

Kepler's Explanation of the Rainbow*

CARL B. BOYER

Brooklyn College, Brooklyn, New York

IN a well-known work on optics one reads that "The first theory of the rainbow was given by Descartes in 1637."¹ Another recent author, likewise ascribing the first scientific explanation to Descartes, says that until the middle of the seventeenth century the theory of the rainbow remained in the domain of poesy.² Such views are, of course, as naive as they are widely held.

To begin an account of the rainbow with the year 1637 conceals the fact that serious explanations had been attempted over a period of two thousand years. It is not the intention here to survey in detail the developments within these two millenia; the aim is to call particular attention to a portion of the history of physics which appears not to be well known.

One of the very earliest naturalistic and mathematical theories of the rainbow was that given by Aristotle. Accounts of this explanation, based upon reflection from a cloud, can easily be found in books and periodicals devoted to the history of science.³ It is intriguingly complicated—making use for the first time of the locus known as the circle of Apollonius—and has evoked numerous commentaries from his day to this. Among the commentators in the medieval age were Alhazen, an Arab, and Witelo, a Pole. Witelo (and possibly also Alhazen) knew of the need for refraction as well as reflection, but did not develop this idea. The modern approach to the rainbow through reflection and refraction of light within the individual drops of rain appeared, independently, in the works of two men who were close to each other in time but far apart geographically—the

Teutonic Dominican theologian Dietrich (or Theodoric) of Freiburg and the Persian astronomer and physician Qutb al-dīn al-Shīrāzī.⁴ The close similarity of the views of these men, both of whom died in 1311, or shortly thereafter, and their resemblance to the ideas of Descartes more than three hundred years later is a striking coincidence. Although there is no available evidence to show that Dietrich or Qutb al-dīn influenced either Descartes or his immediate predecessors, nevertheless the work of Theodoric was extant for some time in Germany. Regiomontanus thought of publishing it and the theory was taught at the University of Erfurt until the beginning of the sixteenth century. Thereafter it was lost and not rediscovered until Venturi ran across one of two surviving manuscript copies and published it in 1814.⁵ European scholars of the early sixteenth century appear to have been familiar with the science of the fourteenth; but with the rise of humanism, interest in medieval thought declined, and this may account for the neglect of Dietrich's work. The ideas of Qutb al-dīn were developed by his student, Kamāl al-dīn (d. c. 1320), in a commentary on the optics of Alhazen; but the new theory seems to have had little influence, and a fresh start had to be made.

Early in the sixteenth century, just as Dietrich's work disappeared, there arose a wave of renewed interest in the theory of the rainbow, and this continued for at least two hundred years. It is probably safe to say that more volumes on the rainbow appeared between 1500 and 1700 than during all the years which preceded or succeeded; and most of these were pre-Cartesian, many appearing in Germany. Kepler lived during the very middle of this period—from 1571 to 1630. Could he have ignored these works devoted to one of the most striking of optical phenomena? After all, what Gilbert was to electricity, or Galileo to dynamics, or what Boyle was to pneumatics, that

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¹ Robert W. Wood, *Physical optics* (The Macmillan Company, New York, new ed., 1928), p. 342.

² J. Cabannes, "L'explication scientifique de l'arc-en-ciel," *La Science Moderne*, 8, 217–226 (1931).

³ See, for example, Fr. Poske, "Die Erklärung des Regenbogens bei Aristoteles," *Zeitschrift für Mathematik und Physik, Historisch-literarische Abteilung*, 28, 134–138 (1883); A. Sayili, "The Aristotelian explanation of the rainbow," *Isis*, 30, 65–83 (1939); T. L. Heath, *Mathematics in Aristotle* (Oxford, 1949); Josephus Blancanus, *Aristotelis loca mathematica collecta et explicata* (Bononiae, 1615).

⁴ See George Sarton, *Introduction to the history of science* (3 vols. in 5, Baltimore, 1927–1948), II, 761, III, 704–708.

⁵ Giambatista Venturi, *Commentarj sopra la storia e le teorie dell' ottica*, vol. I (only one published), Bologna, 1814, pp. 149–180.

was Kepler to dioptrics. It therefore seemed incredible that Kepler should not have attempted some explanation; yet historical works on optics and the rainbow make virtually no mention of his views.⁶

A search of his works, however, reveals that Kepler did indeed make a determined effort to explain the rainbow—a study almost as earnest as his efforts, far better known, to discover the law of refraction. And one of the striking characteristics of his search is that the development of his own ideas as an individual follows closely the stages found in the wider history of the theory as developed by mankind at large. So close, in fact, is the resemblance that one is almost tempted to see here the operation of a general principle of mental development somewhat akin to the biogenetic law of recapitulation.

