of 1767 (91). In this dissertation Boscovich presented and discussed in substance the results he had obtained in the determination of the refractive and dispersive qualities of crystals and prisms with the water vitrometer, even though in the same dissertation he mentioned the use of the rectilinear and mixed-linear prism (that is, the curvilinear prism), and announced the use of the variable prism (92).

It is quite important to underline the fact that in this disser-

tation Boscovich mentioned a substantially new criterion for the use of the vitrometer, at least with respect to the one illustrated in his first dissertation, written during 1763 (93). In this, as has been seen, the isosceles comparison prism was immersed in the water of the vitrometer and placed at the base of the same vitrometer, while in the second dissertation one side of the prism, which in this case was straight, was placed against the fixed wall of the vitrometer, on the inside or on the outside, as can be seen in Fig. 11 (94).

Boscovich also provided a new, simple theory for the calculation of refractive qualities (95). In fact, from Fig. 11 one can derive, with reference to points of incidence F and O, the following relations

$$M = m \sin x/\sin a, \quad \sin (b - x) = \sin y/m$$

On the other hand, from the same figure it is easy to see that $y = (b - a) + r$. Since by suitably varying the mobile side OL of the vitrometer the refracted ray OQ is corrected for refraction, that is, is parallel to the direction of the incident ray DE, the previous relation, since r must be equal to o, reduces to

$$y = b - a.$$

Since y is thus a known quantity, from the second of the above relations Boscovich immediately found the value of x, and from the first of the above relations, once the refractive quality m of water was known, he obtained the value M for the refractive qualities of the crystal under examination.

It must be pointed out that this procedure is not only in practice simpler and more certain than the previous one, but can also be

applied directly to observations made even with the new variable prism, and it cannot be excluded that Boscovich may have introduced this new method at the same time he introduced the idea, which he had been developing during the height of summer in 1764, of using the principle of the variable prism suggested by Father Abat.

Boscovich also provided a brilliant theory for the calculation of the quantity dM/dm for the vitrometer and the variable prism (96).

He observed, on this point, that by differentiating the two previous relations one has:

$$\sin x\, dm + m \cos x\, dx = \sin a\, dM,$$
$$\sin (b - x) dm - m \cos (b - x) dx = \cos y\, dy.$$

On the other hand, Boscovich noted, since dy = dr, where dr is the angle of dispersion, that since the aperture of the vitrometer is such as to recompose the white sunlight in the emerging beam, we must have dy = dr = o (97). By properly combining the two previous differential equations and imposing the condition dr = o, Boscovich easily concluded with the relation

$$dM/dm = M/m\, [1 + \tan (b - x) \cot x].$$

The application of this new method to the vitrometer must have led Boscovich to desire a completely new one that worked more accurately than the previous one (98). This vitrometer would appear to have been made by Giuseppe Vairani of the College of Jesuits at Brera in Milan (99).

Boscovich, in the meantime, after working on the plans for the

new Brera Observatory, was quite involved in its realization and in the organization of the scientific and observational activities that were to take place there (100).

If we are to believe Conti's continuous solicitations for Boscovich to decide to use the new variable prisms he had built, it can be gathered that during 1765 Boscovich had dedicated very little time to his experiments in optics, and this was also because of Lalande's visit to Italy, which kept him away from Pavia and Milan from June to December of the same year (101).

But even in March of 1766 Conti did not appear to have received anything from Boscovich, because he asked him once again: "Se può ella ripigliare l'esperienze abbia la bontà di farmi sapere come riescono i nuovi prismetti mistilinei" (102). And he appeared even to resort to veiled threats when in a letter dated 20 May 1766 he stated "di non voler più assolutamente far nulla" until Boscovich had taken care of sending him "delle sicure combinazioni" (103).

But besides his observational activities, as well as those regarding the study and verification of the new instruments that were being installed at the Brera Observatory (104), it must be remembered that Boscovich's bad leg was getting worse and worse, and kept him bedridden for many months in the course of 1767 and 1768 (105).

In 1769 Boscovich travelled to Paris and Brussels for treatment of his leg and, during 1770 and 1771, after his transfer to the Palatine Schools in Milan, his interests in astronomy got the upper hand. Thus we can say that in this period of time Boscovich's activities in the field of optics were greatly reduced and, although from time to time he continued to carry out desultory measurements of the qualities

of crystal with his instruments (106), he made no significant progress in observational techniques and the theory of measurement.

As has already been pointed out, it is impossible to reconstruct the actual techniques Boscovich used in his observations with the variable prism. It appears certain that already at the beginning of 1764 the curvilinear prism had been fixed to a special mount and was moved by means of a micrometric screw (107). It is therefore to be presumed that Boscovich must have come up with some device for allowing more or less precise measurements of the movements of the mobile lens with respect to the fixed one, even for the variable prism. This hypothesis appears to be confirmed by Conti who, in a letter to Boscovich dated 3 August 1764, on referring to the two lenses of the variable prism, mentioned a "machinetta che deve mettergli in moto" (108).

What further development this first device of Boscovich's had in the period from 1765 to 1772 we do not know. Only in the spring and summer of 1773, when he was in Venice following the well-known and sad events that had caused his departure from Milan (109), did Boscovich set up, as he stated in the preface to his "Opera pertinentia ad Opticam ed Astronomiam", a new micrometric instrument based on the use of the variable prism (110). The instrument, constructed by the telescope-maker Domenico Selva, shown in Fig. 12, was accurately illustrated in the above-mentioned "Opera" (111), together with the description of the old vitrometer (112) and a passing mention of the first version of the variable prism (113).

As far as we know, in 1772 Boscovich already had the new instrument in mind (114) and, after his move to Paris, where he resided for more than ten years as the director of Optics in the service of the Ministry of the Navy, he wrote the entire Opuscule I of the "Opera" which, as has just been said, contains everything Boscovich had crea-

