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Science and Society: The Case of Acceptance of Newtonian Optics in the Eighteenth Century

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Abstract The present paper presents a historical study on the acceptance of Newton's corpuscular theory of light in the early eighteenth century. Isaac Newton first published his famous book *Opticks* in 1704. After its publication, it became quite popular and was an almost mandatory presence in cultural life of Enlightenment societies. However, Newton's optics did not become popular only via his own words and hands, but also via public lectures and short books with scientific contents devoted to general public (including women) that emerged in the period as a sort of entertainment business. Lectures and writers stressed the inductivist approach to the study of nature and presented Newton's ideas about optics as they were consensual among natural philosophers in the period. The historical case study presented in this paper illustrates relevant aspects of nature of science, which can be explored by students of physics on undergraduate level or in physics teacher training programs.

1 Introduction

There is a widespread agreement about the relevance of history, philosophy and sociology of science (HPSS) in science teachers training programs. Studying the history of conceptual development and the process of acceptance of scientific ideas by the scientific community may help teachers to incorporate valuable concepts about the nature of science. In order to choose a specific historical episode, it is necessary to consider some of its potentials for discussing nature of science allied to scientific content (Klassen 2007; Metz et al. 2007). In addition, the episode must also cover elements which make it attractive for the audience such as human and dramatic ones.

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The historical episode explored in this paper includes the discussion of some aspects of Newton's optics and its reception in the first decades of the eighteenth century.[1] One reason for choosing this episode is that it involves a very important historical character, Isaac Newton. Regarding scientific contributions, modern popular narratives about Newtonian optics are usually restricted to superficial (and even wrong) introductions to Newton's theory of colours including the idea that white light is a mixture of rays of different colours (Martins and Silva 2001). The selected historical period is quite rich, because science went through major transformations such as institutionalization, separation of academic disciplines and professionalization of scientific practices in general.

Regarding Newton's optics, there are good historical studies discussing his experiments with prisms, the heterogeneity of white light as a mixture of coloured rays, and the reflecting telescope (Westfall 1962; Sabra 1981; Guerlac 1983; Hall 1993; Silva 1996; among others). On the other hand, there is a growing interest of historians of science on less explored parts of Newtonian optics (Buchwald and Cohen 2001; Shapiro 1993). Among them, we include the contents of Book II of *Opticks*, where Newton dealt, among other phenomena, with the phenomenon of coloured rings in thin films, known as "Newton's rings".[2]

The impact and acceptance of the contents of Book II of *Opticks* were not exhaustively explored by historians of science yet. While there is a vast number of studies on the reception of the most well known parts of Newton's optics as the content of Book I of *Opticks*, mechanics and natural philosophy (Cohen 1963, 1966; Westfall 1980, pp. 402–468, 627–697; Stewart 1986; McMullin 2001), there are few studies on the acceptance of parts which were not integrated in the main body of current optical knowledge, for instance the content of Book II of *Opticks*.

After the publication of *Opticks* in 1704, its content and style became quite popular and an almost mandatory presence in cultural life of Enlighten societies. The impact of the *Opticks* almost equalled to that of the *Philosophiae Naturalis Principia Mathematica*, first published in 1687. Though, the *Opticks* were less revolutionary compared to the *Principia*, it allowed easier access to a wide audience since it was written in English instead of Latin. The book required almost none mathematical knowledge and presented a large number of very well described experiments and few hypotheses, suggesting an inductive construction of Newton's optical theory. Due to its accessible style, the book is a pleasant and interesting to read until today and is reach of physical as well as of philosophical aspects.

However, Newton's optics did not become popular only via Newton's words and hands, but also via public lectures and short books with scientific contents devoted to general public (including women) that emerged in the period (Cantor 1983, pp. 42–49; Hans 1998;

[1] In this period, criticisms to Newton's ideas on optics were rare. Situation changed after the 1740's when new research on optics took place and several papers, books and articles were published by supporters of different ideas. Among them the books *Nova theoria lucis et colorum* (1746) by Leonhard Euler (1707–1783), *An attempt to demonstrate, that all phenomena in nature may be explained by two simple active principles, attraction and repulsion* (1754) by Gowin Knight (1713–1772), and *A dissertation upon the philosophy of light, heat and fire* (1794) by James Hutton (1726–1797). Although we consider the critics of Robert Hooke (contemporary of Newton), Euler and other continentals and Thomas Young (early 19th century) as highly relevant in order to have a full picture of history of optics in eighteenth century, they are not the main scope of this paper which focuses on the first half of 18th century.

[2] Seventeenth century natural philosophers studied this phenomenon using lenses pressed against each other or against a glass plate. Currently, this phenomenon is explained by the concept of interference between light waves reflected on the first and second surfaces of the glasses. Newton, in his turn, developed different explanations for this phenomenon which are discussed in Sect. 3. For instance, the one based on the concept of fits of easy reflection and easy transmission, published in the Book II of the *Opticks*.

Turner 2003, pp. 516, 521–522). The lectures and writers presented Newton's ideas on optics as they were consensual among natural philosophers in the period, likely to be unified with his mechanics and stressed the inductivist approach to the study of nature.

From a historical perspective, the present paper contributes to a better understanding of less known aspects of Newtonian optics and its acceptance in the eighteenth century. From an educational perspective, the present episode allows discussion of aspects of the nature of science in a level accessible to undergraduate students of physics or other scientific disciplines, and future physics teachers.

2 Newton's Studies on Optics

Light and the phenomena related to it fascinated Isaac Newton since he was a young student at Trinity College in Cambridge. His first experiments with prisms and attempts to explain the observed phenomena can be found in his notebook from 1664 and 1665 entitled *Quaestiones Quaedam Philosophicae*. The notebook comprises his discussions about several natural phenomena, including light and colours, colours of chemical solutions and human vision. Since then, he devoted a significant part of his time to develop a wide range of explanation to optical phenomena.

