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A short history of the rainbow

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Abstract The history of the rainbow is as old as that of science. The ancient Greek philosophers tried to describe the rainbow, and Aristotle was the first to fully include it among the phenomena studied by physicists. Sunlight reflected in the clouds, the incidence of light rays, the reason for the rainbow's circular shape, the optical effect of an infinite depth are aspects that have for centuries intrigued scholars, who studied the rainbow with a mixture science and alchemy, sense and sensibility. In the 17th century the rainbow became a strictly physical phenomenon, the object of rigorous investigations according to the law of reflection and refraction. Here we survey this often forgotten history, from ancient Greeks to modern scientists, the rainbow's colours belonging to the world of physics but also—as Thomas Young wrote in 1803—to the world of speculation and imagination.

Keywords Optics · Theory of colours · Rainbow

> "Hic ubi sol radiis tempestatem inter opacam
> adversa fulsit nimborum aspargine contra
> tum color in nigris existit nubibus arqui".
> (Lucretius, *De rerum natura*, VI, 524–526).

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1 Introduction

The history of the rainbow is as old as the history of science itself. As long ago as in the 3rd-2nd centuries BCE, Alexander of Aphrodisias tried to describe the rainbow as a phenomenon involving light and colour; he is regarded as the discoverer of the darker region between the primary and the secondary rainbows (Fig. 1).

However, Aristotle (384/383-322 BCE) was the first one to give a complete description of the optical phenomenon, in Book III of his *Meteorology* (here given in the translation by E.W. Webster):

> The rainbow never forms a full circle, nor any segment greater than a semicircle. At sunset and sunrise the circle is smallest and the segment largest: as the sun rises higher the circle is larger and the segment smaller. After the autumn equinox in the shorter days it is seen at every hour of the day, in the summer not about midday. There are never more than two rainbows at one time. Each of them is three-coloured; the colours are the same in both and their number is the same, but in the outer rainbow they are fainter and their position is reversed. In the inner rainbow the first and largest band is red; in the outer rainbow the band that is nearest to this one and smallest is of the same colour: the other bands correspond on the same principle. These are almost the only colours which painters cannot manufacture: for there are colours which they create by mixing, but no mixing will give red, green, or purple. These are the colours of the rainbow, though between the red and the green an orange colour is often seen.

Fig. 1 Primary and secondary rainbows with, between them, "Alexander's dark band" (a reference to Alexander of Aphrodisias): The Aegean Sea (c. 1877) by Frederic Edwin Church (1826–1900), Metropolitan Museum of Art (public domain image)

At that point the rainbow fully became one of the phenomena investigated by physicists. However, according to Lee and Fraser [31]:

> Despite its many flaws and its appeal to Pythagorean numerology, Aristotle's qualitative explanation showed an inventiveness and relative consistency that was unmatched for centuries. After Aristotle's death, much rainbow theory consisted of reaction to his work, although not all of this was uncritical.

In Aristotle's description, the colours of the rainbow are just three; this interpretation was accepted for a long time, with subtle numerological differences associating the three colours to the Trinity or, in other cases, four colours to the four elements of Empedocles' tradition. The way sunlight gets reflected among the clouds, the analysis of the angle of incidence of light rays, an explanation of the circular shape of the rainbow, the optical effect of an infinite depth with respect to the origin of the phenomenon are all questions that for centuries excited the curiosity of scholars working in various fields.

In his *Naturales Quaestiones* (ca. 65 CE), Lucius Annaeus Seneca (ca. 4 BCE-65 CE), devotes some chapters of Book I to explaining this phenomenon. He suggests that the rainbow, which always appears opposite the sun, is created by the reflection of sunrays on water droplets, as well as by their reflection in a hollow cloud. He describes how it is possible to observe a rainbow when a light ray passes through a glass cylinder, thus anticipating the experiments by Isaac Newton (1642–1727) with the optical prism.

Roger Bacon (1214–1294), Theodoric of Freiberg (Meister Dietrich, Theodoricus Teutonicus de Vriberg, ca. 1250–ca. 1310),[1] and René Descartes (1596–1650)—to mention just a few—investigated the phenomenon in a speculative way, mixing science and alchemy, sense and sensibility: the rainbow's colours arrive to the eye by way of effects that are physical and sensory, interpretative and experiential. We owe to Willebrord Snell (Willebrordus Snellius, 1580–1626) the insight of 1621 that the rainbow is a strictly physical phenomenon and, as such, has to be studied rigorously, according to the physico-mathematical laws of reflection and refraction. Later, in 1666, Newton understood that the refractive index depends on the wavelength: hence, each sunray generates its own rainbow.