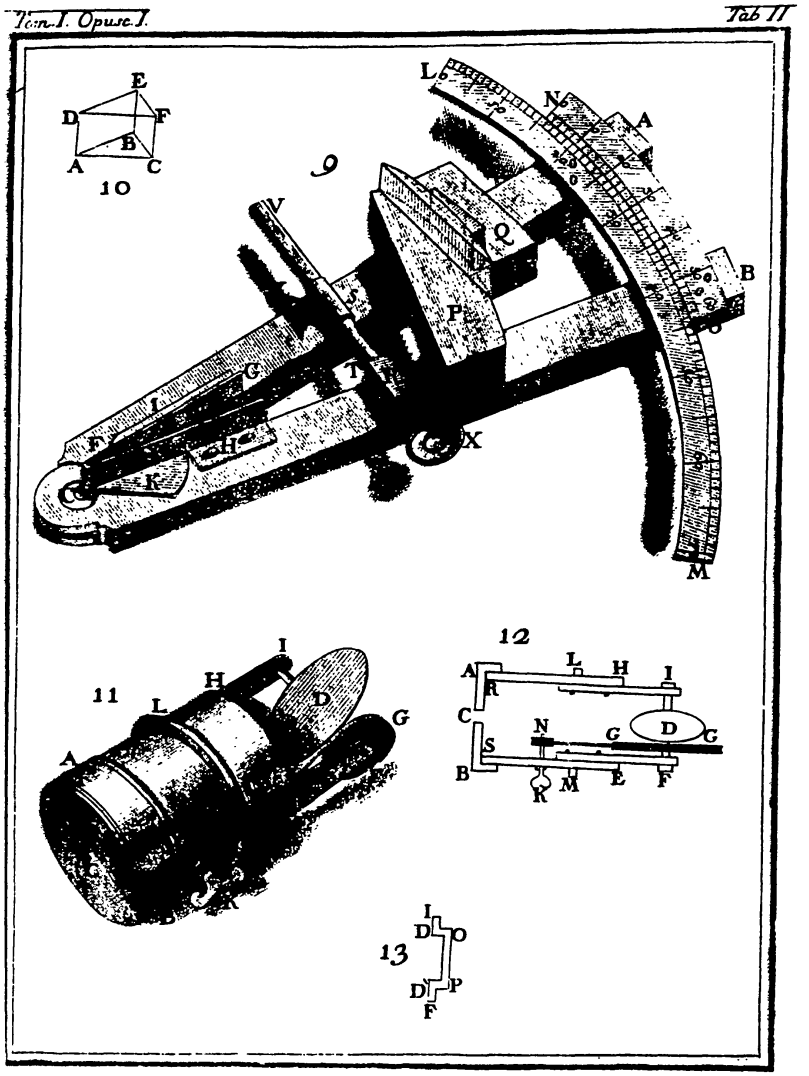

fig. 12. Description of the new instrument conceived by Boscovich in 1772 and constructed by Domenico Selva (Spring - summer 1773) for the measurement of the refraction index . The drawing 11 and 12 show the famous "eliostato ", giving a fixed and horizontal ray of solar light across the little opening C.

ted and accomplished in the field of optics starting from 1763.

It is difficult to reconstruct the activities that Boscovich must have carried on in the course of his residence in France in the field of the measurement of the refractive and distractive qualities of crystals and lenses.

It is however certain that at this time Boscovich designed a new type of vitrometer which was surer, more reliable and more manageable than the old one (115).

He has left us with an accurate description of this new vitrometer in Opuscule I of the first volume of the "Opera" (116), pointing out that he had made only a prototype which, however, could not be properly tested because of the craftsman's negligence (117). Fig. 13 shows the diagram of this new vitrometer that Boscovich provided. In the course of his meticulous description, he insisted on the reasons why this vitrometer was superior to the first. In practice, the vitrometer is composed of two cylinders, one inside the other, with the first being fixed and holding the comparison prism on base KK'LL' and allowing the passage of the horizonal ray of sunlight from the heliostat through the water-tight shaft GG'II'. The second cylinder (figure 46 of Fig. 13 in the text), which is inside the first, contains water held in on side PP'OO' by the wall of the first cylinder and on side HH'II' by a plane-parallel sheet of glass. The system, as can be seen more clearly in Fig. 14, is a kind of water prism, conceptually analogous to Dollond's prism (cf. Fig. 3), but capable of defining phenomena corresponding to the absence of refraction and dispersion with much greater accuracy. The possibility of reading the angles horizontally and allowing the measurement of larger angles (up to 50 degrees), since there is no danger of the water coming out, as was the

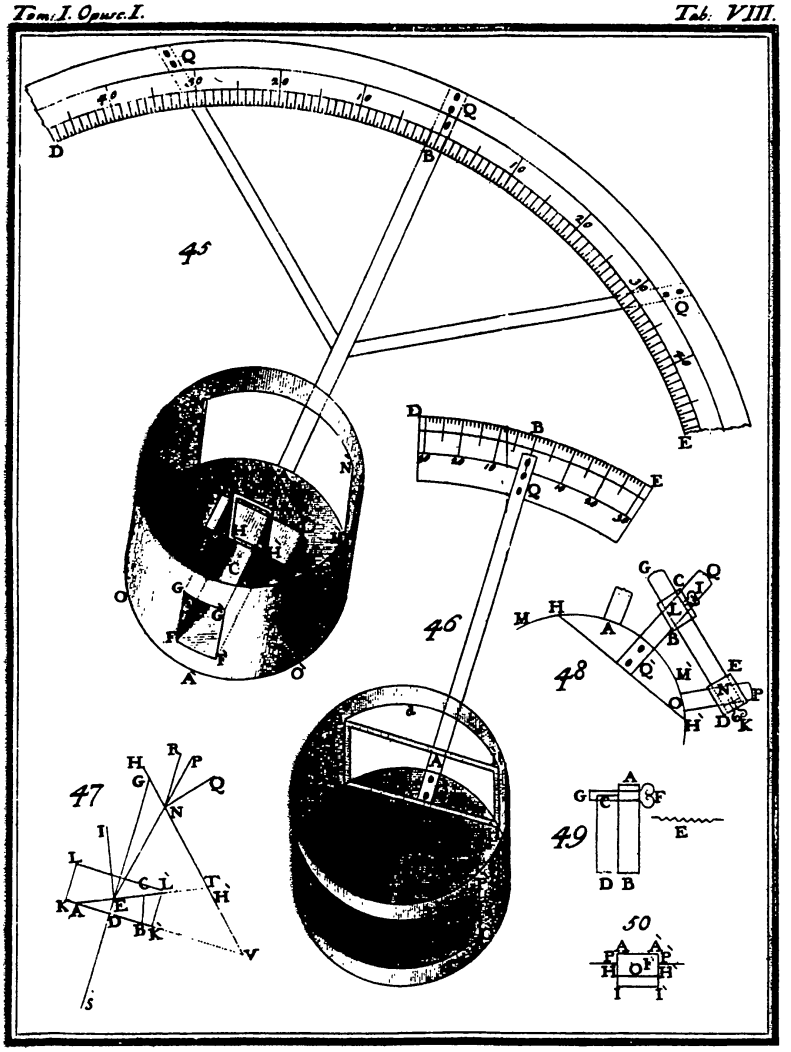

Fig. 13. The new horizontal vitrometer realised by Boscovich during the stay in Paris (1773-1782).