Between 1670 and 1672, Newton wrote a long and rigorous ensemble of lectures called *Optical Lectures*, with lectures taught by him as Lucasian Professor at Cambridge. The Lucasian Professor should teach an one hour long lecture per week and deposit each year at least ten of these lectures at the university library for public use. Newton fulfilled these obligations with a delay of about 4 years, when he delivered a set of thirty-two lessons entitled *Optica* and kept in his possession a smaller version entitled *Lectiones Opticae*.[3] In this work, Newton used sophisticated geometry to discuss in depth topics such as reflection and refraction of light by parallel plates, spherical and non-spherical lenses, the colour of objects, refrangibility of coloured rays, and the composition of white light.

In February of 1672 Newton published his paper "New theory about light and colours" in the *Philosophical Transactions of the Royal Society*. This was his first publication, due to his description of the reflective telescope and for the experiments with prisms, he immediately became well known among the scientific community of the seventeenth century. After the publication, several critics manifested their disagreement with Newton's ideas, including Robert Hooke, Christiaan Huygens and the French priest Ignace Pardies. They questioned his results and interpretations of experiments with prisms; especially the assertion that white light is a heterogeneous mixture of rays with different colours and refrangibility (Martins and Silva 2001, pp. 290–291).

In 1675, Newton submitted two long papers to the Royal Society of London: the "Hypothesis of Light" (Newton 1995) and an untitled manuscript, known as "Discourse of observations" (Newton 1978).[4] The idea of classifying the work as a hypothesis allowed Newton to develop models for light and ether without being in conflict with other studies as had happened with the "New theory of light and colors" (Silva 1996). In the "Hypothesis of light" Newton exposed some of his views on the use of hypothesis in science:

[3] Both works were translated and published in 1984 by Allan Shapiro (Newton 1984) as *Optical papers of Isaac Newton: The Optical Lectures (1670–1672).*

[4] Both papers were first published many years after Newton's death (1727) in Thomas Birch "The History of the Royal Society of London" (London 1756/57), Vol. III.

> […] because I have observed the heads of some great virtuosos to run much upon hypotheses, as if my discourses wanted an hypothesis to explain them by, and found, that some, when I could not make them take my meaning, when I spoke of the nature of light and colours abstractedly, have readily apprehended it, when I illustrated my discourse by an hypothesis […]; that no man may confound this with my other discourses, or measure the certainty of one by the other, or think me obliged to answer objections against this script: for I desire to decline being involved in such troublesome and insignificant disputes. (Newton 1995, p. 14)

Newton's method sought to infer the properties of natural phenomena from the experiments by induction without the use of hypotheses. Newton began the third edition of Book III of *Principia* with a set of four rules in a section entitled 'Rules for the Study of Natural Philosophy'. In the last one, he stated that

> [in] experimental philosophy propositions gathered from phenomena by induction should be considered either exactly or very nearly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions. (Newton 1999, p. 796)

An even fuller statement is found in Query 31 of *Opticks*:

> And although the arguing from Experiments and Observations by Induction be no Demonstration of general Conclusions; yet it is the best way of arguing which the Nature of Things admits of, and may be looked upon as so much the stronger, by how much the Induction is more general. And if no Exception occur from Phenomena, the Conclusion may be pronounced generally. But if at any time afterwards any Exception shall occur from Experiments, it may then begin to be pronounced with such exceptions as occur. (Newton 1979, p. 404)

In the *General Scholium* written in 1713 for the second edition of the *Principia*, Newton enunciated his famous

> […] I do not feign hypothesis. For whatever is not deduced from the phenomena is to be called hypothesis; and hypothesis, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. (Newton 1999, p. 943)

Newton argued that in his natural philosophy, particularly in his published works in optics, experimental and phenomenological aspects should be prioritized, rather than building a science based on the use of hypotheses: "My Design in this Book is not to explain the Properties of Light by Hypotheses, but to propose them by Reason and Experiments" (Newton 1979, p. 1). Thus, much of the content of the "Hypothesis" does not explicitly appear in the *Opticks*.

The controversy caused by the 1672 paper made Newton to silence about optics for almost 30 years. Only in 1704, after the death of his main rival, Robert Hooke, Newton finally published his theory in the *Opticks*. This book is divided into four parts. Book I treats chiefly with composition of white light and colours of objects. Book II deals with colours of natural bodies and coloured rings in thin films using the concept of fits of light. The subject of Book III discusses phenomena related to the inflection of light (diffraction of light, in current language). The last part of Book III is known as Queries, where Newton introduces and discusses several important ideas that permeated his work, for instance, existence of an universal ether, forces acting at distance, corpuscularity of light, among others, without explicit commitments to any of them.

Despite of what is commonly believed, Newton seldom exposed an explicit discussion about the materiality of light,[5] except in "Hypothesis of light" and in the Queries of *Opticks*, where he discussed hypothesis about nature of light and its behaviour. Newton

[5] As materiality of light, Newton understood that light is made of material substances. In the Query 29, Newton speculated about the possibility that light was constituted by small material particles: "Are not the Rays of Light very small Bodies emitted from shining Substances?" (Newton 1979, p. 370).

assumed that experiments and mathematical demonstrations of properties of light did not require the use of conjectures about its nature,[6] instead, it should be based only on induction.[7] Therefore, he was often cautious in explicitly assuming any hypothesis about the physical nature of light. Instead, he used the well know and traditional concept of "ray of light" to circumvent any premature decision and commitment about the nature of light (Hall 1993, p. 12). Thus, the common notion that Newton advocated the corpuscularity of light is not supported by historical studies (Moura and Silva 2008).

3 Different Models for the Interaction of Light and Matter

Along the years, Newton considered four different models to explain the interaction between light and matter: deviation caused by the difference of the ether's densities in the matter, vibrations caused by the light rays in the ether, force acting at a certain distance between the bodies and light, and an innate property of the rays of light called fits of easy reflection and easy transmission.

In the "Hypothesis of Light" (1675) Newton developed a description of ether constitution, its interaction with light, and two different models for explaining the refraction[8] and reflection of light rays. The first model is based on variation of the ether's density, while the second is based on vibrational motion of the ether caused by light particles. This model could also explain the advent of coloured rings in thin films, the so called "Newton's rings".

