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The "invisible light": Tracing its journey from scientific history to physics teaching

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Abstract: The history of science in teaching has been the subject of much discussion, analysis, practices and educational evaluations in recent decades. The objective is to present an important historical process of physics in the 19th century and to discuss its use and contribution to the understanding of the electromagnetic spectrum. The first part of the work describes the main experiments that led to the confirmation of the existence of 'invisible light', that is, radiations in the infrared and ultraviolet range. The second part explores how one of the original experiments concerning infrared radiation can be used to demonstrate and discuss the existence of radiation outside the visible spectrum. The proposal of the work is that these two dimensions, the historical approach and the accomplishment of pertinent experiments, are concatenated in the didactic exploration of this important content: the meaning of the unified electromagnetic spectrum and its important applications in people's daily lives.
Keywords: electromagnetic spectrum; infrared radiation; history of physics

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Introduction

When one analyzes certain periods in the history of physics, it is often perceived that various experiments, interpretations, and theoretical models, which were fundamental to the development of science and new technologies, do not receive significant attention or are presented in many high school textbooks in a manner very different from their historical origins. Often, a scientific "discovery" is presented as having been made by a certain individual, on a precise date, but the process, when examined more deeply, differs significantly from what the scientist proposed and even from the interpretation of their contemporaries. There is a complex process of historical reconstruction that reshapes the meaning of the initial works and retrospectively gives them the characteristic of a precisely dated discovery. This is the case with the recognition attributed to William Herschel and Johann Ritter: they are considered the discoverers of infrared and ultraviolet radiation, in 1800 and 1801, respectively, observed from the solar spectrum. But when one examines the history of these 'discoveries' in more detail, it becomes apparent that such credit to their work oversimplifies the initial formulation process, experimental observations, interpretations, subsequent reformulations, and final acceptance of the idea of a unified solar spectrum, in which all observed radiations - heat, chemical, and luminous - were embedded, as seen in illustrations in current textbooks. Many questions arise from the analysis of this process, for example: did Herschel investigate the solar spectrum already with the idea of finding infrared radiation or did he do so by chance? Did the same happen with Ritter, in the case of ultraviolet radiation? How did they interpret their experimental observations? How did the acceptance and reformulation of their initial propositions occur? How did the idea arise that such radiations were similar to visible "luminous rays" and how did the idea of a unified spectrum come about?

This work aims to highlight that a historical analysis of the studies that led to the identification of these two non-visible radiations and the establishment of the concept of a unified spectrum of luminous radiations may be of interest from a didactic standpoint. The chosen period spans from 1800, when the first observations of such radiations were made, to the mid-1850s when the idea that they were all part of a unified spectrum, which also included visible radiations, and qualitatively of the same type, differing only in their frequency, became accepted by the majority of scientists in the field. This occurred within a wave conception of luminous radiation, which emerged parallelly in the first half of the 19th century.

The pioneer in the observation of infrared radiation (Herschel, 1800), which he named 'Calorific Rays', was Frederick William Herschel (1738 - 1822). Besides being an astronomer, he was a musician and composer and made significant contributions to science, particularly astronomy, throughout his long life. He was highly skilled experimentally and was the greatest telescope maker of his time; among his works, he notably made the first observation of the planet Uranus and made early developments on the concept of galaxies. At the age of 61, Herschel, in his astronomical observations and in the quest for more efficient telescopes, began to study heat, maintaining the same method of observation and description as in his celestial studies. In the context of discussions about the concept of light and phenomena of reflection, refraction, and interference, Herschel focused on the study of solar rays. This led to the publication of several works (Herschel, 1800) in Philosophical Transactions, read at the Royal Society, which evidenced a large number of observations on the heating of different materials exposed to solar radiation. In one experiment studying solar rays through a prism, Herschel placed thermometers in various colored regions of the spectrum and also in the region below the visible, i.e., in the region adjacent to red. The thermometer placed in this latter region recorded the highest temperature after some exposure time, indicating the existence of some type of radiation, even outside the visible spectrum. He named this radiation 'Calorific Rays'. Herschel's model for light was the corpuscular Newtonian view. He also analyzed the range corresponding to the luminous spectrum region above violet but did not detect any heating in the thermometer.