Kepler's interest in the rainbow seems to date from about the time of his *Mysterium Cosmographicum* (1596), when faith in the mathematical harmonies of the universe appeared to have been strikingly vindicated. Shortly after the publication of this work had launched Kepler upon a successful astronomical career, he sought to extend the harmonies of astronomy and music to include the phenomena of color. In marginal notes to the *Mysterium*, written apparently toward the very close of the century, the range of colors in the rainbow is compared to the infinity of tones in the musical octave. Yellow is taken as a sort of mean; and from this one passes, outward, through red into black as the solar influence diminishes and the admixture of the crass material in the cloud increases. From yellow inward

one passes through green, blue, purple, and violet into black, and this transition is due to quite another cause, namely, refraction. Kepler adds that often he had considered whether or not the proportion of the angle of refraction determines the limits between the colors green, blue, etc. Direct vision, in which the angle of refraction is zero, results in yellow light; and when the angle of refraction is a right angle, all light ceases, so that this corresponds to blackness. But, added Kepler, how the greatest angle of refraction is to be subdivided in terms of color, it is difficult to say. Nevertheless, he believed that if the right angle were divided into parts corresponding to the simple unit fractions $\frac{1}{6}$, $\frac{1}{5}$, $\frac{1}{4}$, $\frac{1}{3}$, and $\frac{1}{2}$, the five colors would be yellow, green, blue, purple, and violet respectively. "And lo, is not the magnitude of the rainbow always about 45° , which is the measure of half of a right angle?" Kepler added cautiously, however, "But these may be notions."⁷

This, Kepler's early explanation of the rainbow, is a strange mixture of Aristotelian color theory and Pythagorean numerology. Had he thought of Occam's razor, he would scarcely have postulated two distinct causes of the rainbow. It will be noted further that the explanation is Aristotelian in the tacit assumption that it is the cloud as a whole which causes the phenomenon. Kepler seems to have been completely unaware of earlier theories (such as that of Johann Fleisher (1539–1593)⁸ explaining the bow in terms of individual spherical drops. It is astonishing how poor scientific intercommunication of the time appears to have been. One wonders whether the radius of 45° which Kepler, throughout his life, accepted for the bow, was determined independently or was borrowed from others. Kepler cites no authority for it.

The early views of Kepler on the rainbow were immature in the extreme, and yet he hastened to publish them. In an astrological treatise of 1602⁹ he reiterated the Aristotelian distinction between reflection from the surface of a mirror, in which form is preserved, and reflection from an uneven

⁶ Alfred Kunze, *Zur Geschichte der Theorie des Regenbogens* (*Jahresbericht über das Karl-Friedrichs Gymnasium zu Eisenach* (Eisenach, 1870), does not mention Kepler. J. C. Sturm, *Thaumantias, sive iridis admiranda* (Norimbergae, 1699), apparently knew only of Kepler's work of 1604. Etienne Montucla, *Histoire des mathématiques* (new ed., 4 vols., Paris, 1799–1802), devotes but a paragraph to Kepler's letter to Harriot (see vol. I, p. 702). Henri Brocard, the eminent geometer, devoted a long account to Kepler's meteorology ["Essai sur la météorologie de Kepler," *Bulletin de la Société de la statistique de l'Isère*, Grenoble, series 3, 8, 360–400 (1879); 10, 281–313 (1880); but only a few paragraphs treat of the rainbow, and these do not touch upon his geometrical explanations. The *Kepler Festschrift* edited by Karl Stöckl, *Bericht des Naturwissenschaftlichen Vereins zu Regensburg*, 1928–1930, Heft 19, contains excellent papers on Kepler's dioptrics but includes nothing on the rainbow. Two excellent little works, one by Friedrich Just, *Geschichte der Theorien des Regenbogens* (Marienburg, 1863), and the other by Reclam, *Über den Regenbogen* (Neustettin, 1877), mention letters of Harriot to Kepler but not those of Kepler to Harriot.

⁷ Johann Kepler, *Opera omnia* (ed. Ch. Frisch, 8 vols., Francofurti a. M. and Erlangae, 1858–1870), I, p. 200.