In the first model, Newton assumed that the density of ether varies in different materials in order to explain refraction and total reflection of a light ray:

> The ray therefore in passing out of the rarer Medium into the denser, inclines continually more and more towards parallelism with the refracting Superficies, and if the differing densities of the Medium be not so great, nor the incidence of the ray so oblique as to make it parallel to that Superficies before it gets through and is refracted; but if through the aforesaid causes the ray become parallel to that Superficie before it can get through, then it must turn back and be reflected. (Newton 1995, p. 21)

In this model, the total reflection (represented by ray $\mu\nu\pi$) in Fig. 1 is a special case of refraction (represented by ray MNL). The density of the ether is smaller in denser materials as glass due to smaller amount of pores in these materials. In less dense materials the porosity is bigger as well the density of the ether. For Newton, a light ray moving through different media (and different ether's densities) will suffer a pressure toward the less dense ethereal medium. Therefore, the ray will be accelerated or delayed depending on the direction of its motion, as illustrated in Fig. 1. In this figure, the ray can either suffer total

[6] For example, in a letter to the French priest Ignace Pardies of the 10th June 1672, Newton states that "Accordingly I understand light to be any entity or power of an entity (whether substance or some force, action or quality possessed by it) which precedes directly from a bright body and is adapted to excite vision: and I understand rays of light to be the least, or the indefinitely small parts of it, which are mutually independent, as are all rays which luminous bodies emit along straight lines either synchronously or in succession."

[7] At the end of the *Opticks* Newton made his defense to the inductivism very clear: "As in Mathematicks, so in Natural Philosophy, the investigation of difficult things by the method of analysis, ought ever to precede the method of composition. This analysis consists in making experiments and observations, and in drawing general conclusions from them by inductions […]" (Newton 1979, p. 404).

[8] In *Opticks* Newton derived the sine law of refraction assuming "that Bodies refract Light by acting upon its Rays in Lines perpendicular to their Surfaces" in Book I, Part I, Prop. VI, Theorem V. While in Book II, Part III, Prop. X, he derived the refraction law assuming that "the Forces of the Bodies to reflect and refract Light, are very nearly proportional to the densities of the same Bodies".

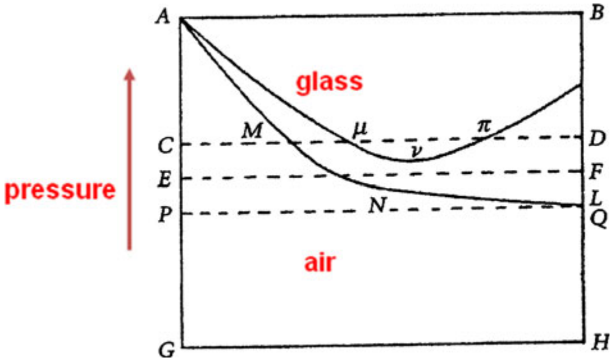

Fig. 1 Refraction and total reflection of light rays in different media with different ether densities discussed by Newton in "Hypothesis of Light" (1695)

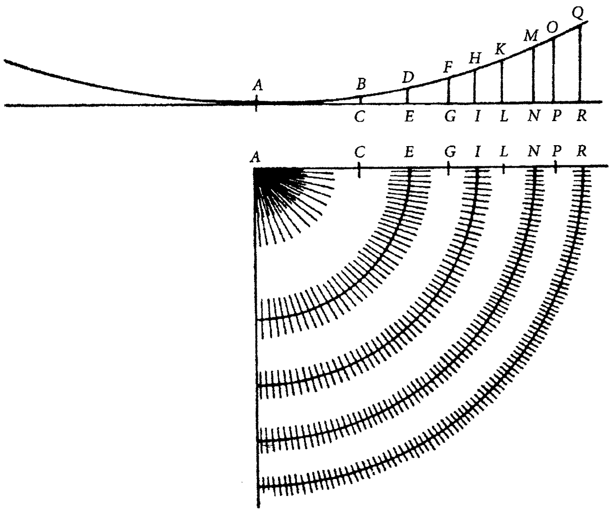

Fig. 2 Light rays being alternately reflected and transmitted, occasioning *dark* and *bright* rings discussed by Newton in "Hypothesis of Light" (1695)

reflection or be refracted when it moves from glass to air, depending on the angle of incidence.

This model does not explain why part of the rays of light is also reflected by a refracting surface. Then, in order to explain why rays with the same angle of incidence are partly reflected and partly transmitted, Newton proposed a second model considering vibrations in the ether (Fig. 2):

> […] and so supposing that light, impinging on a refracting or reflecting æthereal superficies, puts it into a vibrating motion, that physical superficies being by the perpetual appulse of rays always kept in a vibrating motion, and the æther therein continually expanded and compressed by turns; if a ray of light impinge upon it, while it is much compressed, I suppose it is then too dense and stiff to let the ray pass through, and so reflects it; but the rays, that impinge on it at other times, when it is either expanded by the interval of two vibrations, or not too much compressed and condensed, go through and are refracted. (Newton 1995, p. 24).

In this model refraction and partial reflection of a light ray are ascribed to different ether densities caused by vibrations in the ether. Vibrations in the ether as described by Newton are generated by the interaction of light rays with the ether present in the surrounding material—they are not light itself, as in wave theories of light. This model cannot explain the total reflection neither the dependence of the amount of reflected light with the angle of incidence because the intensity of the vibrations produced by the rays does not depend on their angles of incidence on the surface. Newton's intention in proposing this model was to combine refraction and reflection in order to explain the formation of rings, when refraction and reflection occur alternately (Hall 1993, p. 75). In order to explain the formation of coloured rings due to the incidence of white light, Newton introduced the idea that rays of different colours differ in "magnitude, force or effect" and excite vibrations in the ether of different intensities, as represented in Fig. 2.

In the "Hypothesis of Light" Newton apparently did not try to present an unified model to explain the basic known optical phenomena such as refraction, reflection, total reflection and "Newton's rings". The first model based on density difference in the ether explained refraction and total reflection. While the second model based on vibrations excited in the ether, explained refraction and partial reflection without considering the influence of the angle of incidence.