In this short note, we intend to retrace an often forgotten history which, from the first insights by the Greek philosophers to modern science, has characterised research in a field of physics where the rainbow's colours belong both to the natural world—in 1803 Thomas Young (1773–1829) gave through a simple experiment, midway between investigation and speculation, "so simple and so demonstrative a proof of the general law of the interference of two portions of light" [47], that two light rays from a single source passing through two slits may interfere with each other and produce on a screen alternate light and dark stripes—and hence the theoretical world, and to the world of imagination.[2]

2 The beginnings of our history

The first scientific—in the modern meaning of the word—studies date back to the Arabic Middle Ages: the Persian astronomer and mathematician Qutb Al-Dīn al-Shirāzī (1236–1311) and his pupil al-Fārisī, also known

[1] In his treatise *De iride et de radialibus impressionibus*, Theodoric provided a first scientific explanation, still considered phenomenologically valid, of the rainbow, a phenomenon that had already attracted the interest of such scholars as Robert Grosseteste (ca. 1175–1253), Roger Bacon and Witelo (Erazmus Ciolek Witelo, also known as Vitellio, (ca. 1230-post 1280/ante 1314). The German Dominican gave an interpretation of the rainbow as a result of refraction of light in its spectrum of colours, even though he was not actually a scientist, nor in particular an experimentalist, and as a consequence he did not master the experimental method; nevertheless, he showed an attitude to research with a properly scientific object. So the German scholar is a natural interpreter of studies "in the tradition of Albertus Magnus" [see Elisa Chiti, article "Teodorico di Freiberg" in online *Manuale di Filosofia Medievale* published by the University of Siena, Faculty of Letters and Philosophy]. As regards Theodoric's work, see his *Opera Omnia* [44]; it includes the writings *De coloribus*, *De elementis corporum naturalium*, *De iride et de radialibus impressionibus*, *De luce et eius origine*, *De miscibilibus in mixto*, *De tempore*. See also Venturi [45], part III: "Dell'Iride", pp. 149–246 and Krebs [30].

[2] See, in this regard, Corradi [14].

a

b

Fig. 2 **a** *Above* Title page of Opticae Thesaurus (Basileae, Friedrich Risner, 1572), which includes Alhazen's treatise on optics (Kitāb al-Manāzir), where rainbows, parabolic mirrors, images bent by refraction of light in water and other optical effects are featured. **b** *Below* The refraction of light through a spherical bowl full of water, from Roger Bacon or possibly Robert Grosseteste: Opus Majus [British Library, manuscript: Royal 7 F. VIII, Page Folio Number: f.25. Crombie [16] describes the image as follows: "Diagram illustrating Grosseteste's theory, in De natura locorum (see pp. 122, 149) of the focusing of the sun's rays by a spherical lens; from Roger Bacon's Opus Maius, iv. ii. 2, MS Roy. 7. F. viii, f. 25v"]

as Kamāl al-Dīn (1260–1320),[3] tried to give a first mathematical explanation of the rainbow, which was quite accurate for its age, since it was based on the phenomenon of refraction as described in the *Book of Optics* by Alhazen (965–1039), a Persian mathematician born in Basra, and on the studies by Avicenna (980–1037) (Fig. 2a). Alhazen suggested that, in order to be able to form a rainbow, sunlight had to be reflected by clouds before reaching human eyes. Thus the water drops composing the clouds reflect the light ray and create the rainbow's colours through a refraction and two or more reflections, like an image forming in a reflecting, smooth, concave, spherical mirror consisting of dense, wet air.[4] It is undoubtedly difficult to verify this experimentally, but, according to the Persian scholar, it could be done by studying the phenomenon of refraction of a light ray through a transparent glass sphere full of water, a large-scale experimental model of a raindrop. In order to evaluate the colour spectrum, it is necessary to study the model in a dark room having a controlled opening to let a sunray in. Both Alhazen and the polymath Avicenna further imagined that the rainbow forms, not in the dark cloud itself, but in the narrow layer of fog between the cloud, the sun and the observer. The cloud acts as a background to this subtle substance, just like the lining of quicksilver applied to the back of a mirror.[5] Several trials with accurate observations about reflection and refraction allowed al-Fārisī to establish that the rainbow's colours result from a decomposition of light, as he reported in his treatise on optics (*Kitāb Tanqīh al-Manāzir*, ca. 1319). How exactly colours are formed is much harder to explain; al-Fārisī imagines that they are generated by a superposition of different versions of an image on a dark background, mixed by light. In this he relays a theory stated by his mentor al-Shirāzī.[6]