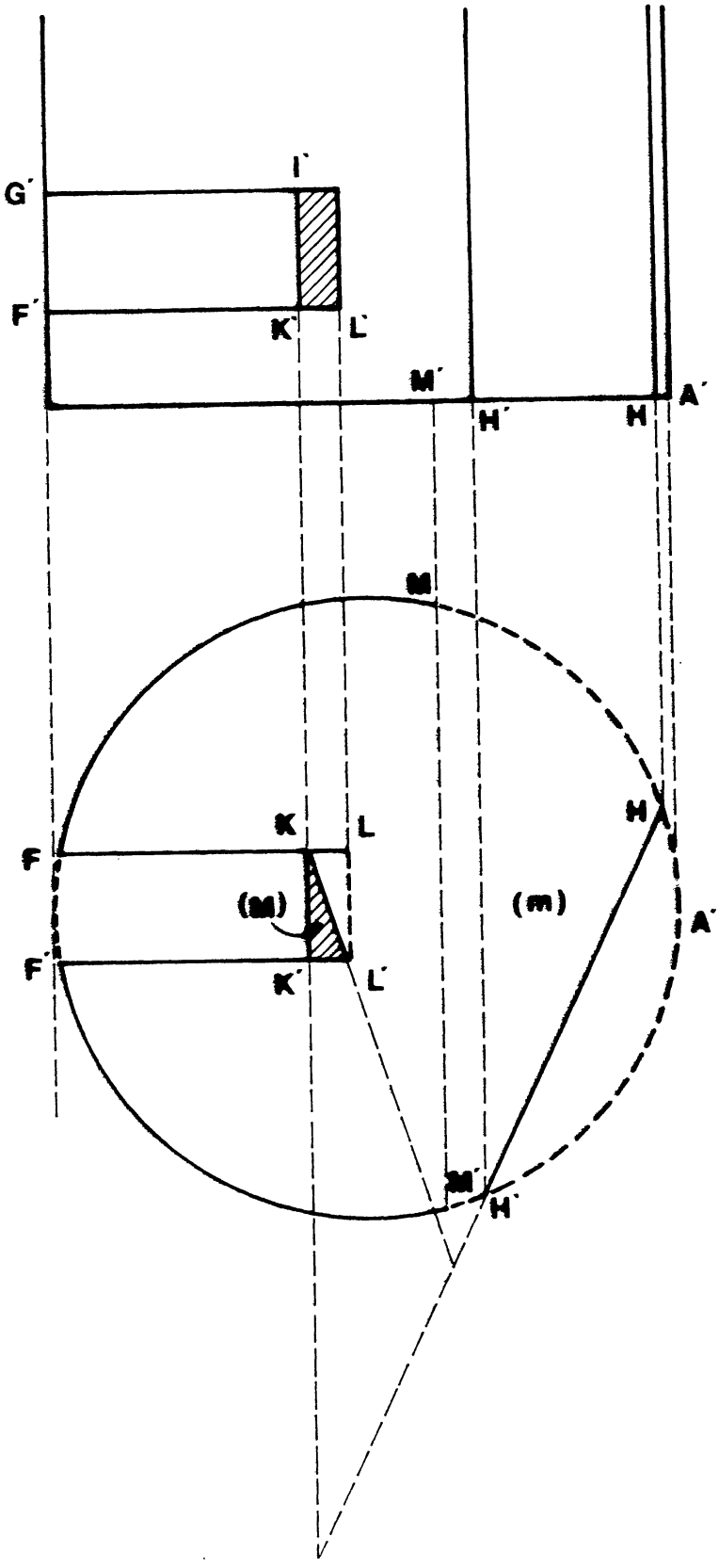

Fig. 14. Perspective projection showing the operation principle of the horizontal vitrometer. The moving wall HH' determine with the fixed the spread angle a of the vitrometer.

case with the first vitrometer, and finally the possibility of rotating the mobile cylinder (the water prism) with sufficient rapidity with respect to the very slow motion of the previous vitrometer (118), constitute clear advantages. And it is certainly to be lamented that Boscovich had been forced to interrupt his attempts at testing this new vitrometer.

The fact that Boscovich was involved in the invention of different devices in an attempt to improve the precision of measurements of the refractive and distractive qualities of lenses for the different colours of the spectrum corresponds to a necessity which, starting from the 1770s, became more and more impellent with the rapid progress that was being made in the realization of flint and crown crystals, which were becoming more and more homogeneous and free of impurities, together with corresponding progress in the field of lens-making.

It must be recognized that the practical realizations and theories that Boscovich elaborated in relation to the old vitrometer, the new variable prism and the new vitrometer, represented a significant step forward in the measurement of the physical parameters of lenses and objective systems in the period from 1765 to 1780.

The contribution made in this field by Dollond, Clairaut and later by Rochon appear to be objectively less relevant.

The need to determine the value of the index of refraction of different types of glass for different colours and wavelengths of the spectrum could hardly be met with systems made up of two different substances, because of the impossibility of completely annulling the image of the spectrum because of the existence of the so-called secondary spectrum on which Boscovich had experimented so much.

Only when J. Fraunhofer, about thirty years after the publication of Boscovich's "Opera", discovered that the spectrum of a sodium lamp is given by two brilliant yellow lines very close to each other, and provided a map of the absorption lines of the solar spectrum, did the possibility of making a significant step forward in the measurement of the index of refraction and the dispersive power of lenses become a reality (119).

Bibliographical Notes

1) Newton discussed this experiment in the "Opticks", published in London in 1704: Book I, Part II, Experiment 8, 130. In this paper we shall use the following edition: I. Newton, "Opticks", Dover Public. Inc., N. Y., 1952, based on the fourth edition London, 1730.

2) Ibid, 129.

3) "Seeing therefore the Improvement of Telescopes of given lengths by Refractions is desperate; I contrived heretofore a Perspective by Reflection, using instead of an Object-glass a concave Metal." With these words Newton discouraged, for about fifty years, every attempt at constructing achromatic telescopes. Cf;, ibid., 102.

4) Euler, L., Mem. Acad. Berlin, 1747, 274-296.

5) In 1755, S. Klingenstierna, professor of mathematics at Uppsala, communicated to Dollond the results of his research, which showed that Newton's experiment was good only for prisms having a small aperture. For the history of the development of the achromatic telescope see: Henry C. King, "The History of the Telescope", New York, 1979, 47-71 and 144-161.

6) In the description of "Experiment 8", Newton states: "This I try'd by refracting Light with Prisms of Glass placed within a Prismatick Vessel of Water." Cf., op. cit. in (1), 102.

7) The description of John Dollond's experiments on the extinction of the chromatic aberration with the use of his "wedge-like vessel" containing water is to be found in: "An Account of some Experiments concerning the different Refrangibility of Light", by Mr. John Dollond, Philos. Trans., 50, 1758, 733-743.

8) Ibid., 740-43.

9) Ibid., 740.