On the other hand, in the *Opticks*, Newton adopted a different strategy. He replaced the ideas about the ether by the concept of "fits of easy transmission and easy reflection", which played a central role in Book II of *Opticks*. Nevertheless, even in the *Opticks* Newton considered and discussed different models to explain the interaction between light and matter. Before introducing the fits, Newton described two other explanations for optical phenomena. In Propositions I to V of Book II, Newton defended that what determines if a body reflects or transmits light rays is the size and densities of the its corpuscles. While in Propositions VIII to X, Newton defended the existence of a power of bodies acting upon the light rays:

> And this problem is scarce otherwise to be solved, than by saying, that the reflection of a ray, is effected, not by a single point of the reflecting body, but by some power of the body which is evenly diffused all over its surface, and by which it acts upon the rays by immediate contact. (Newton 1979, p. 266)

In Proposition IX, Newton continued his argumentation, asserting that "bodies reflect and refract light by the same power, variously exercised in various circumstances" (Newton 1979, p. 269). In the next proposition, Newton affirmed that this power is a force and explained its effect upon the rays in a similar manner of his explanations about the interactions between bodies in the *Principia*. Newton returned to the issue in the Queries:

> Have not the small particles of bodies certain powers, virtues, or forces, by which they act at a distance, not only upon the rays of light for refracting, reflecting, and inflecting them, but also upon one another for producing a great part of the phenomena of nature? (Newton 1979, pp. 375-6)

Finally, in Proposition XII, Newton replaced the explanation based in forces by the fits of light. According to him, the fits were connate properties of light and explanations about their origins were unnecessary. He defined fits as:

> The returns of the disposition of any ray to be reflected I will call its Fits of Easy Reflection, and those of its disposition to be transmitted its Fits of Easy Transmission, and the space between every return and the next return, the Interval of its Fits. (Newton 1979, p. 281)

By a complex argumentation, Newton used this property to explain the two principal phenomena discussed in Book II, viz., the colours of bodies and the coloured rings in thin films. The fits are transient states that induce the light rays to be transmitted or reflected:

> Every ray of light in its passage through any refracting surface is put into a certain transient constitution or state, which in the progress of the ray returns in equal intervals, and disposes the ray at

every return to be easily transmitted through the next refracting surface, and between the returns to be easily reflected by it. (Newton 1979, p. 278)

Although Newton discussed different models to explain the interaction between light and matter, he adopted the fitsin the major part of Book II of *Opticks*. In addition, according to Shapiro (1992, p. 199), *Opticks* was unfinished when it was published and Newton intended to publish four books, instead of three. The last one would be devoted to the discussion of forces between light and matter. However, as Newton abandoned the plan of publishing the Book IV, its content was distributed along the other books. Therefore, Newton added the *Queries*, where he allowed himself to express his considerations, as thoughts or speculations.

Regardless the fact Newton exposed his ideas on the nature of light as queries, not as experimentally based propositions, they were pivotal to eighteenth century Newtonian natural philosophers who developed relationships between dynamics and optics. The next section is devoted to a discussion of the process of selection and development of the ideas presented in *Opticks* by the eighteenth century followers called Newtonians.

4 Newtonian Optics in the Early Eighteenth Century

Newton's theories of light and colours strongly influenced optical studies of early eighteenth century (Cantor 1983, pp. 32–42; Hakfoort 1995, pp. 27–41). The empiricist approach conveyed by the *Opticks*, particularly Book I, the arguments about the materiality of light and its interaction with other bodies by forces were the main reasons of the success of Newton's optical ideas among natural philosophers in the period. But, the triumph of Newtonian optics was not only due to its scientific merit. Social, cultural and scientific changes that were taking place in this period played an important role as well.

When *Opticks* was published in 1704, Natural Philosophy was gradually assuming a more complex and independent form, away from philosophical foundations and closer to what is currently known as science (Gascoigne 2003, p. 285). The valorisation of Natural Philosophy as a cultural product and as a path to obtain a true view of the world was closely related to the development of technology. Historical studies indicate that many lecturers presented by natural philosophers were related somehow to the commercial world. Hence, the propagation of knowledge about nature was regarded as a powerful tool to increase the profit and minimize the losses (Stewart 1986).

Moreover, several important changes occurred in education, contributing to the increase of the value attributed to scientific knowledge. Knowledge used to be a privilege of a small part of the society, being admired and inspiring by its members. In the early eighteenth century, instead, the idea of systematization and practical use of knowledge, together with its diffusion to other social classes, echoed in the educational system (Hans 1998). There was a raising perception that knowledge should not be restricted to universities and consequently to the upper class of society. It should be widely popularized instead (Brockliss 2003).

These changes stimulated a culture of popular conferences where fellows of important universities of Great Britain and Europe presented their results and ideas. The systematization of knowledge and the valorisation of its practical use also favoured the organization and publication of encyclopaedias and companions, since universities were no more regarded as the exclusive source of education and knowledge (Yeo 2003, p. 241). Embedded in this context of remarkable changes, popular conferences and encyclopaedias offered access to recent discoveries and theories of natural philosophers. Emphasizing the role of experiments and observations, the conferences presented Natural Philosophy as a set of unquestionable truths, attracting the attention of different people, from clergy men to instrument makers (Turner 2003, pp. 511–520). As Stewart (1986, p. 179) has pointed out, "public lectures where the vehicle by which an otherwise esoteric and incomprehensible mathematical natural philosophy was made intelligible to a wider public".

The influence of the inductive method, represented mainly by the works of Francis Bacon (1561–1626), has played an important role. Several eighteenth century natural philosophers were convinced that Natural Philosophy should be based solely on the experimental method (Cohen 1966, p. 178). Natural knowledge should be useful and based on experimental prove. This inductivist ideal was well represented by popular conferences which boomed in the first decades of eighteenth century (Cantor 1983, pp. 42–49). Popular conferences and encyclopaedias were good vehicles for the dissemination of the inductivist ideal. In this context, the inductivist approach to nature became more and more popular in science.