In Chinese science, at the time of Song dynasty (960–1279), a versatile scholar named Shen Kuo (1031–1095) suggested, like Sun Sikong (1015–1076) before him, that a rainbow was formed by sunrays meeting rain droplets suspended in the air,[7] according to the principles underlying the modern scientific explanation.

In Europe, Albertus Magnus (1206–1280), in Chapter XXVIII of his *Libri quattuor meteororum* (Cologne, 1250),[8] attributed to single raindrops, rather than to the whole cloud, the formation of the rainbow, which happened not just by virtue of a simple reflection on a convex surface, but by refraction too. So, in order to explain the phenomenon, he introduced "reflection" and "refraction" of light on drops, even though only reflection on the inner surface of drops was supposed to create the coloured arc.[9] At the same time, the English philosopher Roger Bacon (also remembered as the *Doctor mirabilis*), expanding on the studies on light by Robert Grosseteste (ca. 1175–1253)—the founder of the tradition of scientific thinking in medieval Oxford, according to Alistair Cameron Crombie (1915–1996)—devoted himself to the study of this phenomenon. Using an astrolabe, he attempted to measure the angle formed between the incident sunlight and the light diffused by the primary and secondar

[3] Kamāl al-Dīn Hasan ibn Ali ibn Hasan al-Fārisī, or Abu Hasan Muhammad ibn Hasan, a mathematician born in Tabriz (Iran), gave important contributions to number theory and to the mathematical theory of light, with interesting insights about colours and rainbows (see Roshdi Rashed, s.v. al-Fārisī, in [48]).

[4] See Gazi Topdemir [23].

[5] See Boyer [7].

[6] See Boyer [8], pp. 127–129.

[7] See Sivin [43], p. 24.

[8] See Albertus Magnus [2], *Meteora*, Liber III, Meteororum, Trac. IV, Caput X "De causa efficiente et materiali colorum iridis in communi", pp. 678–679.

[9] See Hackett [27].

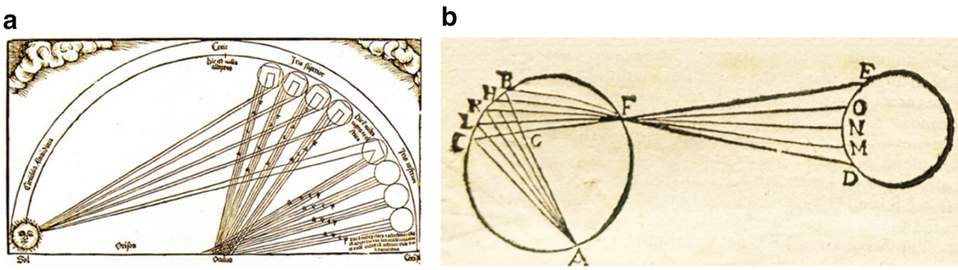

Fig. 3 **a** *Left* A representation of the secondary rainbow, according to Theodoric of Freiberg. **b** *right* The phenomenon of multiple reflections according to Maurolico (Photismi, Theorema XXIX, p. 54, Neapoli: Tarquinij Longi, 1611)

arcs of a rainbow, obtaining values in the range 130°–138°. The colours are light embedded within matter, stimulated by an external light (from the sun); the more the matter is stimulated, the brighter the light shines. In his experiments he analysed the passage of light rays through crystals and water droplets (*Opus Majus*, Part V: *Optics* and Part VI: *Experimental Science*, 1628)[10] (Fig. 2b). Let us remark that the treatise about optics by ibn al-Haytham had been translated into Latin by Robert Grosseteste and almost surely Roger Bacon knew it.