⁸ *De iride doctrina Aristotelis et Vitellionis certa methoda comprehensa* (1571). I cite this on the basis of the article "Regenbogen" in J. S. T. Gehler's, *Physikalisches Wörterbuch* (new ed., vol. 7, part 2, Leipzig, 1834), pp. 1318–1340.

⁹ *De fundamentis astrologiae certioribus* (Pragae, 1602). See his *Opera*, I, p. 425.

surface, in which the light is imbued with color. Pursuing this thesis, he held, somewhat as had Seneca, that the colors of the rainbow fall into two classes: those arising from the darkening or privation of light; and those from refraction or tincturing. Kepler here seems to use the term refraction in the Aristotelian sense of reflection. Of the former class, the first color is the light of white heat itself, which cuts the circle of the rainbow as if in two. On the one side the intensity of illumination diminishes, producing first yellow, then red, a darkish color, and finally black; on the other side it is refracted and reflected, resulting in green, blue, purple, and, finally, dark violet.

Kepler's views of 1602 still were strongly tinged with Peripateticism; and two years later he published, in his classic commentary on the optics of Witelo,¹⁰ a crude qualitative modification, based upon refraction, which had been suggested by medieval commentators on Aristotle. Here Kepler again reiterated the idea that the colors of the rainbow result from two distinct causes—the attenuation of light and the injection of aqueous material—and he asserted categorically that the diameter of the rainbow is always 90° . Then he said that the bow is due to the refraction of the rays of light by rain or aqueous material *between the spectator and the sun*. It is therefore not true, he argued, that the rainbow is caused by the reflection or refraction of the rays of the sun or of vision in that portion of the cloud in which the bow appears—repeating a proposition which had long been argued pro and con in scholastic circles. In this same treatise Kepler naively cited the colors in the rainbow as supporting his quasi-medieval belief that comets and novae are aqueous in origin and nature. In a description by Cornelius Gemma Frisius (1535–1577) of the variations of color in the nova of 1572, Kepler had read that the new star was at first red in color, then became brilliantly yellow, then green, and finally disappeared after having taken on a violet color. But this is precisely the order of the colors in the rainbow, which results from humidity in the air; and from this Kepler

felt that one may reasonably conclude that the star was engendered by humidity!

Kepler apparently was soon convinced that his views of 1604 were untenable, as his correspondence in the following year indicates. David Fabricius (d. 1617) had written him asking why lunar haloes are always half the apparent radius of the rainbow, i.e., half of 45° . Kepler replied that he could not say more of the rainbow and halo than he had given in his *Optics* [the *Paralipomena* of 1604] except that he had erred in placing the source in the sublime region far above the cloud, and that the cause lay in the drops or vapors in which the bow appears.¹¹ In this same year Kepler made his first crude attempt to explain the rainbow geometrically in accordance with his revised views and to answer the question raised by Fabricius. Writing to Johann Georg Brengger, professor of medicine at Kaufbeuren,¹² Kepler said one sees clearly that for the formation of the rainbow it was not so much rain which was necessary as it was the disposition of the air to collect into drops. His explanation, nevertheless, is based, not upon individual drops, but upon the spherical shape of the cloud as a whole. Let the rays of the sun, regarded as parallel, be given by the lines *HDC*, *IE*, and *KFAB*, and let the points *B*, *C*, *D*, *F* lie on a circle with center at *A* (Fig. 1). If the eye of the observer is at *A*, then the angle of the rainbow, angle *BAC*, is 45° . Kepler apparently followed Aristotle in assuming that in reflections causing color, the law of the equality of angles need not be satisfied. Therefore, Kepler argues, inasmuch as the rainbow and the halo are both due to refraction, were the eye to be placed at *C*, the sun would be observed directly along the line *HDC* and the halo would be seen along the ray *CFK*. But from geometry the angle *DCF* is precisely half the angle *BAC*, so that the radius of the halo is $22\frac{1}{2}^\circ$. Years later Pierre Gassendi (1592–1655) likewise was unable to resist the temptation of seeing in the relation between central and inscribed angles the fact that the apparent size of the primary rainbow is double that of the ordinary halo.¹³

Kepler realized that his explanation gives rise

¹⁰ *Ad Vitellionem paralipomena quibus astronomiae pars optica traditur* (Francofurti, 1604). This is found also in *Opera*, 2, pp. 119–397.