The recently published *Opticks* (1704) was more than a description of optical phenomena. It presented discussions about the nature and behaviour of matter, ideas about electricity, magnetism, heat, chemistry, and several other issues. Immediately, *Opticks* became the chief reference in optics. Although the *Opticks* was a widely received book not all of its content was popularized. Special attention was given to the *Queries* of the Book III, and to those parts of the book which favoured an inductivist view, viz. the Book I.

The main goal of the popularisers of Newton's optics was to establish relations between his dynamics and theories of light and colours, since for most of the supporters of a corpuscular conception of light, optics should be able to mechanically explain interactions between light rays and bodies (Cantor 1983, pp. 32–42). These authors intended to merge optics with the principles of Newton's mechanics, as those presented earlier in the *Principia*. However, not all Newton's optical models could be incorporated in this new corpuscular theory of light. Among them was the model of fits of easy transmission and easy reflection discussed in Book II of *Opticks*. Although fits of light were a pivotal concept in the Newtonian optics, they were almost ignored, unknown, or treated superficially by Newton's followers (Cantor 1983, p. 84).

5 Popularizing Newtonian Optics

Being a "Newtonian" meant to accept some parts of Newtonian optics, but not necessarily it as whole. The majority of the content of Book II was entirely ignored, including the central concept of fits of easy transmission and easy reflection of light. Two elements of Newtonian optics were emphasized in conferences, encyclopaedias and popular books: the valorisation of the inductivist view of Natural Philosophy derived from the experiments with prisms of Book I and the belief in the corpuscular character of light, gathered from the *Queries* of Book III. Thus, there was a selection of aspects that could be suited to the mechanical ideal of the Newtonian world. In this selection concepts which were either more abstracts or which could hardly fit to the mechanical approach to optics were ignored. The fits of easy transmission and easy reflection were among the ignored concepts.

Public conferences played a major role in the process of popularizing Newtonian optics in the early eighteenth century. The lectures of John Teophilous Desaguliers (1683–1744) for instance became some kind of pattern to be followed in this respect. Desaguliers frequented John Keill's (1671–1721) conferences about Natural Philosophy, soon becoming his successor. A few years later, he was named the Royal Society's curator of experiments, being known by his defence of Newton's theories (Cohen 1966, p. 243). Desaguliers published articles and books presenting a simple account of the world and praised Newton as an example to be followed.

In his conferences, Desaguliers presented natural philosophy as an ensemble of undoubted truths about nature exemplified by several easy handling and comprehensible experiments (Turner 2003, p. 521). In optics, Desaguliers explored selected parts of Newtonian optics which were first and foremost based on experiments and demonstrations, chiefly experiments with prisms. In *Physico-mechanical lectures* (1717), a selection of issues discussed in his conferences, Desaguliers assumed that the corpuscular character of light was evident from the observation of simple optical phenomena, like refraction:

> THAT Light is a body, appears from its Reflection, Refraction, Composition, Division, and moving in Time; but especially from its being propagated in right Lines, and being stopp'd by an Obstacle, (how thin soever, if not transparent) which shews, that it cannot be an Action upon the Medium, which wou'd be communicated beyond an Obstacle, as in the case of Sound. (Desaguliers 1717, p. 42)

Newton's followers transformed what Newton had considered as queries or hypothesis to be further investigated into assertions. For instance, the *Lexicon technicum*, a scientific dictionaries organized by John Harris, and published in two volumes in 1705 and 1710. In the entry "Light", Harris explicitly transformed the content of Query 29 of Book III of the *Opticks*, where Newton ask "are not rays of light very small bodies emitted from shining substances?" (Newton 1979, p. 370) into the statement:

> The Rays of Light are therefore certainly little Particles, actually emitted from the Lumni Body […]. (Harris 1723, entry "Light", n.p.)

This kind of attitude contributed to the common belief that Newton established the corpuscularity of light in his optical studies, although historical studies clearly indicate the opposite (Hall 1993; Moura 2008).

Popular books also contributed to popularization of Newton's optics—and other parts of his natural philosophy. The books *Eleméns de la philosophie de Neuton* (1738) by Voltaire (1694–1778) and *Il newtonianesimo per le dame* by Francesco Algarotti, commonly known as *Newton per le dame*, are examples of widely read books on Newtonian science.

The *Newton per le dame* was first published in Italian in 1737 and translated into English and French.[9] The book is structured in six dialogues between a Marchioness and a Chevalier. By the words of these two characters, Algarotti illustrated the great superiority, beauty and perfection of Newton's natural philosophy—chiefly his optical studies—and, at the same time, strongly criticized Descartes theories.

The interest of the Marchioness for optics emerged from her doubt about the meaning of the expression "seven-fold light", that she had found in a poem written by the Gentlemen to the natural philosopher Laura Bassi (1711–1788):

[9] Since its first edition until the last edition of 1752, Algarotti's *Newton per le dame* underwent through several modifications in its content and title (Mazzoti 2004, p. 123). One of the reasons for these changes was its condemnation to the *Index Librorum Prohibitorum* by the Catholic Church in 1739. The concrete causes for this still remain uncertain, but this surely impacted the content of the next editions, which were free of Church punishment (Mazzoti 2004, pp. 137–138).

> That Seven-fold Light, that golden Ray, Short from the bright Orb of the Day, In the whose direct transparent line, United, all the colours shine. (Algarotti 1742a, pp. 11-2)

According to the Chevalier, if the Marchioness had understood

> the whole Force of that Expression, you might see in it a Kind of Newtonian Painting, perhaps, indeed, too philosophical for Poetry, but at the same time full of truth, and without the least Hieroglyphick Obscurity. (Algarotti 1742a, p. 12)

After Marchioness's insistence, the Chevalier explained more about the expressions "seven-fold light" and "Newtonian painting", discussing some of Newton's experiments with prisms and his ideas about the heterogeneity of white light. The Marchioness was, as that time, very impressed by Newton's achievements, being really impatient "to become a Newtonian too" (Algarotti 1742a, p. 16). But before becoming a Newtonian, the Marchioness is portrait as a silly woman who changes her opinion according to the Chevalier argumentation, being convinced by Descartes' theory of light as well. Algarotti's defence of superiority of Newtonian natural philosophy is remarkable:

> You are going, Madam, to be introduced to a World quite new, quite enriched with the most charming Truths: Newton is the discoverer: You will not find, throughout the whole, the least Track of preceding Philosophers. There cannot be a better Pattern of true Philosophy than his treatise of Opticks, it was the Product of thirty Years of Application and Study. (Algarotti 1742b, p. 196)

Algarotti, as Desaguliers and others, considered the corpuscularity of light as evident and the force between it and bodies was

> the Key of all Philosophy, the great Spring that actuates the Frame of Nature; the universal and mysterious Force discovered and calculated by Sir Isaac Newton [...]. (Algarotti 1742b, p. 125).