The scientist to whom current texts attribute the discovery of the ultraviolet range of the solar spectrum is the physicist and chemist Johann Wilhelm Ritter (1776-1810). He named the radiations he observed 'Chemical Rays,' having passed away before the term 'ultraviolet radiation' emerged (Ritter, 1801). He was also a philosopher and was fascinated by experiments related to the excitation of muscles and sensory organs; his studies gained special attention due to his use of his own body exposed to very high voltages, which possibly contributed to his premature death. After becoming aware of Herschel's results and strongly motivated by his concepts emanating from Naturphilosophie, Ritter acquired the conviction that there would be invisible rays on the other polarity of the spectrum. He made observations using plates with chemical products and discovered that silver chloride was transformed more rapidly from white to black when placed in the region of the spectrum beyond violet. Ritter named them 'Chemical Rays'. This discovery was published with the significant title: "The chemical polarity of light" (Ritter, 1801). Ritter summarized his conclusions as follows: 1- There are rays of sunlight that do not illuminate, and of these, one part is refracted with greater intensity, and another with less intensity, compared to all the rays that illuminate; 2- Sunlight in its undivided state is a neutralization of the two exclusive determinants of all chemical activity: oxygenation and deoxygenation (= hydrogenation); 3- Through a prism, sunlight is divided into two similar poles. The red side of the spectrum and the one bordering it externally (infrared) become the side of oxygenation, whereas the violet side, on the contrary, and the one bordering it, become the side of hydrogenation. The maximum of both is outside the visible spectrum; however, their differences within the visible spectrum lie in the green region. After the identification of Chemical Rays, Ritter was responsible for the first prototype of a dry cell in 1802 and for the construction of the first electric accumulator in 1803.

Following Ritter's observations, and the subsequent year (1802), the English physicist and chemist William Hyde Wollaston (1766–1828) conducted experiments that confirmed the existence of radiation beyond violet in the solar spectrum (Wollaston, 1802). These scientists conducted their work on radiations during a period in which the hegemonic conceptions regarding the nature of light followed Newton's corpuscular model. Hence the frequent expression of 'rays' of light, heat, or chemicals. In the decades that followed these pioneering works, the formulation and widespread acceptance of the wave theory of light occurred, with Thomas Young (1773-1829) and Augustin-Jean Fresnel (1788–1827) serving as starting points. Between 1800 and 1850, many scientists conducted studies and research on the nature of these radiations, building upon the works of Herschel, Ritter, and Wollaston. Notable figures in the development of the unified solar spectrum concept, anchored in the emerging wave model of light, include Ludwig Moser, Edmond Becquerel, Macedonio Melloni, Wilhelm Eisenlohr, and George Stokes, between the years 1842 and 1854. Investigating these original articles enables the discernment of experimental procedures and reflections that established the concept of the unified spectrum of luminous radiations. This result was important for the pioneers of the rising electromagnetic theory in that period, particularly for the works of Maxwell and Hertz, which would prove the electromagnetic nature of luminous radiations.

The theme, it seems to us, has not been considered with the importance it deserves, particularly in more general books on the history of science in the 19th century, including the excellent text by Harmann (1985). There are some significant articles published in recent decades that specifically touch on the subject, but they are not many, such as the articles by Barr (1960), Caneva (1978, 1988, 1997), Lovell (1968), Hong (2003), and Frercksa, Weberb, and Wiesenfeldt (2009). An important work on Herschel's early experiments was developed in the master's dissertation of Rilavia Almeida de Oliveira (2014), supervised by Ana Paula Bispo da Silva. There, Herschel's procedures and conceptions in his first two articles on the subject of heat radiation are discussed in detail (Oliveira and Silva, 2014). However, most of the articles and books we have investigated do not address the theme we seek, which discusses the subsequent process of constructing the idea of a unified spectrum and aims to use, at least in part, such historical considerations in physics teaching, in conjunction with experiments using equipment available in the daily lives of most students.

At this stage of the work, we advocate that the use of Herschel's experiment and some experiments, which we have already employed in teaching and outreach activities and which utilize modern equipment, enables interesting moments of observation and conviction for students about the existence of 'invisible light' in the infrared range. In a second phase of the work, we intend to proceed with a more careful reconstruction of Ritter and Wollaston's experiments. This will hopefully allow us to consolidate a broader proposal on how to approach this subject in high school, drawing initial inspiration from the main developments and experiments, the historical interpretations associated with them, as well as some more recent experiments.