At the beginning of the 14th century, Theodoric of Freiberg, a Dominican, suggested that the rainbow phenomenon is due to sunlight being reflected through water drops suspended in mid-air. He performed some experiments by using spherical bowls filled with water and gave an accurate description of both the primary and the secondary rainbows (Fig. 3a). According to the Saxon scholar, the primary rainbow forms.

> When sunlight falls on individual drops of moisture [and] the rays undergo two refractions (upon ingress and egress) and one reflection (at the back side of the drop) before transmission to the eye of the observer ([32]),

while the secondary rainbow is a phenomenon that, analogously, implies two refractions and two reflections. In Theodoric's opinion, the colours are a mixture of two qualities: brightness and darkness. The same ideas recur in the 1571 treatise by Johann Fleischer (1539–1593) on Aristotle's theory of rainbows [21].

Gregor Reisch (ca. 1467–1523), in his *Margarita philosophica* (Freiburg im Breisgau: Johannes Schott, 1503) claimed that a primary rainbow appears when light reflects on a concave surface, and that the way it looks depends on the multitude of drops. Girolamo Cardano (1501–1576) elaborated on the theories by Albertus Magnus, Roger Bacon, and Witelo. Francesco Maurolico (1494–1575), in his *Photismi de lumine et umbra* [37], probably one of the best works about optics in the 16th century,[11] claimed that light reflects both on the convex external and on the concave internal surfaces of the water drop, and that the rainbow was formed through a large number of reflections (Fig. 3b). Giambattista Della Porta (1535–1615), in his *De refractione optices* (Neapoli: Iacobum Carlino, 1593), imagined the two arcs as generated by refractions through different clouds.

Dalmatian scholar Marco Antonio de Dominis (1560–1624) published in 1611 the first work tackling rainbows from a physico-geometrical viewpoint. His book, titled *Tractatus de radiis visus et lucis in vitris, perspectivis et iride* [17], provided a very convincing explanation of rainbows. He showed that sunrays crossing a glass sphere full of water formed a rainbow on his laboratory's walls. By observing the light rays' path, he observed that they were reflected by the bottom of the sphere, which behaved as a concave mirror, and on exiting it they underwent a new refraction. His treatise followed a series of studies performed through experiments similar to Theodoric of Freiberg's; his studies demonstrate a profound knowledge of the literature on the subject.

In 1604, Johannes Kepler (1571–1630) followed up on the studies by Polish monk, mathematician, physicist, philosopher and theologian Witelo, but he was unable to establish the law of refraction.[12]

Later, Sicilian astronomer Giovan Battista Hodierna (1597–1660) studied the phenomenon of light passing through a prism, anticipating Newton's research, as his *Thaumantiae miraculum* (Palermo: Nicolai Bua, 1652), shows. He also gave a vague explanation for rainbows. Moreover, he introduced a distinction between "strong" and "weak" colours, separated by white. In his text, the

[10] See vol. II, pp. 172–201 of Bridges [12]. Moreover, it is necessary to remark that, at the end of 13th century, the Polish philosopher and physicist Witelo, building on Alhazen's hypoteses, had claimed that the bending of light by refraction was larger the denser the medium through which light had passed. Witelo's essay, *Vitellonis Thuringopoloni opticæ libri decem*, is contained in *Opticæ Thesaurus* by Friedrich Risner (1533-1580), published in Basel in 1572. See also El-Bizri [20].

[11] The writings appearing in this treatise were composed between 1521 and 1552.

[12] See Gedselman [24].

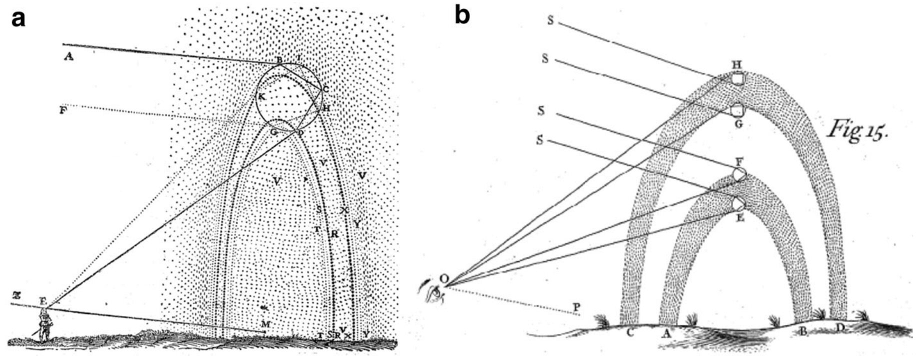

Fig. 4 **a** *Left* René Descartes, Discours de la méthode…, p. 251. **b** *Right* Newton's rainbow (illustration from Isaac Newton's treatise Opticks, London: S. Smith and B. Walford, 1704)