The *Newton per le dame* reinforced a view that Newtonian optics and natural philosophy were the ultimate truths, the correct portraits of nature, painted by an inductivist brush. Behind the words of the Chevalier and the Marchioness, Algarotti adapted the complex and sophisticated Newtonian theories and experiments into an ensemble of simple understandable words and sentences. At the end of the book, immersed in Newton's thoughts, the Chevalier said to the Marchioness:

> The light of Newtonianism has dissipated the Cartesian Phantoms which deluded your Sight. You are really now a Newtonian, and it is no small Advantage to truth that you are so. (Algarotti 1742b, p. 223)

Views on Newtonian optics similar to those of Harris, Desaguliers and Algarotti became more and more common throughout the first decades of the century. Their main goal was to build a coherent corpus for the corpuscular conception of light that led to the elaboration of several mechanical models to explain optical phenomena. These models contributed even more to establish definitely the portrait of Newton as the great defender of the corpuscularity of light.

6 Mechanical Models of Corpuscular Optics

In the previous section we have discussed books which were written for the general public, popularized elementary ideas of Newton, and thereby antagonizing Cartesianism. This section discusses books written by scientist comprising independent scientific contributions within the recently erected framework based on Newton's work.

One of the first natural philosophers to present an explicit dynamical treatment for light was George Cheyne (1671–1743). In his book *Philosophical principles of religion* (1705), he affirmed that light is composed of extremely small corpuscles. According to him, this could be proved by the fact that such corpuscles

> […] pass through almost all bodies that are pervious, such as crystals, glasses, several gems, and almost all fluids, but mercury; and that it freely passes where no other fluid, how thin soever, can enter […]. But what most of all demonstrates their smallness, is, that light may be propagated from innumerable different luminous bodies, without any considerable opposition to one another […]. (Cheyne 1715, pp. 69-70)

In order to discuss the interaction of light and bodies through forces, Cheyne transformed Newton's Query 5 content into an affirmation:

> Bodies and Light, act mutually upon one another; i.e. Bodies act upon Light, in emitting, reflecting, refracting and bending its Rays, and Light upon Bodies, in heating them, and putting their Parts in a vibrating motion, wherein Heat consists, according to Sir Isaac Newton's discoveries. (Cheyne 1705, p. 74)

Cheyne and other natural philosophers attempted to join Newton's optics and mechanics not only repeating Newton's words, but creating new explanations for optical phenomena through mechanical models.[10]

At the beginning of 1720 decade, the book *Mathematical elements of natural philosophy*, by Wilhelm Jacob 'sGravesande (1688–1742), brought a mechanical model derived from Newtonian optics and mechanics. Translated to English by Desaguliers, 'sGravesande's book was widely read in Great Britain, becoming an important reference in the period. In the preface of the second volume of the *Mathematical elements*, 'Gravesande demonstrated his appreciation for Newton's works, particularly, his optical studies:

> Before him [Newton], Naturalists were in the Dark in numberless Things relating to Light, and especially to Colours […]. ('sGravesande 1726, p. ix)

In order to explain refraction of light 'sGravesande developed a model based on the concept of "space of attraction". According to him, the basic cause of refraction was the different densities of the medium between two surfaces, which resulted in an attraction towards the denser zone. This attraction occurred in the "space of attraction", delimited by the planes GH and IL in the Fig. 3.

With the "space of attraction" 'sGravesande also explained the total reflection. Depending on its obliquity, the ray traveling from the denser medium towards the rarer one could not be able to overcome the action of the attractive force, then being totally reflected. Although 'sGravesande's model was coherent, it did not explain partial reflection and refraction. Given the attractive nature of forces, this model did not explain why rays of light could be partially reflected and partially transmitted when they reach a glass surface? As other authors of the period, 'sGravesande restricted his mechanical treatment of light to refraction (as an ideal case) and total internal reflection (Moura 2008).

In a similar manner, Robert Smith (1689–1768) in his *A compleat system of optics* (1738) elaborated a model based on the concept of "space of activity" to explain optical phenomena such as refraction and reflection. Quite popular in the period, Smith's book was translated into French and German (Cantor 1983, p. 34; Gjersten 1986, p. 549). It contained

[10] Besides George Cheyne, Wilhelm Jacob 'sGravesande and Robert Smith, other natural philosophers also devoted themselves to unifying optics and mechanics using similar approaches. Among them, John Rowning (1701–1771) who published *A compendious system of optics* between 1734 and 1738 and Richard Helsham (1682–1738) who published *A course of lectures in natural philosophy* in 1739.