10) Clairaut's works are published in Mem. Acad. Sc., 1761 and 1762, and are dated 1756, 127, and 1757, 153 respectively.

11) See: Mem. Acad. Sc., 1764, dated 1762, 160.

12) S. Klingenstierna, "De Aberrazione luminis, in Superficiebus et Lentibus Sphaericis Refractorum", Philos. Trans., 51 1761, 944 - 977. Clairaut translated Klingenstierna's works into French in the Journal des Sçavants, October 1762, 664-78.

13) See: Hist. de l'Acad. Royale: "Sur les moyens de perfectionner les lunettes d'aproche", 1762, 120-21.

14) Ibid., 121.

15) R. G. Boscovich, "De Novo Telescopii usu ad Objecta Coelestia Determinanda", Romae, 1739.

16) R. G. Boscovich, "De Lentibus et Telescopiis Dioptricis Dissertatio", Romae, 1755.

17) In an interesting letter from Vienna addressed to Giovan Stefano Conti dated (3 April) 1763, Boscovich wrote: "Porterò anche meco una dissertazione, che attualmente lavoro sulli telescopi Dollondiani (this is the dissertation "De recentibus compertis, etc." that Boscovich published in the Annals of the Accademia di Bologna, cf. Note 38), nella quale tutte le cose essenziali sono di Clairaut messe ne' tomi dell'Accademia del 1756, e 1757, benché lette assai poco". Cf. R. G. Boscovich, "Lettere a Giovan Stefano Conti, edited by G. Arrighi, Firenze, 1980, 90.

18) Cf., op. cit. in the preceding note, 102-03.

19) In his biography of Boscovich, Angelo Fabroni points out the fact that on the occasion of Boscovich's being called to Pavia, "l'orazione, che recitò nell'ingresso, se non era pomposa per l'eloquenza, lo era per la copia delle cose ottiche trovate di fresco, e da lui o migliorate o spiegate con più facilità ed eleganza", cf., A. Fabroni, "Elogio dell'Abate R. G. Boscovich", Mem. di matem. e fis. della Soc. Ital., Tomo IV, 1788, 33-34.

20) In the letter sent from Pavia to G. S. Conti on 8 May 1764, Boscovich informed him: "...non sono, che 9 giorni, dacché son qui, e i primi giorni mille seccature di visite attive, e passive, ... Orazione inaugurale, etc., ...". Cf., op. cit. in Note 17, 133.

21) V. Dvořak's work "Bošković ev rad na polju fisike" is to be found in: Zivot i ociena djela R. J. Boškovića. Zagreb, 1887-8, 470-542.

22) Stanko Hondl, "Bošković ev hružni mikrometar", Almanah Bošković, 1955, 98-123.

23) Branimir Marković, "Boškovićev staklomjer-vitrometrum", Almanah Boskovic, 1961, 193-202. An illustration of Boščovich's optical works is given by Željko Markonic in his monumental biography of Boscovich (cf., Ž. Markonić, "Rude Bošković", II part, Zagreb, 1969, 677-94).

24) August Ziggelaar, "R. Bošković Experimental approach to Optical Questions", in: The Philosophy of Science of R. Bošković, Zagreb, 1987, 139-62.

25) Cf., op. cit. in Note 7, 740.

26) On Giovan Stefano Conti see: G. Arrighi, "Scienziati lucchesi del Settecento: Giovan Stefano Conti", La Provincia di Lucca, II 1762, 31, and the "Introduzione" by G. Arrighi to the op. cit. in Note 17.

27) The first known letter Boscovich wrote to Giovan Stefano Conti dates back to 28 December 1756. Cf., op. cit. in Note 17, 23-24.

28) In his letter to Boscovich dated 15 June 1761, Conti informed him: "Io osservo con un cannocchiale nuovo copiato da un cannocchiale che portò a Lucca l'anno scorso un certo inglese che stava a Firenze chiamato M. Henri, il qual cannocchiale è stato immaginato in Inghilterra da un certo M. d'Olond, e di cui v'è una descrizione in certi giornali di un tal M. Maty. Questo cannocchiale è fatto con sette lenti. L'obiettivo è di due lenti pian-convesse una di un cristallo bianco, e l'altra verde mare messe al contatto (non matematico) una dell'altra dalla parte piana, in modo che formano una lente utrinque convessa." (Cf., Bancroft Library, Berkeley University, MS "Boscovich's Correspondence and papers", 587-9, subsequently indicated as MS).

29) Letter by Boscovich to G. Stefano Conti dated 28 June 1761, (cf., op. cit. in Note 17, 44).

30) Giovan Stefano Conti has left us a detailed description of his attempts and experiments for the construction of achromatic objectives and telescopes carried out over a twenty-year period starting from approximately 1761. Conti's manuscript, entitled "Racconto e Descrizione delle Tentativi da me fatti per la costruzione de Cannocchiali Acromatici Dolondiani etc.", has been published by Gino Arrighi, (cf., G. Arrighi, "la collaborazione di R. G. Boscovich con G. S. Conti nella costruzione di cannocchiali acromatici", and is to be found in Atti del Convegno inter. celebrativo del 250° anniversario della nascita di R. G. Boscovich, Milano, 1963,

153-203. Conti's text is on pp. 158-203.

31) Cf., Conti's "Racconto" cit. in the preceding note, 159. On Abbot Nicolao Narducci, cousin and close collaborator of Giovan Stefano Conti's, see the brief bibliographical information given in the "Introduction" to the op. cit. in Note 17, 8-9.

32) From the "Racconto" by G. S. Conti, cit. in Note 30, we learn that: "il primo telescopio acromatico dollondiano fu veduto al Bagno nell'anno 1762 dal sig. Abate Narducci in mano ad un tale Monsieur Henrij cavaliero inglese il quale disse essere quella una nuova invenzione. Questo strumento era buonissimo, e fatto con un doppio obiettivo composto di due lenti e di cinque oculari." Keeping in mind that this instrument is spoken about in the two letters cited and dated 15 and 28 June 1761 between Conti and Boscovich, it is more than probable that Conti made a mistake in the dates at the time he wrote his "Racconto", certainly quite some time after the first events mentioned.

33) G. S. Conti's proposal to invite Boscovich to Lucca on the pretext of publishing his out-of-print works must go back to the end of May 1761, if Boscovich, in his letter to Conti written in Venice on 6 June, showed himself to be disinclined to accept the pretext. Boscovich suggested to Conti, in order to justify the visit, that he should "trovare qualche pretesto di pubblico servizio per venire, come per una visita di alcune cose etc.". But Conti thought this idea would be "alquanto difficile" to bring about (cf., Conti's letter to Boscovich dated 15 June 1761, MS 587-9). And, in a subsequent letter to Conti dated 28 June, Boscovich showed that he had by then decided to put off the visit, and points out to Conti: "In ordine al mio venir costà, giacché quella strada è innaturale, ella non la tenti nemmeno; ne troveremo alcun'altra, ma certamente ciò non sarà per ora" (cf., op. cit. in Note 17, 43 and 45).