¹¹ *Opera*, 2, p. 100.

¹² For the little that is known of his life see Kepler, *Opera*, 2, p. 37.

¹³ See Gassendi, *Opera omnia*, (6 vols., Florentiae, 1727), 2, pp. 86–93.

to many questions. Why, for example, should one not see a rainbow of radius 45° about the sun [presumably between the lines HDC and KAC],¹⁴ or a halo of radius $22\frac{1}{2}^\circ$ opposite the sun [allowing the ray EI to be extended to touch the circle a second time and be reflected to A]? Or does the surface of the air really have the spherical figure assumed in the explanation? The nebula in which the bow is seen is usually agitated by rapid wind and does not preserve any particular form, whereas the rainbow is always circular. Moreover, the water and drops descend swiftly in paths which are not always straight lines. Kepler is unable to explain why such irregularities do not manifest themselves in the shape of the rainbow, except to suggest that it must be the body of the aqueous air, rather than the surface, which serves as the agent.

Kepler, in his correspondence with Brengger, makes a number of other suggestions, some of which are wildly imaginative. Inasmuch as halos are seen generally through fine mists, whereas rainbows appear during a downpour, Kepler asks whether refraction in air in which drops are just beginning to be formed may not be half as great as that in air in which rain is already falling. Perhaps, on the other hand, the double radius of the rainbow is due to the combined effect of refraction and reflection, the halo resulting from refraction alone. He seems to be unable to decide whether it is water or a shower of raindrops or simply aqueous air which causes the rainbow; and he asks whether the bow is peculiar to each observer or is due to the coloring of the whole mass of the air in question. Of one thing he is certain, however, and that is that such phenomena are not optical illusions, but come to the eye by real rays; for he himself has admitted into his room light from parhelia and has seen the colors on the wall. Then Kepler brings his feet to earth and suggests to his correspondent that he examine the refraction of solar rays through a spherical globe of water. Is it not true that rays traversing near the center of the globe are not colored while those passing near the edge are? Color therefore seems to depend upon the magnitude of the angle of incidence. Kepler's letter closes, however, with a

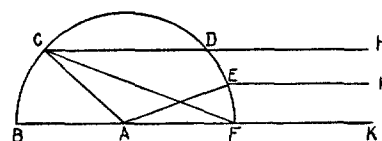


FIG. 1. Kepler's early explanation of the production of the rainbow by reflection from a spherical cloud.

frank admission of failure—what can one say about the origin of haloes and the rainbow? "I don't know," is his answer.

It was almost three years before Brengger replied to the letter of 1605, and in this interval Kepler developed his ultimate explanation of the rainbow.¹⁵ On October 2/11, 1606 Kepler wrote to Thomas Harriot (1560–1621), an Oxford mathematician and scientist, proposing problems in optics and mechanics. (Harriot is one of the earliest scientists to have visited America, for in 1584 he accompanied Sir Walter Raleigh on his expedition to survey and map the Virginia territory.) Kepler had heard of Harriot's work in chemistry and optics (as well as his criticism of astrology!) and hence he requests the latter's views on the *Paralipomena*. If Harriot will but tell him the cause of color in refraction and send him the measures of refraction in his experiments, Kepler believes that the explanation of the rainbow will be much expedited. Then follows a lengthy description of Kepler's views on the rainbow, views contrasting sharply with those of the previous year. The demonstration of the rainbow, he holds, depends not on the cloud as a whole but on the smallest elements of it—tiny drops of rain which are exactly round. Kepler finally had reached the point at which his predecessors had arrived three centuries before. Just how he came to this view is not made clear, but it appears likely that he had followed his own advice to Brengger to study refraction in a spherical globe of water—a step which later led Descartes to success. Inasmuch as rays near the center of the sphere are not colored, while those passing near the edge are brightly tinted, Kepler made the assumption that the solar rays which produce the rainbow are those which strike the drop along a line of tangency. If, for example, S is the sun and O_2 the eye of the observer (Fig. 2), he assumed

¹⁴ Kepler would have been greatly pleased to know that there is indeed about the sun a halo, not often seen, of radius about 46° .