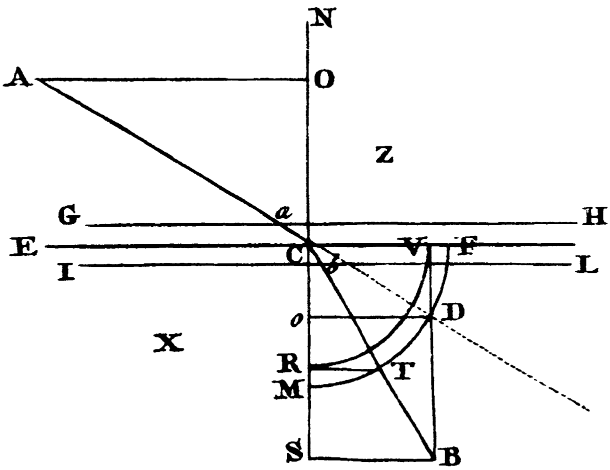

Fig. 3 ‘sGravesande scheme to explain the refraction of light. When a light ray Aa enters the “space of attraction” between the planes GH and IL, it suffers a perpendicular force of attraction towards the denser medium, bending its trajectory

explicit declarations about the corpuscularity of light and therefore represents another genuine attempt to combine Newtonian optics and mechanics:

> Whoever has considered what a number of properties and effects of light are exactly similar to the properties and effects of the bodies of a sensible bulk, will find it difficult to conceive that light is any thing else but very small and distinct particles of matter […]. (Smith 1738, p. 1)

Smith discussed the concept of “space of activity”. According to Smith, the “power” of a body being limited by two planes, parallel to each other and to the surface of the body, illustrated by Fig. 4. When a ray of light entered this zone, called “space of activity”,

> […] its particles will be accelerated or retarded in the same perpendicular direction, according as the power of the medium acts with or against the course of their motion; and when the particles are got through that space they will proceed with an uniform velocity. (Smith 1738, p. 91)

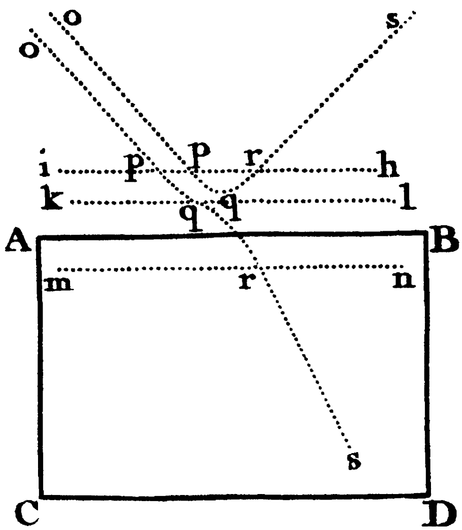

Fig. 4 The “space of activity” is limited by the planes *ih* and *mn*. According to Smith, in this “space” there is a zone of repulsion (between *ih* and *kl*), causing reflection, and a zone of attraction (between *kl* and *mn*), causing refraction

The "space of activity" has a zone of repulsion, responsible for the reflection of light, and a zone of attraction, responsible for the refraction of light. The intensity of the repulsion and attraction in these zones depends on the refractive density of the body. By this mechanical model, Smith explained not only refraction and total internal reflection, but also partial refraction and reflection.

Although the mechanical optics developed in the first decades of eighteenth century had weaknesses, there were only a few people who attempted to criticize them. According to Cantor (1983), along the first half of eighteenth century, the natural philosopher Robert Greene (1678–1730) was among the few who defended a fluid theory of light and questioned mechanical corpuscular theories of light. However, none of them pointed out significant problems of the theory. This little criticism can be explained by two intertwined scientific and sociological reasons. From a scientific perspective, in this period, there was no theory of light able to surpassing the tacit corpuscular conception and mechanical models of light in explanatory power. The vibrational theory developed by Christiaan Huygens (1629–1695) was no longer considered as valid; even by those who believed that light was a pulse or wave (Hakfoort 1995, p. 3). Furthermore, fluid theories had difficulties in explaining some basic optical phenomena like refraction and reflection (Cantor 1983). From a sociological perspective, at this time, Newton was a prestigious and respected person, especially in Great Britain. He used to be the president of the Royal Society since 1703 and had gained several supporters, which facilitated the wide acceptance of his theories. They propagated a Newtonian style of science, creating and expanding what is known as the *Newtonianism* (Cohen 1966). Therefore, few people tried to run against the great success of Newton's achievements.

The situation began to change in the 1750s, when some traditional experiments were reinterpreted, calling attention to problems with corpuscular theory (Cantor 1983, pp. 50–52). In this period, books and papers were published defending vibrational interpretations of light and criticizing some aspects of Newtonian optics. Among them, it is worth of mention the *Nova theoria lucis et colorum* (1746) by Leonhard Euler, *New experiments in electricity* (1789) by Abraham Bennet, *A dissertation upon the philosophy of light, heat and fire* (1794) by James Hutton and *An attempt to demonstrate, that all the phaenomena in nature may be explained by two simple active principles, attraction and repulsion* (1748) by Gowin Knight. The main critics were related to the mass and volume of light particles, the influence of gravity in the movement of light rays, the explanations on the inflection and the existence of forces acting between light and bodies.

In the early nineteenth century, the increasing number of works based on the wave conception, mainly those by Thomas Young, William Wollaston, David Brewster and Augustin Fresnel, gave a great impulse to the subsequent development of wave theories of light. Along the century, wave theories of light gained space due to the fact that they could quantitatively and qualitatively explain important optical phenomena, for instance, "Newton's rings", polarization and diffraction of light. In this period, Newtonian optics went through a downward trajectory and was not regarded as an authority and a model to be followed anymore.

7 What Can We Learn from This Case?

Few decades after the publication of the *Opticks* in 1704, Newton's original optics and Newtonian corpuscular conception of light were considered the main paradigm in optical studies. Although *Opticks* was a quite popular and successful book, influencing many people during the eighteenth century, Newton's followers did not assimilate all of its ideas. In order to create a corpuscular optics based on Newtonian mechanics, they combined results of the *Opticks* with those of the *Principia*. In fact, they used parts of his mechanical theory to develop a "mechanical" optics, discussing corpuscularity of light and its interaction with other bodies through forces acting at distance. The mechanical models developed by the Newtonians were characterized by the assumption of forces acting between bodies and light corpuscles. They did not take into account Newton's concept of fits of easy transmission and easy reflection neither tried to explain the rings between two thin plates, which was the main topic of the Book II of *Opticks*. The consequence of this process was the formation of a Newtonian optics that palely resembled Newton's original ideas.

7.1 The Use of Hypothesis in Science

Newton is widely known as one of the main advocates of inductivism. Until today, science textbooks and popular books present an idealized image of him as one who developed his optical theory only by observing and experimenting. However, a closer analysis of Newton's writings on optics reveals that Newton not only used hypothesis, but also that they played a central role in his theories, especially those discussed in Book II, as has been shown in Sect. 2 of this paper. Newton developed various hypothetical explanations in order to explain phenomena like the colours of bodies and Newton's rings. Although he had claimed that hypothesis played no role in his Natural Philosophy, he used them to structure his ideas about the coloured rings and the model of fits.