34) "Io quà non son giunto, che il penultimo giorno dell'anno dopo altre vicende", Boscovich announced to Conti from Vienna in a letter of 3 January 1763 (cf., op. cit. in Note 17, 87.).

35) In the same letter from Vienna dated 3 January 1763 Boscovich said to Conti "le malattie non mi hanno permesso di essere in Italia prima dell'inverno, per vedere, se è eseguibile il suo progetto", (ibid., 88).

36) "Porterò anche meco una dissertazione, che attualmente lavoro sulli telescopj Dollondiani, nella quale tutte le cose essenziali sono di Clairaut", Boscovich told Conti in a letter dated 3 April

1763. (Cf., op. cit., in Note 17, 90).

37) "Sub finem anni 1763 transmisi ad Academiam dissertationem, quae impressa est in prima parte huinsce Tomi": with these words Boscovich began his second dissertation entitled: "De unione colorum aliorum post alias per binas sustantias, ac unione multo majore per tres", published in the Commentarii of the Istituto di Bologna, Tomi Quinti, Pars Altera, Boromiae, 1767, 265. This second dissertation was presumably written by Boscovich between the second half of 1764 and the first months of 1765. In fact, Clairaut refers to this dissertation in his letter to Boscovich dated 19 July 1764, in which he observed: "Quant à votre Memoire destinè au Volume de l'Istitut de Bologna il me semble bien plus propre à avancer l'optique que le 3.me volume des Opuscoles de m. D'Alambert qui abonde en recherches analitiques, en formules bien longues, en considerations savants, mais qui ne decelent point du tout le genie propre à la physique". (Cf., op. cit. in Note 28, MS, 587-9). Referring to the same dissertation, Boscovich wrote to Conti from Pavia on 1 February 1765: "Mando attualmente la seconda dissertazione a Bologna, ma non ho tempo da ordinarla a modo mio;", (cf., op. cit. in Note 17, 174).

38) R. G. Boscovich, "De recentibus compertis pertinentibus ad perficendam dioptricam", De Bonomiensi Scient. et Art. Instituto atque Academia, Commentarii, Tomi Quinti, Pars Prima, Bonomiae, 1767, 169-235. Both the first and the second dissertations were later published by Boscovich in Vienna in the work: "Dissertationes quinque ad dioptricam pertinentes", Vindobonae, 1767.

39) Cf., Note 36. In "De recentibus compertis" Boscovich developed in a much simpler and easier way, with a quite original geometric procedure, the theory on dioptrical systems made known by Clairaut in his works presented to the Parid academy in 1756 and 1757 and published in 1761-62 (cf., op. cit. in Note 10).

40) In a letter dated 8 May 1763 written to Boscovich, Clairaut wrote: "J'ai eté charmé de voir que vous avés eté content de mes recherches sur les nouvelles Lunettes, et les reflexions qu'elles vous ont occasioné de faire m'ont fait beaucoup de plaisir. Comme je suis bien aise de donner aux amateurs tous les sujets d'émulation possibles sur cette matiere j'ai fait faire une traduction de votre morceau, et je vais l'imprimer dans le Journal des Savans, imaginant bien que vous ne serés point faché de l'y voir paraitre." Cf., V. Varićak, "Drugi Ulomak Bošković́eve korespondencije", Rad Iug. Akad., 103, 320). Clairaut presented these results of Boscovich's in the Journal des Sçavans, Aoust, 1763, 550-58.

41) "et instrumentum quoddam cuvavi construi simplex admodum, et per quam idoneum ad deprehendendas, et inter se comparandas qualitates refractivam, et distractivam vitrorum, etc." (cf., op. cit. in Note 38, 176).

42) "Les formules que j'ai donnés dans le seconde Opuscule pour determiner les rayons de sphericité d'un objective ou oculaire composé capable de corriger a la fois les deux arreurs de réfrangibilité, et de sphericité, n'ont besoin que des valeurs m, m' dont chacun soit le moyen entre celles qui appartiennent aux rayons extrêmes, qui sont le moins et plus réfrangibles, avec la raison de deux dm, dm', c'est-à-dire, la valeur de la fraction dm/dm'," said Boscovich in his fundamental, but late, work published in 1785, (cf., R. G. Boscovich, "Opera pertinentia ad opticam et astronomiam", Tomus Primus, Bassani, 1785, 376-77).

43) Cf., op. cit. in Note 38, Tav. II, 234.

44) In a letter to Boscovich dated 8 June 1763, Clairaut informed him that he had found the value 1.65 for the index of refraction of strass glass, and added: "comme celui que vous avez trouvè", from which it can be desumed that Boscovich had already carried out observations on the refractive qualities of lenses during his stay in Vienna (cf., op. cit. in Note 40, 321).

45) In two letters, dated 16 January and 21 March, Giovan Stefano Conti, on referring to the idea Boscovich had expressed in his letter of 3 January "di venire a Lucca", told his friend that: "non rinuncerà mai a questo progetto". (Cf., MS cit. in Note 28).

46) "Io partirò verso la fine di questo mese", Boscovich said to Conti on 9 April 1763, "ed avrò il piacere di rivederla prima di andare a Roma", (cf., op. cit. in Note 17, 89).

47) "Al fine dello stesso mese di giugno venne a Lucca il mio insigne e venerabile Amico il P.re Ruggero Giuseppe Boscovich che si trattenne in casa mia 19 giorni", wrote Conti in his "Racconto" (cf., op. cit. in Note 30, 160). On the other hand Boscovich, in a letter to Conti dated 21 June 1763, stated: "Dopo, che avrà ricevuta la presente, starò poco a sopravenire, cioè forsi un par di giorni, e forsi meno" (cf., op. cit. in Note 17, 90).

48) Boscovich mentioned Conti's and Narducci's contribution to the construction of the vitrometer in "De recentibus compertis" and stated that they were "Artefici hoc instrumentum", (cf., op. cit. in Note 38, 231).

49) Cf., the letter from Boscovich to Conti written in Modena in August 1763, op. cit. in Note 17, 91.

50) Boscovich developed his theory on the vitrometer and the rectilinear and curvilinear prisms in § VI (de iisdem inveniendis ope prismatum) and in § VII (vitrometri constructio, et usus) of the "De recentibus compertis" (cf., op. cit. in Note 38, 215-235).

51) The reference is to the work in 5 volumes: R. J. Boscovich, "Opera pertinentia ad opticam et astronomiam", Bassani, 1785, cit. in Note 42. Boscovich's contributions to optics which concern this work are contained in Tome I, Opuscule I and in the five supplements, 1-168.