¹⁵ *Opera*, 2, pp. 67–71; This is found also in Kepler's *Epistolae* (ed. by M. G. Hansch, Lipsiae, 1718), letters nos. 152, 223.

that the tangent ray SA would be refracted along the line AB , then reflected from the concave surface of the drop along BC , and finally at C leave the drop refracted along the tangent line CO_2 . Now Kepler assumed that the radius of the rainbow is 45° , and hence the arc AC must be 135° . Therefore $AB = 67\frac{1}{2}^\circ$ and $RAB = 33\frac{3}{4}^\circ$. Here one has a beautifully clear and simple explanation of the bow; but Kepler noted at least one fly in the ointment. The angle $33\frac{3}{4}^\circ$ is too small, for tables of refraction indicated that the angle should be at least 37° . (For such a refraction the radius of the bow, under Kepler's explanation, would be about 32° .)¹⁶ Kepler rather half-heartedly suggests that perhaps lukewarm rainwater, being less dense than our standing waters, may cause a lesser degree of refraction. He anticipates scepticism with respect to the tangency requirement for the solar rays and reiterates that only thus are colors formed.

The faith Kepler placed in his plausible explanation was confirmed by the fact that, with some modification, it served equally well for haloes. Not all of the ray AB is reflected at B , for a portion of it passes through the transparent surface, undergoing refraction along the tangent line. If the eye were at a point O_1 on this line (Fig. 2), it would see a halo of radius $67\frac{1}{2}^\circ$, whereas experience shows that the actual radius is only $22\frac{1}{2}^\circ$. To account for this one could assume that the angle SAB is $168\frac{3}{4}^\circ$, but then how much less dense would be the substance causing the halo than that which produces the rainbow! Even Kepler hesitated here; and so he devised an alternative explanation for the halo which is based upon the same refractive index as is that for the rainbow. A portion of the ray BC , which causes the bow

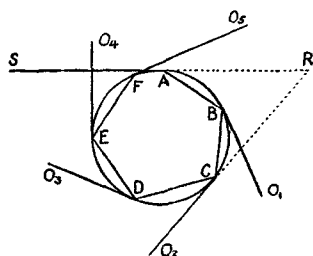


FIG. 2. Kepler's later explanation of the production of the rainbow by a combination of reflection and refraction from spherical droplets.

¹⁶ Montucla, reference 6, incorrectly says that the diameter of the bow would be only $14^\circ 24'$.

seen from O_2 , is again reflected internally along CD and leaves the drop, after undergoing another refraction, along DO_3 (Fig. 2). This would cause a halo or rainbow of radius $22\frac{1}{2}^\circ$ in opposition to the sun. The fact that this is never seen Kepler ascribes, rather inadequately, to the fact that it would be visible only when the sun is near the horizon—i.e., within $22\frac{1}{2}^\circ$. Now a portion of the ray CD will undergo a third internal reflection, followed by a refraction at E along EO_4 . This should cause a bow or halo of radius 90° , but this likewise is never seen. Finally, part of the ray DE is reflected a fourth time and leaves the drop at F , undergoing a refraction along FO_5 . This ray does indeed make, with the solar rays, the required angle of $22\frac{1}{2}^\circ$!

Kepler for several reasons hesitates to accept his beautiful pinwheel theory. In the first place, he thinks it incredible that the colored light, following so many reflections, would reach the eye in sufficient strength to cause an impression of color. Then, too, he found it difficult to reconcile the mobility of the falling drops with the constancy of the circular arch of the bow. Perhaps, he suggested, the bow is caused principally by dew. After all, there are, besides the common bow, also many kinds of extraordinary rainbows; and, after describing one of June 10/20 seen at Mogontia, Kepler closes with the challenge: "Thou, then, oh excellent priest of the mysteries of nature, tell the causes."

Harriot replied from London on December 2/11; but the reply must have been a disappointment to Kepler. The bulk of the letter is made up of a table of refractive indices of more than a dozen substances and an attempted explanation of the simultaneous reflection and refraction of rays by transparent media. Of the rainbow Harriot says only that when he writes on this he will give the proximate and immediate causes, for these are not correctly explained by the Peripatetics. He asks Kepler to be patient, adding: "I would say this of the rainbow just now, that the cause is to be demonstrated in a droplet through reflection on a concave surface and refraction on a convex. However, I have said nothing in consideration of the mysteries which are concealed."¹⁷

¹⁷ Kepler, *Opera*, 2, pp. 71–72. See also *Epistolae*, pp. 376–378.