Method

Experiments in the Classroom on Invisible Radiation

Human vision, sensitive to electromagnetic waves, is limited in its perception to a small range of frequencies. The electromagnetic spectrum provides us with a much wider variety of electromagnetic waves existing in nature. Among the additional waves to those already mentioned, which we know through their technological use, are X-rays, endowed with higher energy, microwaves, and radio waves, with lower energy. Despite not being able to see the entire spectrum of electromagnetic radiation, humans can detect it through artificial sensors and, thus, use it in various applications. Everyday examples include microwave ovens, X-ray machines, cell phones, radios, televisions, motion sensors, etc. Understanding the electromagnetic spectrum, the various radiations, and their uses is important knowledge for a citizen in today's world. Understanding and detecting the invisible can be useful in various situations in everyday life. But how can we contribute didactically to better understand how we "see" the invisible?

In this set of proposed experiments, we aim to explore the detection of infrared radiation. There are several ways to do so. We begin the didactic proposal with Herschel's original experiment.

Experiment 1 – Herschel Experiment. The illustrated scheme in the original experiment utilizes a set of thermometers placed in the spectrum produced by a prism (Figure 1). An interesting version of this experiment was proposed and developed by Oliveira (2014).

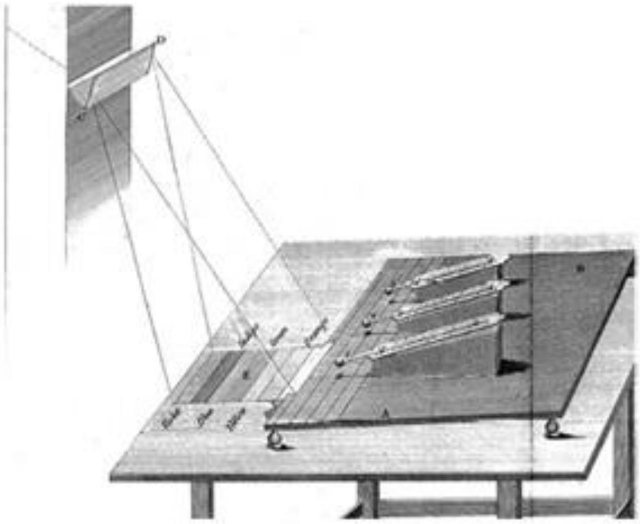

Figure 1. William Herschel's Original Experiment for Detecting Infrared Radiation

In addition to using thermometers, there are other more modern ways of detecting infrared radiation, based on the change of some physical property of materials. A particular class of materials, semiconductors, can be used for this purpose. They have the characteristic of modifying their electrical properties when subjected to radiation. Among semiconductor materials, silicon (Si) stands out the most for its commercial use. In addition to being low-cost, it is convenient for applications where it is desired to detect the visible (400 nm to 700 nm) and near-infrared (700 nm to 1400 nm) radiation range, as it absorbs this type of radiation in this range of wavelengths.

One application of silicon's optical properties is its use in visible imaging systems, such as conventional digital cameras. These cameras have a filter to block infrared radiation in order to detect only visible light. To make a popular digital camera (webcam) sensitive to both visible and infrared radiation, the infrared filter must be removed. The camera then captures images like a video camera and is sensitive to both infrared and visible light.

The Figure 2 shows the steps for identifying and removing the infrared filter, followed by assembling the lens system without the filter (Micha et al, 2011).

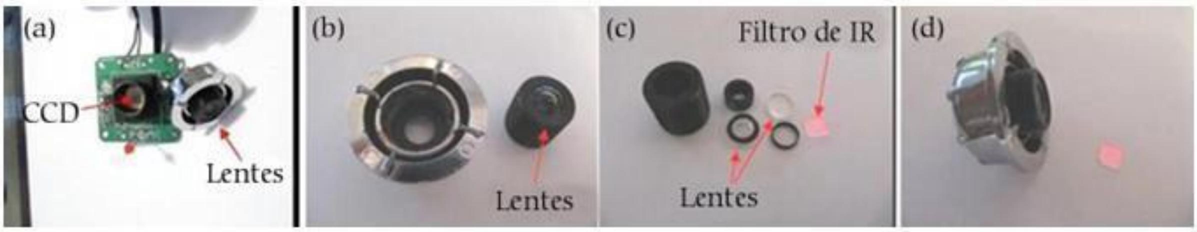

Figure 2. Sequence for Removing the Infrared Filter: (a) Disassembling the webcam, (b) Removing the lens system, (c) Separating the IR filter, and (d) Reassembling the lens system