52) In the letter of August 1763 to Conti (cit. in Note 49), Boscovich referred analogously: "Fatto il calcolo trovo che le penultime (observations) danno il dM/dm = 1.5535", and, further on, "Le migliori osservazioni dello spettro lo danno = 1.5481, and, still later, "Quelle dell'acqua lo danno 1.5326". It would thus appear that Boscovich, besides the water vitrometer and the rectilinear prism for the "spettro", had used a third method as well, perhaps a curvilinear prism. (Cf., op. cit. in Note 17, 91). See also Notes 54 and 55.

53) On 6 August 1763 Boscovich declared to Conti: "Penso di farmi fare una (apparecchiatura) approposito per li prismi rettilineo, e curvilineo, tale da potervi adattare qualunque prisma". (Cf., ibid., 93).

54) In the letter to Conti dated 24 December 1763 from Rome concerning the calculation of the observations, which Boscovich called "nostre" (which would lead one to believe that they went back to the time of his sojourn in Lucca), Boscovich observed: "fidandomi sopra tutto di quelle fatte col prismetto curvilineo". (Cf., ibid., 105).

55) In the same letter cited in the preceding note Boscovich noted: "Se vedesse come ho montato il suo prismetto curvilineo! Và incassato con una vite che ha il micrometro, e l'avrò dimani: già l'ho visto e va assai bene". It appears that the prism mounting was made by a craftsman in Rome. (Cf., ibid., 106).

56) In a letter dated 28 July, Giovan Stefano Conti informed Boscovich: "Il suo Prisma ad acqua è quasi finito ed è bellissimo e da fissarsi con la vite con tutta la precisione". And further on: "Io farò la divisione essendoci più abituato che l'Abate (Narduc-

ci), e spero che quanto prima se gli potrà spedire". (Cf., MS cit. in Note 28).

57) "Ho ricevuto l'instrumentino sano, e salvo", announced Boscovich to Conti from Bassano on 9 September 1763. Further on, however, he mentioned that "vi è un difetto, che rimedierò a Milano. Il vetrino delle linee doveva essere messo in modo, che toccasse la zona d'ottone: stando staccato fa quella parallassi, che fa il filo", and added: "Le divisioni pure sono anche a occhio disuguali". (Cf., op. cit. in Note 17, 97).

58) Ibid., 97.

59) On 19 November 1763 Boscovich informed Conti he had received the "3 specchietti", of which "quell'ovale è di fatti il migliore", that Boscovich had ordered from Conti on the 5th of the same month ("Per mettere in opera l'istrumentino avrei con somma necessità di un piccolo pezzo di specchietto piano di metallo") and which were used in the building of the heliostat. (Ibid., 100 and 99).

60) See the reference cited in Note 54 (letter from Boscovich to Conti dated 24 December 1763). The same concept ("fidandomi più del curvilineo") was expressed by Boscovich in a letter to Conti dated 7 January 1764, in which he spoke of the defects of the various instruments for the measurement of refractive qualities and of the necessity of finding "Artefici, che eseguiscano meglio gli strumenti", (cf., ibid. 108-110).

61) Letter from Clairaut to Boscovich dated 15 January 1764 (cf., op. cit. in Note 40, 322). See also Boscovich's letter to Conti of 8 February 1764, in which he refers to Clairaut's letter (cf., op. cit. in Note 17, 121-22).

62) Clairaut's letter, cited in the preceding note.

63) See Boscovich's letter to G. S. Conti dated 7 January 1764 (cf., op. cit. in Note 17, 108).

64) "Un curvilineo buono, che faccia ben distinta l'immagine, benché sempre la farà bislunga, mi servirebbe assai", Boscovich confessed to Conti on 23 January 1764, and he insisted on the same topic on the following 6 and 27 March (ibid., 120-21, 130, 131).

65) Speaking of the patina on which the curvilinear prism was modelled, Conti, in agreement with Boscovich, showed great perplexity. This is what he said in a letter dated 15 March 1764: "In quello

la Patina era una porzione di zona cilindrica fatta con una centina, tanto nella forma concava quanto in quella convessa, ma non son sicuro che per il lungo, parallelamente all'asse del cilindro, la superficie sia veramente retta, e di più non son nemmeno sicuro che sia veramente circolare per l'altro verso, appunto perché è parte di una zona cilindrica". (Cf., MS cit. in Note 28). The translation of the passage given in the text is as follows: "I am working on your curvilinear prism and mirror. The first ones are ready. You were quite right when you said you were not happy with the curvilinear prism you have. I found the ones I have to be most irregular, and I have fixed them to send to you. I certainly won't tell you they are perfect, but they are surely better than the one you have."

66) Conti's letter to Boscovich dated 23 April 1764, (ibid.).

67) Ibid.

68) "Ricevetti jer sera la sua de' 16 (see Note 70), ed aspetto con ansietà i prismetti per far le esperienze con frutto. Spero, che dà sferici pure tirerò partito, e coll'averli ne esaminerò anche la teoria. La ringrazio anticipatamente di essi, e dello specchio. Pure se vi fossero stati què cilindrici, che ella mi diceva, ne avrei avuto piacere, che con più confronti si sarebbe accertato più; ma non importa molto, farò uso degli sferici", (cf., op. cit. in Note 17, 135). It is not sure that the spheric prisms that Boscovich spoke about in this letter of 22 May from Pavia are the same ones Conti mentioned in the letter of 23 April cited in the text.

69) "In ordine a' curvilinei li aspetto con impazienza", Boscovich told Conti in a letter from Pavia dated 8 May 1764. And further on he added: "Pel curvilineo sferico vi vorrà un poco di teoria più complicata, ma pure mi servirà (ibid., 134).

70) "Sapendo da essa che i Prismi Sferici possono servire, subito ho terminati quelli che già avevo preparati, e li manderò quanto prima etc.", Conti wrote to Boscovich in a letter dated 16 May 1764. Further on in the same letter Conti specified: "Con detti curvilinei che sono due uno di Boemia, e l'altro di Flint interamente compagni, ma che lei distinguerà subito al colore, e poi colla refrazione, etc.. (Cf., MS cit. in Note 28).

71) Letter Boscovich wrote to Conti from Pavia on 4 June 1764 (cf., op. cit. in Note 17, 140).