geometrical, quantitative study of light phenomena has its roots in what we could call a metaphysics of light, thus justifying the primacy of optics over other sciences, on the basis of the ontological primacy of light.

The beginning of the Eighth Discourse of *Les Météores*, in which Descartes covers rainbows (Fig. 4a), marks a paradigm shift in the investigations of the rainbow's physical phenomenon. Descartes begins his discourse with this claim:

> L'Arc-en-ciel est une merveille de la nature si remarquable, & sa cause a esté de tout tems si curieusement recherchée par les bons esprits, & si peu connuë, que i.e. ne sçaurois choisir de matiere plus propre a faire voir comment par la methode dont i.e. me sers on peut venir a des connoissances, que ceux dont nous avons le escrits n'ont point euës ([18], p.250).
> (The rainbow is such a remarkable phenomenon of nature, and its cause has always been so carefully sought after by good minds, yet so little understood, that I could not choose anything better to show you how, by means of the method I am using, we can arrive at knowledge not possessed by any of those whose writings we have [19]).

Descartes tackled the problem on a strictly scientific and mathematical basis, starting from the laws of refraction that now bear his name. He gave an interesting proof of the reason why the rainbow has a semicircular shape using the recent instruments provided by calculus, which was being developed in those years. His goal was to improve the scientific explanation of the phenomenon through the use of mathematical tools and experimental evidence.

Descartes studied the passage of a light ray through a large glass sphere filled with water. By measuring the angles of the rays getting out, he concluded that the primary arc was created by a single reflection inside the drop, while the secondary one may be caused by two inner reflections. To reach this result, Descartes expounded the theory of refraction—just as Snell[13] had done—and correctly computed the angles of incidence of light rays for both arcs. He established that the ratio of the sines of the incidence and the refraction angles was constant, for all incidence angles. The light rays from the Sun, assumed to be point-like, arrive along parallel directions at different points of the water drop and intercept it with different incidence angles. Those undergoing a single reflection form the primary arc, while the secondary one, outward with respect to the primary, consists of a double reflection within the drop. However, not all incident rays are equally effective, that is, visible to the observer: only those with an angle of incidence close to 59° for the primary arc and to 71° for the secondary one are visible to the human eye.

On the other hand, Descartes's explanation on how colours form is not quite convincing, since it was based on a mechanistic version of the traditional theory in which colours are generated by a modification of white light. In his 1637 treatise about *Les Météores* (Fig. 4a), he gave an explanation of the physical phenomenon quite close to that given by de Dominis, but without mentioning him, perhaps not to be guilty of disobedience of the *damnatio memoriae* pronounced by the Catholic Church towards the heretical ex-archbishop.

Descartes's reasoning about the rainbow is of a geometric nature, ridding the phenomenon of poetic or mystical overtones—a reproach that John Keats (1795–1821)

[13] Snell's law, also known as Snell-Descartes law, describes how a light ray is refracted when passing from a medium to another one with a different refractive index; in general, it is valid only for isotropic substances, such as glass, and shows several similarities to Fermat's principle (due to Pierre de Fermat, 1601–1665) that "the path taken between two points by a ray of light is the path that can be traversed in the least time". A first formulation of Snell-Descartes law can be found in a manuscript by the Arab mathematician Abū Sa'd al-'Alā' ibn Sahl (X sec.) written in 984; it was later probably guessed in 1602 by Thomas Harriot (1560–1621), an astronomer and a mathematician, who did not publish his work, though. It was rediscovered by Willebrord Snell in 1621, in a form mathematically equivalent, unpublished until his death, and, phinally, republished by Descartes in terms of sine functions in his 1637 *Discours de la méthode*…, where he used it to solve several problems in optics.

would aim at Newton in his poem of 1820, *Lamia*—and permits men to reason both as poets and as physicists, but certainly no longer as theologians, abandoning a mystic vision that, like Genesis 9:14 which describes the rainbow as a sign of God's promise to man never to unleash another flood, transcends a supernatural significance into a natural physical one.