In addition to Herschel's experiment, the suggested experiments are as follows:

Experiment 2 – "Seeing the invisible generated by a remote control": This experiment helps demonstrate that, although infrared radiation may not be well known outside technical circles, it is widely used in our daily lives in devices such as remote controls. Take a remote control and when a button is pressed, aimed at the modified webcam, the information is processed and seen on a computer screen, while the radiation emitted by the remote control is not visible to the naked eye.

Experiment 3 – "Seeing the invisible light beyond red": Use an incandescent or white LED lamp, and illuminate a CD or DVD. Through diffraction, it is possible to see a spectrum similar to that of a rainbow. By detecting this image with the modified webcam, you can perceive that, in addition to red, there is another radiation (infrared) that is not visible to the human eye.

Experiment 4 – "Seeing the heat from a resistor": By connecting a small resistor to a power source, electrical energy is transformed into thermal energy and the resistor becomes heated. Looking at this resistor with the naked eye, nothing is perceived, but when observing the same resistor with the modified webcam, it is noticeable that it is emitting radiation, which is infrared.

Experiment 5 – "Night vision": A flashlight with a visible LED bulb can have the bulbs replaced with LED bulbs that emit infrared light. In a dark environment, this turned-on bulb does not illuminate anything to the naked eye. However, when viewed through the modified webcam, the environment is "illuminated" by the invisible light.

Experiments 2, 3, and 5 have been successfully conducted on various occasions in classrooms, courses, and lectures – using the "Seeing the Invisible" kit developed by INCT-DISSE (National Institute of Science and Technology – Semiconductor Nanodevices Laboratory – PUC-RJ).

Results and Discussion

The proposal presented here aims to intertwine these two dimensions, the historical approach and the conducting of experiments on invisible radiations, in the didactic exploration of this important content in physics education: the meaning of the unified electromagnetic spectrum and its significant applications in people's daily lives. The first part of the work, the historical research, is in an advanced stage and allows for some interesting conclusions drawn from this historical journey:

i) The discovery of "calorific rays" largely stemmed from the practices of telescope construction, when it became important to analyze the heating produced by sunlight and the use of increasingly larger lenses. Perhaps it is not surprising that Herschel was the precursor, as he was the greatest telescope maker of his time, as well as a keen observer and skilled experimenter.

ii) The philosophical influence on the development of science was evident in Ritter's attitude, who, motivated by the ideas of symmetry and harmony in the Universe derived from Naturphilosophie, came to believe in the existence of radiations also on the other "side" ("polarity") of luminous radiations. He found them using other detection methods, in this case chemical reactions.

iii) The construction of the idea of a unified luminous spectrum, in which calorific rays, luminous rays, and chemical rays all have the same physical nature and are organized into a single sequence of decreasing wavelengths, occurred in a lengthy process in the first half of the 19th century. This process also depended on mathematical developments, particularly through works related to the description of wave behavior. However, the essential factor, from a physics standpoint, occurred through the elaboration and progressive acceptance of the wave theory of light, supported by various experiments, such as those of Young, Malus, Arago, and others, and the theoretical formulations of Ampère, Poisson, and Fresnel. This theory replaced the previous corpuscular model, in which Herschel and Ritter were embedded. It enabled Moser, Becquerel, Melloni, Eisenlohr, and Stokes to arrive at the concept of a unified spectrum, in which the aforementioned radiations were nothing more than waves of the same nature differing only in their frequencies. The next step, the identification of light as an electromagnetic wave, would come with the work of Maxwell, Lorentz, and Hertz.

Conclusion

A challenge to be explored in the final stage of the work, yet to be conducted, will be to present these dimensions jointly and in an integrated manner in classroom activities, seeking to link in the educational process three aspects: historical discussion, which allows showing the complexity of the process of building scientific knowledge, with the emergence of various factors (in this case technological, philosophical, mathematical, etc.) that limit, enable, or stimulate scientific advances; the use of experiments and measurements by students; and the exploration, in this process, of electronic equipment with which we interact in daily life and which embed a lot of physics within them.

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