72) In a letter to Boscovich from Milan dated 8 May 1764, Father Lagrange informed him: "Notre vitrometre n'est pas ancore achevé. Je fais preparer de la peau pour vous e pour nous". (Cf., MS cit. in Note 28). The skin Lagrange spoke about was used for maintaining the impermeability of the mobile wall mentioned by both Boscovich (in the description of the vitrometer (op. cit. in Note 38, 230-31) and Conti (in his letter to Boscovich dated 20 August 1763 - see MS cit. in Note 28). On 19 June Lagrange announced to Boscovich: "Le vitrometre est achevé. Il est parfait à bien des égards, mais le Nonius ne joue pas ancore aussì bien que je voudrais: il fait un frottement, et ce frottement fait plier la branche qui porte l'index. Nous verrons de rémedier a ce petit defaut quan vous serai ici". (Cf., MS cit. in Note 28).

73) On 9 July 1764, in response to Boscovich's letter from Pavia dated 26 June (cf., op. cit. in Note 17, 142) Conti wrote: "Per altro la faccia pur fare la sua machinetta, etc." (MS cit. in Note 28).

74) Boscovich remained in Milan as the guest of the College of Jesuits, with the exception of a short holiday at Merate between the end of August and the beginning of September, practically from July to September of 1744. For the presence of Boscovich at Pavia and Milan in the period from 1764 to 1769, see E. Proverbio, "When did Boscovich stay in Milan while teaching at the University of Pavia?", Proc. Intern. Scientific Meeting on R. Bošković, Dubrovnik, 1987, (in press).

75) On 18 July 1764 Boscovich informed Conti: "La mia machinetta è ita via: qui ne n'è un'altra, ma finora imperfetta. Quella se l'è presa il Duca di York, che stette in camera mia per un'ora a vedermi fare delle osservazioni; indi la chiese per mandarmela più perfetta da Londra sullo stesso gusto. (Cf., op. cit. in Note 17, 149).

76) J. Blair's letter to Boscovich dated 15 June 1765 is above all an occasion to claim priority in the invention of Boscovich's vitrometer for the English inventors Dollond and Hoave, the latter, it appears, the builder of "un instrument de meme nature", over Clairaut and Boscovich himself. (Cf., MS cit. in Note 28, 587-8).

77) Apart from the readings made on the outer scale of the vitrometer (see Fig. 7), which had a parallax error as well as an error in the scale divisions, the measurements made with the rectilinear (the spectrum method), or the curvilinear prism appear to be quite uncertain and difficult. Boscovich gave no description of the "machinetta" of which he sometimes spoke in connection with the

carrying out of these measurements. In a letter dated 21 July 1764 that he wrote to Conti, he said, for example: "piglio le quantità delle rifrazioni sul muro, avendo fatta una machinetta tale da levarne il prisma rettilineo, indi il curvilineo, senza muovere la macchina, e ciò presto, e facilmente". (Cf., op. cit. in Note 17, 151).

78) Cf., ibid., 150. "Up till now I had supposed that your prisms were perfectly spherical, with the parallelism exactly at the top. With a compass I took the distance from the top to where the ray came out and, due to some imperfections in the sphere, for which the chord does not give the angle, and in part the uncertainty of its exact semidiameter, for which, given the chord, the number of degrees remains uncertain, the results came out variable."

79) Ibid., 150.

80) "In esso (the vitrometer) rimangono sempre troppi colori, e si vede che l'acqua fa una divisione di spettro troppo diversa dal vetro, per cui l'inversione delle spettro si fa lentissimamente notando i colori gli uni dopo gli altri con troppe diversità d'angoli", (ibid., 150).

81) "Ma il ritrovamento francese è migliore ed ella è a portata di farlo subito, e mandarmelo", wrote Boscovich to Conti in a letter dated 21 July 1764. And further on he pointed out: "Se lo fa sensibilmente cilindrico potrà facilmente farlo andare innanzi, e indietro quando anche sia stretto; ma se sarà sferico, non so se ugualmente bene si combacerà, etc." (ibid., 151).

82) "Quanto è bella e felice l'invenzione del Prisma ad Angolo Variabile", exclaimed Conti in a letter to Boscovich dated 3 August 1764. "Non mi sono neppure provato a fargli cilindrici perché non mi dà l'animo di far cosa buona. Questo è un lavoro che io non so fare. Credo però che in sferico riusciranno buoni". And he continued: "Un lavoro simile di Boemia non lo posso fare. Oltre l'enorme fatica che senza aiuto di Ruota a questa stagione è quasi intollerabile non ho cristallo di quella sorte di tanta grossezza, etc.". (Cf., MS cit. in Note 28).

83) Letter from Conti to Boscovich dated 8 August 1764 (ibid.).

84) Referring to the new variable prism mentioned in Conti's letter from Milan dated 15 August, Boscovich exclaimed: "Che portentoso lavoro, e insieme, che infelicità, di averlo fatto in una così scelerata materia", (cf., op. cit. in Note 17, 159). That the

material Conti used was not good had been mentioned by the latter to Boscovich in his letter of 8 August ("Io non lo volevo mandare perché il cristallo col quale è fatto è tanto pieno di vene che è una porcheria vera"). Cf., Note 83.

85) In a letter dated 8 August written in Milan, Boscovich informed Conti that he had "dato qui ad un artefice sufficiente uno de' due pezzi di flint (it was later discovered that it was crown), che ella mi ha mandati, ed egli si è impegnato a cavarmi il cavo, e il convesso da essa per 4 paoli l'uno. Cf., op. cit. in Note 17, 145. The name of this "sufficiente" craftsman is not known, but it is certainly not the Baillù that Boscovich mentions for the first time in a letter he wrote to Conti from Pavia on 8 May, and of whom he said (in a letter dated 15 August) "che fa pagar troppo", (cf., ibid., 160).

86) "Se ella avesse un pezzetto anche di qualunque altro vetro, ma veramente bello, e puro da farne uno come và, le resterei ben obbligato", wrote Boscovich to Conti from Merate on 6 September 1764, and added: "Non sarebbe necessario che avesse molti gradi: ne basterebbe anche una quindicina, o ventina, ma allora converrebbe avere un altro prismetto rettilineo, o due pure di una quindicina, o ventina di gradi, etc.", (cf., ibid., 161).

87) In the letter from Lucca dated 5 October 1764 Conti announced to Boscovich that he had "finiti" the prisms, "un mistilineo composto di Boemia, con due rettilinei pure di Boemia, ed un mistilineo di Flint, con due rettilinei pure di Flint, etc." And further on: "Il mistilineo di Boemia ha 28 gradi. L'altro di Flint ne ha circa 26". (Cf., MS, cit. in Note 28).

88) Boscovich's letter to Conti from Milan, dated 19 September 1764 (cf., op. cit. in Note 17, 165).

89) Boscovich's letter to Conti from Milan, dated 26 September 1764 (ibid., 166). "with this Vitrometer, which is double a thousand times better than the other one with water, whose refractive quality and diversion of the spectrum is far too different from that of the other substances, it is much easier to make more precise observations with the method I have devised and which I habitually put into practice, having found in your prism a site at which the image is clear, and in every observation I find with great precision the three values I need in order to calculate the sphericity, and these are m, M, dM/dm."