Isaac Newton covered the topic in his *Opticks* [39] (Fig. 4b), duly crediting de Dominis with being the first to autonomously explain the phenomenon. However, Newton was the first to give a scientific proof of the composition of light spectrum, by claiming that white light consists of all the colours of the rainbow. According to the English scientist, colours could be separated into their spectrum by allowing a light ray to pass through a glass prism. Newton clearly showed that the iridescent figures generated by prisms are caused by the decomposition of light into its chromatic components, in opposition to the general idea that colours were generated "within" the prism, which would be endowed with this peculiar property, just as water droplets were responsible for rainbows.

He also showed that red light is refracted less than blue, thus providing the first scientific explanation of the main features of the rainbow. However, the corpuscular theory of light as formulated by Newton failed to explain the phenomenon of the "supernumerary" rainbow or arc; indeed, such an explanation would only come with the studies by Edme Mariotte (1620–1684), who first described the "supernumerary arcs" (1679) [35], and especially Thomas Young, who managed to show how, in certain conditions, light behaves as a wave and can interfere with itself.

In the decades following the publication of Newton's *Opticks*, the observation of the first phenomena of interference and diffraction, and the consequent studies on light, led to discovering the wave theory of light. A crucial role was played by the experiment performed by Young [46] in 1801 on the superposition of light rays emitted by two point-like sources, which allowed him to be the first to measure the wavelengths of different light colours[14] (Fig. 5). However, the wave-like behaviour of light was completely accepted only some years later, when the French physicist Augustin-Jean Fresnel (1788–1827), managed, through studying polarisation, to interpret the results of Young's experiment by assuming, as already suggested by Young himself in 1816, transverse rather than longitudinal elastic waves.[15] The Newtonian approach was also abandoned due to the experiments aiming to determine the speed of light performed by Armand Hippolyte Louis Fizeau (1819–1896) and Jean Bernard Léon Foucault (1819–1868) in 1850, which showed how speed decreases when the density of the medium increases, contrary to Newton's predictions.

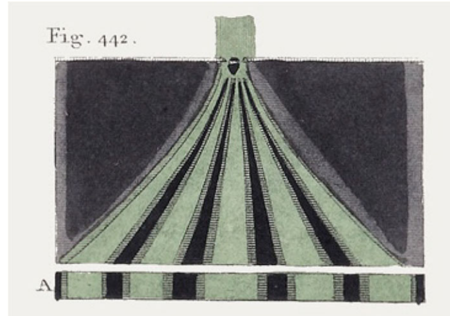

Fig. 5 Fig. 442 from Table XXX of Lectures by Thomas Young (Vol. 1, 1807), which comprise the set of works presented to Royal Society of London in 1802. The *image* shows the two-slit experiment underlying the wave theory of light. A single ray of monochromatic light passes through two tiny holes and consequently form *light and dark alternate fringes*. T. Young, A Course of Lectures on Natural Philosophy and the Mechanical Arts, 2 vols. London: Joseph Johnson, 1807

Young's work was later developed and improved in the 1830s by the English astronomer George Biddell Airy (1801–1892) [5], who worked on the wave theory by Christiaan Huygens (1629–1695) and Augustin-Jean Fresnel, while the phenomenon's mathematical treatment was partly carried out by the chemist Richard Potter (1799–1886) in 1835, and published in 1838 in the proceedings of the *Cambridge Philosophical Society* [42]. Potter explained how the intensity of the rainbow's colours also depended on the size of the water drops. The meeting of several light rays within a drop forms a curve called a "caustic", which is simply the envelope of a system of rays corresponding to a maximum value of light.