Kepler answered from Prague on August 2/11, 1607 that he was filled with eagerness to see Harriot's works on colors and the rainbow. They are in apparent agreement that the arc is caused by the individual drops and that the colors are produced by reflexion on the concave surface and refraction on the convex; and so Kepler hopes to receive a more adequate reply to his first letter.¹⁸ It was almost a year before Harriot wrote again, on July 13/22, 1608. He pleaded lack of time for writing and philosophizing. He reported on some arguments for the existence of a vacuum which had been directed by William Gilbert (1544–1603) against the Peripatetics; but he said nothing further about the rainbow.¹⁹ Kepler in turn delayed over a year before sending a reply on September 1, 1609, in which he argued against the possibility of a void.²⁰ The correspondence between them appears to have been broken off here, and we have no further information on Harriot's theory of the rainbow. Kepler meanwhile had resumed correspondence with Fabricius on November 10, 1608, giving some of his latest thoughts on the rainbow. Contrary to his previous letter of some four years before, he cites it as certain that the cause is to be found in the individual drops, and that the halo likewise is caused by the very smallest dew drops. He adds that he can give a beautiful cause for the fact that only the arc, and not its interior, is colored. Here he clearly has in mind the explanation which he had sent to Harriot, for he says that colors arise only at places where the refraction is a maximum, i.e., where the angle at the drop between the incident ray and the visual ray is 135° .²¹ In a work defending astrology,²² published in 1610, Kepler again asserted that the colors of the rainbow are due to solar rays passing through round droplets of rain; but he did not explain his views further.

Most assuredly one would have expected Kepler to go into further detail in his second classic treatise on optics, the *Dioptrice* of 1611. Nevertheless, one finds here only the familiar statement

that the colors of the rainbow arise where refraction is great.²³ In the preface Kepler said that he had thought of adding a little book on the rainbow but that satisfactory causes of parhelia, which are also the causes of extraordinary rainbows, were to be desired, and these at present have failed to appear.²⁴ Kepler apparently never did write this projected book, even though he seems to have maintained confidence in his ultimate explanation. In correspondence with Jo. Remus in 1619 he declared that certain things concerning the rainbow and halo are clear. The radius of the primary bow is 45° , that of the secondary being 11° greater; and the radius of the halo is $22\frac{1}{2}^\circ$. The reason is to be sought in the maximum refraction in the round drops of water, for where the refraction is greatest, there do colors arise. The same explanation is given by Kepler in notes accompanying his translation from Greek into Latin of Plutarch's *De facie in orbe lunae*. Here he says that Aristotelians too readily conceded that the secondary bow is a mirror image, upon an outer cloud, of the primary bow which appears on an inner cloud; yet Kepler's failure to explain the secondary rainbow is a serious deficiency in his own work.

Kepler and Harriot were not the only men of their time to explain the rainbow in terms of refractions and reflections in individual drops. In 1611, the very year of Kepler's *Dioptrice*, there appeared two other treatises on vision, light, and the rainbow—the *Photismi de lumine*²⁵ by Francisco Maurolico (1494–1575), Abbot of Messina, and *De radiis visus et lucis in vitris perspectivis et iride tractatus*, by Marco Antonio de Dominis (1566–1624), Archbishop of Spalatro. The former work includes three books on refraction, of which the second, devoted to the rainbow, was completed in 1553. It explains the rainbow in terms of internal reflections, forming within the drops octagonal star polygons, without recourse to refraction. The work of De Dominis, composed also a score of years or so before its publication, includes a short section on the best known pre-

¹⁸ *Opera*, 2, pp. 72–73; *Epistolae*, pp. 378–379.

¹⁹ Kepler, *Opera*, 2, pp. 73–74; *Epistolae*, pp. 379–380.

²⁰ *Opera*, 2, pp. 75–76; *Epistolae*, pp. 380–382.

²¹ *Opera*, 2, p. 100. See also Brocard, reference 6, pp. 379–380.

²² *Tertius interveniens. Das ist, Warnung an elliche Theologos, Medicos und Philosophos Dass sie nicht das Kindt mit dem Badt ausschütten* (Frankfurt a. M., 1610). In *Opera* 1, pp. 547–651. See especially p. 570.

²³ *Dioptrice*, 1, 26; *Opera* 2, p. 530.

²⁴ *Opera*, 2, pp. 524, 574.

²⁵ A portion of this work had appeared earlier at Venice in 1575, but this edition is rare. An English translation from the 1611 edition, made by Henry Crew, was published at New York in 1940.