90) Boscovich's letter to Conti from Rimini, dated 13 October 1764, (ibid., 168).

91) Cf., op. cit. in Note 37.

92) Cf., op. cit. in Note 37, 277.

93) The new theory of the vitrometer and the variable prism was given by Boscovich in his second dissertation "De unione colorum, etc.", cit. in Note 37, in § 4 (De refractionibus radii ingredientis ad perpendiculum in primum e binis prismatis conjunctis cum applicatione ad successivam colorum unionem), 293-99.

94) "Plerumque autem applicabam prismatis latus ad planum fenestrae vitrae lateris immobilis, etc.", (cf., ibid., 270). It is to be noted that Boscovich had had recourse to the new way of using the vitrometer most of the time (plerumque).

95) Ibid., 293-95.

96) Ibid., 295-99.

97) In this circumstance Boscovich observed: "bini colores uniantur", and, "differentia refractionum dr evanescit". (Ibid., 298). In reality, on combining two prisms or two lenses, the colours of the spectrum do not elide one another two by two (bini). Boscovich had seen this on using his vitrometer and observing the phenomenon of the inversion of the spectrum of sunlight (inversio spectri) (cf., ibid., 271-76, 279-85), and this led him to design objectives and eyepieces made up of three lenses (ibid., 322-29).

98) After giving the vitrometer made by a craftsman in Milan to the Duke of York, Boscovich had a fourth one made (it is known that Boscovich kept the other two, made by Conti and Narducci, in Pavia). (Cf., quotation in Note 75).

99) "Ho fatto principio delle sue Opere intorno alla luce, a proposito di (quello) che mi ha comunicato eziandio il P. La Grange (in) una sua lettera riguardante il celebre e meraviglioso vitrometro. Farò da mè que' progressi che posso; ma non so dirle con quanta impazienza attendo la venuta sua a Milano per trattar seco, giacché il tempo ora me lo permette, di tal materia e vedermi a segno di farne anche uso nelle pubbliche tesi". From these words, and the rest of the letter the Jesuit Giuseppe Vairani wrote to Boscovich on 30 January 1765, it would seem Vairani had in mind the construction of a water vitrometer. (Cf., MS cit. in Note 37,

587-14).

100) On this subject, besides the work by Ž. Markovic (cit. in Note 23, 765-83), see the work: E. Proverbio, "La strumentazione astronomica all'Osservatorio di Brera-Milano e l'attività di R. G. Boscovich from 1765 to 1772", Giorn. di Astron., 1986, 3, 25-32.

101) "Se ella è tanto affollata di faccenda da non poter neppure una volta provare quei nuovi Prismi che mandai, e che nel loro genere dovevano essere più tosto buoni, vi sarebbe anche il rimedio che ella facesse supplire da alcuno de mattematici dell'Università di Pavia, se alcuno ve n'è di non tanto occupati, etc.". With these words, written on 27 February 1765, Conti appears almost to be imploring Boscovich to go back to his observations in optics, which the latter had evidently given up because of his new duties at the Brera Observatory. Again on 17 December 1765 Conti asked Boscovich: "Se si è servita di prismi composti e se se ne servirà mi scriva che riuscita le abbiano fatto, e come torni bene con essi a fare le esperienze". Cf., MS cit. in Note 17.

102) Cf., letter from Conti to Boscovich dated 5 March 1766 (ibid.).

103) See Conti's letter to Boscovich dated 20 May 1766. In this letter Conti appeared to be quite upset about continual failures in attempts at constructing achromatic objectives. (ibid.).

104) Cf., the work: E. Proverbio, "Il contributo di R. G. Boscovich allo sviluppo dei metodi per la verifica e rettifica dei cerchi graduati", Giorn. di Fisica, (in press).

105) Cf., on this subject the work by Proverbio cit. in Note 100.

106) Still in February 1769 Boscovich was involved in the measurement of the refractive and distractive qualities of glass by means of a variable prism ("doppio mistilineo") and the vitrometer, (cf., letter to Conti dated 20 February 1769, op. cit. in Note 17, 320).

107) "Sento con piacere che abbia così bene adattato il Prismetto curvilineo e che il suo moto con la vite e col micrometro sia egli buono. Nelle sue mani gl'Istrumenti non possono che acquistare". (Conti's letter to Boscovich dated 2 January 1764, cf., MS cit. in Note 27).

108) Cf., ibid.

109) Cf., work by Ž. Marković cited in Note 23, 784-801.

110) "Instrumentum praecipium, quo nunc utor, fuse describitur in Opuscolo primo, adjecto ejus usu multiplici: ejus forma mihi in mentem venit Venetiis anno 1773, ubi ipsum curavi perficiendum ab egregio telescopium artefice Domenico Selva: plura alia ad ejus imitationem deinde constructa sunt et ibi, et alibi". Cf., op. cit. in Note 42, XXXVI.

In a letter from Paris dated 26 December 1774 to (Domenico) Selva, son of Lorenzo Selva (1716-1800), the author of a description of the vitrometer (see: Lorenzo Selva, "Sei dialoghi ottici teorico-pratici", Venezia, 1787, Tav. III, Fig. XXV-XXVI), Boscovich mentioned possible "commissioni" for the purchase of the vitrometer and the heliostat by French buyers (cf., MS Boscovich, Institut de France: Archives).

111) Ibid., Opusculum I, 1-132.

112) Ibid., Op. I, Suppl. II, 137-140.

113) Ibid., Op. I, Suppl. V, 159-164.

114) "Pro primo mihi commode accidit, quod superiore anno excogitaveram, et Venetiis perficendum curaveram, ut itidem innui in generale Praefatione, instrumentum ad eam rem maxime idoneum, etc.", (cf., ibid., Op. I, 1).

115) "... adjecto alio ejus generis instrumento pro angulo variabili itidem aqueo, quod adhuc est magis idoneum ad usus nonnullos, et quod posterius excogitavi". Cf., ibid., Op. I, 4).

116) Ibid., Op. I, Suppl. III, 141-155.

117) "Curaveram id perfici in Gallia, sed negligentia artificis ipsum reliquit imperfectum. Paullo ante impressionem hujusce Operis accepti minus male elaboratum, quod usui esse potest". (Cf., ibid., Op. I, 82, (note)).

118) One of the criticisms contained in Blair's letter to Boscovich dated 15 June 1765, cit. in Note 76, concerned the slowness of movement of the aperture of the vitrometer ("le coté mobile de l'Instrument a un mouvemente si lent causé par la vis du milieu, etc.").

119) J. Fraunhofer, "Denkschriften der K. Acad. der Wissen. zu München", 5, 1815, 193-226.