Modern physical descriptions are based on the complete and mathematically rigorous solution of the problem of the optical scattering of an electromagnetic wave on a sphere or a cylinder. This phenomenon is called 'Mie scattering' and follows from the studies published by the German physicist Gustav Mie (1869–1957) and by Peter J.W. Debye (1884–1966) in 1908. It is based on the equation for electromagnetic waves formulated by the Scottish mathematician and physicist James Clerk Maxwell (1831–1879), who gave a precise mathematical description of the optical aspects of the rainbow. The uninterrupted progress in both theory and scientific computation throughout the 20th century have led to an ever more complete understanding of the phenomenon, taking into account the wave-like properties involving interference, diffraction and polarisation, as well as the particle-like ones related to the momentum carried by a light ray; in this regard an interesting contemporary interpretation is due to the Brasilian physicist Herch Moysés Nussenzveig (1933-) [41] and, in

[14] See Brand [10], pp. 30–32.

[15] See Crew [15] and Kipnis [29].

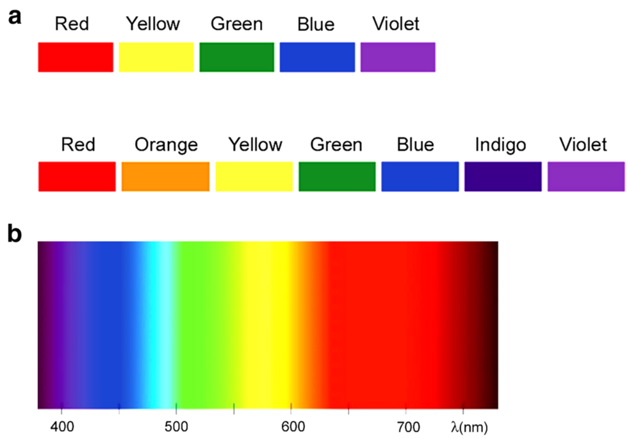

Fig. 6 **a** *Above* The colours of the rainbow according to Newton: first and second hypothesis. **b** *Below*: the spectrum of colours; the image shows an approximate representation of the colour associated to each wavelength in the visible region. Under 400 nm (nm) and over 750 nm, colours fade to *black*, because the human eye is not able to detect light out of this boundaries

computational terms, to Vijay Khare [28], who in 1975 obtained results similar to Mie's.

3 The colours of the rainbow

The spectrum of the colours of the rainbow is continuous and consists of a set of approximate ranges for each colour[16]; this is due to the structure of the human eye and to the way the brain processes the data about the coloured image from the photoreceptors, which differ from one person to the next. What one actually gets by using a glass prism and a point-like light source is a continuous spectrum of wavelengths with no separate bands and hence no precise distinction of single colours. Isaac Newton, in his treatise on optics, discerns just five primary colours: red, yellow, green, blue and violet; only after more precise investigations he added orange and indigo (Fig. 6a), thus creating a seven-colour scale by analogy with the notes of the musical scale,[17] based on the suggestions of Greek sophists, who saw a relation between colours and musical notes (Fig. 7).

Nevertheless, Newton himself admitted to a difficulty in recognising the colours forming the rainbow: "My own eyes are not very critical in distinguishing colours".[18]

[16] See Berlin-Kay [4].

[17] "Ex quo clarissime apparet, lumina variorum colorum varia esset refrangibilitate: idque eo ordine, ut color ruber omnium minime refrangibilis sit, reliqui autem colores, aureus, flavus, viridis, cæruleus, indicus, violaceus, gradatim and ex ordine magis magisque refrangibiles", Newton [40], Propositio II, Experimentum VII.

[18] See Gage [22], p. 140.

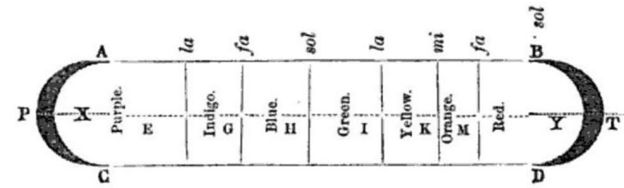

Fig. 7 The description of the spectrum of colours, correlated, according to Newton, to the musical scale, as given by David Brewster (1781–1868) in his *Memoirs of the Life, Writings and Discoveries of Sir Isaac Newton*, Edinburgh: Thomas Constable, 1855

Between the end of the 18th and the beginning of the 19th century, the structure of the visible spectrum was completely revealed. Later studies also clarified the phenomena of the light outside the visible range: infrared was discovered and analysed by William Herschel (1738–1822), ultraviolet by Johann Wilhelm Ritter (1776–1810) and Thomas Johann Seebeck (1770–1831). Seebeck also described how light acts on silver chloride, an important step towards colour photography.