Newton used a rhetorical style in the *Opticks* which hid hypothetical foundations of his models. By a superficial reading, the style of the Book II seems to be similar to the style adopted in Book I: several observations were described followed by conclusions apparently draw from them. Nonetheless, after a closer reading, it becomes quite clear that experiments played a less prominent role in Book II than they did in Book I. Thus, the study of Newton's optics clearly indicates that hypotheses do play a central role in science, and their use is necessary part in the construction of scientific models and theories. Newton's explanations were related to his own beliefs and expectations, which went far beyond the pure observation and description of optical phenomena. As Pumfrey (1991, p. 69) asserts, "meaningful observation is not possible without a pre-existing expectation". Despite of Newton's reputation as an inductivist, the central role of hypothesis for the development of his models clearly puts him as an illustrative example that scientific theories and models are not supported only by experiments.

7.2 Previous Prestige of Scientists Influences the Acceptance of Their Ideas

At the time of the publication of the *Opticks*, Newton was already known not only in Great Britain, but also in the rest of the European continent. His first book, the *Philosophiae Naturalis Principia Mathematica*, as well his theory of light and colours were very successful and influential. Newton had recently became the new Royal Society's president (in 1703), and made significant contributions in other areas, like his contribution as Master of the Royal Mint of England from 1699 until his death in 1727. His success in different spheres of society contributed to promoting his popularity. Therefore, for the wide public, knowing and accepting his ideas was also a matter of respecting one of the most famous national personages.

In the scientific field, his defence of inductivism called the attention of natural philosophers in the first decades of the eighteenth century. In fact, until today, his reputation is also sustained by the popular citation “Hypothesis non fingo” They strongly believed that the true scientific knowledge should mainly be gathered by observations and experiments and Newton provided a fancy and sophisticated role model to them, particularly in the Book I of *Opticks*. Furthermore, Newton’s discussions about the materiality of light in the Queries of Book III gave to his followers the arguments to develop corpuscular models for light.

The common-sense belief that scientific theories can be proved as truth by experiments and this is what determines their acceptance is inadequate. This case study indicates that the popularity of a scientist among other scientists due to previous achievements also influences the acceptance—or rejection—of his or hers new ideas. Through this particular analysis, it is possible to create a debate on science classrooms about how the reputation of a scientist among his peers motivates the success or failure of his theories.

7.3 Ideas of Famous Scientists Can Be Substantially Changed by Their Successors

The present case study provides elements to discuss that theories and models change over time and in few decades some core concepts (as the fits of easy transmission and reflection) can be forgotten and even ignored by the next generation of scientists.

Although Newton’s models to explain optical phenomena were successful, his followers selected and modified them. They transformed hypothesis speculated in the Queries of *Opticks* into assumptions about the corpuscular nature of light. A few decades after the publication of the *Opticks*, the so called Newtonian optics palely resembled Newton’s original theory of light and colours.

The Newtonians of early eighteenth century transformed Newton’s ideas in a simplified corpuscular theory of light supposedly proved by experiments, while for Newton the corpuscularity of light was an open question to be developed further. The experiments performed by Newton and his argumentation in order to demonstrate the heterogeneity of white light were based on several implicit assumptions and complicated aspects, which should be taken into account in teaching situations (Martins and Silva 2001). On the other hand, the mechanical models developed by Newton’s followers were vague and based in Newton’s speculations about materiality of light and the existence of forces between light and material bodies.

Therefore, this case study highlights that the ideas of a scientist are frequently selected and changed by his or her successors. No theory is immune to reformulation and, eventually, improvements. This indicates that scientific ideas are not built by only one person and are not immutable. On the opposite, they are fruit of a collective construction and subject to developments and changes.

This episode shows that scientific knowledge is “tentative” and “changing” (Abd-El-Khalick et al. 1998, p. 418; Eflin et al. 1999, p. 108) and not static and immutable, as commonsense beliefs. In science teaching, it can be useful to discuss the validity of scientific theories and how and why they are received by the society where it emerged.

7.4 Scientific Ideas Can Be Ignored, Even If They Hold a Significant Role in Their Original Context

Even though *Opticks* was a quite successful book, only a selection of its ideas was adopted by Newtonians. Newton’s followers avoided discussing almost the entire content of Book II, including the theory of fits.

What currently is called Newtonian optics does not resemble what Newton himself had published and defended. Pictures of Newton studying the colours of the light spectrum with a prism in his hands became popular in textbooks. References to Newton's optics are often related to the idea that he used to defend the corpuscular nature of light (which is not the case, as discussed in previous sections) and to the content of Book I: experiments with prisms, and the heterogeneity of white light. Some of Newton's ideas on optics, mainly the content of Book II, were virtually ignored by Newtonians. As a result these ideas are forgotten by scientists, researchers and even historians of science until today.

7.5 Scientific Ideas Are Affected by Their Social and Cultural Milieu

Literature in nature of science and science education often emphasises that science is part and is affected by social and cultural factors, thus, being "socially and culturally embedded" (Abd-El-Khalick 2005, p. 17). This case study shows that the status and views about natural philosophy changed dramatically along the early eighteenth century. Many efforts to make Natural Philosophy accessible to the general public were undertaken. For instance, popular conferences and encyclopaedias presented Newton's ideas as the correct description of natural phenomena and the inductive method as the best approach to the study of nature. This illustrates that science is a human enterprise that depends on the social, religious and political traditions of society (McComas et al. 1998, p. 513; Lederman et al. 2002, p. 501).

According do Eflin et al. (1999, p. 109), "few deny that theoretical commitments and social and historical factors play some roles in science", but there is a lot of disagreement about "their nature and strength". In this particular case, we advocate think that the process of acceptance of Newton's ideas on optics allows the discussion of how significant the influences of historical and social contexts are, without disregarding the merit of Newton's scientific for the period.

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