Cartesian explanation of the rainbow.²⁶ So closely does the theory of De Dominis resemble, qualitatively, the account in the *Les météores* of 1637 that Leibniz and Newton, apparently quite unfairly, virtually accused Descartes of plagiarism. However, the explanation which De Dominis gave of the primary bow is incomplete, since he overlooked the fact that the rays must be refracted on emerging from the raindrops, as well as upon entering; and his account of the secondary bow is entirely mistaken.²⁷ Moreover, De Dominis did not account quantitatively for the size of the bows; and hence it is not clear why his explanation should be preferred to that of Kepler.²⁸ After all, as Maurolico said, nearly the whole of the demonstration depends upon the apparent size of the bow.²⁹ To Kepler one owes the clear recognition that "to measure is to know;" and to him physics appears to be indebted for the earliest *quantitative* theory of the rainbow based upon refraction in raindrops. Had he but measured more accurately, he might have anticipated the theory that Descartes gave half a dozen years after Kepler's death.

Snell, in a work on the comet of 1618, referred to haloes and rainbows as caused by reflection and refraction, promising that on another occasion he would comment more fully on this idea; but his commentary, if written, is not extant. One wonders if it might not have served as a connecting link between De Dominis, with whose work Snell apparently was familiar, and Descartes. Kepler, however, seems not to have been aware of the works of Maurolico and De Dominis, for he never referred to their theories of

the rainbow. There appears to be but a slim chance that Descartes was directly indebted to Kepler, for the explanation sent to Harriot in 1606 was not published until 1718.³⁰ However, it is not unlikely that the efforts of Kepler were known to scholars in Germany. Years later, in 1653, G. A. Kinner von Löwenturn, tutor in the household of the emperor Leopold I, wrote to Huygens from Prague that the explanation of Descartes did not satisfy him.³¹ He referred instead to works on the rainbow written by two Jesuits, Balthasar Conrad (1599–1660) and Johannes Marcus Marci (1595–1667). These men had spent many years in Prague, where Kepler had lived while he was studying the rainbow, and Kepler's relations with the Jesuits had been very friendly. Kinner says that many years before, in connection with a demonstration which Conrad had proposed and Marci had attacked,³² the question had arisen as to whether rays which strike the spherical drops tangentially are refracted in the same manner as those which travel along secant lines.³³ It would appear from this query that the theory of Kepler did indeed live on—in spirit if not in fact—for half a century or more; and it is not impossible that its influence was felt indirectly by Descartes. One thing at least is certain, and that is that the Cartesian explanation was not an exception to the rule that scientific theories do not come as unanticipated bolts from the blue.

²⁶ See Kepler's *Epistolae*, reference 15. Leibniz, however, called attention to a remark by Huygens that the basis of what Descartes had given on the rainbow "has been taken from a place of the incomparable Kepler." See Leibniz, *Opera omnia*, vol. V (Genevae, 1768), p. 547.

³¹ See Christiaan Huygens, *Oeuvres complètes* (19 vols, La Haye, 1888–1937), I, p. 239.

³² Conrad wrote *Propositiones physico-mathematicae de flamma iride* (Olomutii, 1634); Marci published two works on the rainbow, *Thaumantias, sive liber de arcu caelesti deque colorum apparentium natura, ortu et causis* (Pragae, 1648), and *Dissertatio physica curiosa in propositiones mathematicas de natura iridis* (Pragae, 1650). I have seen only Marci's *Thaumantias*.

³³ Huygens replied that tangential rays are indeed refracted as are other rays, but he expressed confidence in the Cartesian theory nevertheless.

²⁶ The work was revised by the author before publication, and an account of the telescope, invented shortly before, was added.

²⁷ For a critical summary of this work see R. E. Ockenden, "Marco Antonio de Dominis and his explanation of the rainbow," *Isis* 26, 40–49 (1936).

²⁸ Certainly it is misleading to say [as does H. E. White, *Modern college physics* (New York, 1948), p. 401] that "The elementary theory of the rainbow was first given by Antonius de Demini [sic] in the year 1611 and later developed more exactly by Descartes."

²⁹ See *Photismi de lumine* (Crew translation), p. 103.

But for the scientist it is not only honorable to doubt, it is mandatory to do that when there appears to be evidence in support of the doubt.—ROBERT OPPENHEIMER, "Encouragement of Science," *Science* 111, 373–375 (1950).