Finally, research has concluded that indigo is not one of the colours of the rainbow, but just a variation of wavelength in the transition from blue to violet. According to Isaac Asimov (1920–1992):

> It is customary to list indigo as a color lying between blue and violet, but it has never seemed to me that indigo is worth the dignity of being considered a separate color. To my eyes it seems merely deep blue [3].

Indeed, defining the colours of the rainbow is different from defining the spectrum itself, since the colours of the rainbow are less saturated; for each particular wavelength, there is a range of exit angles, rather than a single, invariant angle, and the number of colour bands in a rainbow can be different from the number in a spectrum, especially if the suspended droplets are significantly large or small. Hence, the number of colours in a rainbow is variable. If, on the other hand, the word "rainbow" is inaccurately used to denote the spectrum of colours, then the colours of the rainbow do correspond to the main colours of the spectrum.

The light of a rainbow is almost completely polarised. This phenomenon is due to the angle of refraction in the drop being very close to Brewster's angle, discovered by the Scottish physicist David Brewster (1781–1868) in 1815.[19] Hence, most of the *p*-polarised light disappears during the first reflection (and refraction) within the drop.

The circular shape of the rainbow is strictly related to a problem of minima: the angle at which the sunlight reflected by the water drops has a maximum of intensity is

[19] "When a ray of light is polarised by reflexion, the reflected ray forms a right angle with the refracted ray", Brewster [11], p. 132.

about 40°–42° with respect to the observer; this angle is independent of the size of each suspended droplet, but depends instead on their refractive index (a dimensionless quantity that measures how much the speed of propagation of electromagnetic radiation decreases while crossing matter).

4 Conclusions

Drawing some conclusions from this short history of the rainbow is not at all easy. There is a large bibliography[20] regarding this phenomenon, from scientific, historic, artistic viewpoints and more. The history of the rainbow certainly belongs to the history of science, and in particular to that of physics and optics, for which it is an important, epistemologically wide-ranging subject. However, when studying this optical phenomenon, a scientific approach has not always been favourably received. In literary or artistic fields, after the scientific revolution of Enlightenment, continuous attempts have been made to assign to this physical phenomenon one or another meaning from subjects such as philosophy, religion, mysticism, esotericism or art. There have been, indeed, scholars, writers and artists claiming that a physico-mathematical analysis of natural phenomena lessens their allure. This is why we wish to close this essay with some brief, more literary musings.

If, as Virginia Woolf (1882–1941) points out in her novel *To the Lighthouse*, published in 1927, the rainbow represents the transience of life and man's mortality—"it was all ephemeral as a rainbow"—the cold physico-mathematical representation of an optical phenomenon that is "ephemeral" and evanescent, unreachable and insubstantial, deprives the natural event of all the poetry of an event that strikes human imagination and fancy, opens the soul to hope and life and moves George Gordon Byron (1788–1824) to write ([13], p. 45):

> Or since that hope denied in worlds of strife,
> Be thou the rainbow to the storms of life!
> The evening beam that smiles the clouds away,
> And tints to-morrow with prophetic ray!

Johann Wolfgang von Goethe (1749–1832), in his essay about the theory of colours [25] wrote that the scientific analysis performed by Newton would have "paralysed the heart of nature"[21]: *Einen Regenbogen, der eine Viertelstunde steht, sieht man nicht mehr an* (A rainbow that lasts a quarter of an hour is seen no more).[22] The same opinion was shared by Charles Lamb (1775–1834) and, as we already recalled, John Keats. In the two poets' opinion, Newton "had destroyed all the poetry of the rainbow, by reducing it to the prismatic colours" and, while dining in 1817, they offered a toast to "Newton's health, and confusion to mathematics!".[23]

Translated from the Italian by Daniele A. Gewurz.

[20] See for instance Venturi [45], Mascart [36], Minnaert-Lynch-Livingston [38], Nussenzveig [41], Greenler [26], Boyer [9], Blay [6], Lynch-Livingston [33], Lee-Fraser [31], Maitte [34].

[21] For further reading about the controversy Goethe-Newton about colours, see [14].

[22] From Goethe's *Maximen und Reflexionen*.

[23] For the last two quotations, see [1], p.86.

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