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A Brief Review of the History of Radiative Transfer

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Abstract

The aim of this paper is to present a brief historical survey of the development of research that pertain to radiative transfer. The paper focuses on individuals in their historical context rather that on published literature. The interested reader will have to consult the papers – or selected references to these papers – in the cited literature. As this subject is vast, the space limited, and because publications where numerous after the turn of the 20th century, this review does not pretend to be exhaustive. It nevertheless constitutes a basis for any research that pertain to the history of radiative transfer, a history that necessarily goes by that of the discovery of light which occupies here a preponderant place.

Keywords: History, radiation, thermal radiation, light, infrared, visible.

1. Introduction

In his address as retiring President of the American Association for the Advancement of Science, Samuel Pierpont Langley (fig.1) had these words to write in 1889 [1]: "*We often hear (the progress of science) likened to the march of an army towards some definite end; but this, it seemed to me, is not the way science usually does move, but only the way it seems to move in the retrospective view of the compiler, who probably knows almost nothing of the real confusion, diversity, and retrograde motion of the individuals comprising the body, and only shows us parts of it as he, looking backward from his present standpoint, now sees to have been in the right direction*".

Fig.1: Samuel Pierpont Langley (1834-1906)

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In view of the accuracy of this picture painted by Langley, it is obvious that the present brief account must inevitably result in a distorted representation of the history and evolution of the understanding of the nature of radiative transfer and of the infrared properties. The context of a journal paper of a few pages does not allow for a deep review of each individual contribution. Only a small amount of information about the early workers as individuals can be provided, I regret it. Here, only relatively few papers can be cited, but these, hopefully, should provide adequate information to anyone interested in deeper details. The paper will insist on selected investigators instead of being a commented list of scientific papers. For an exhaustive historical review of the early development of the infrared spectral region, the reader should consult the excellent paper by Barr (1960) [1] or those in German by Kayser (1900) [2] and Winkelmann (1906) [3].

2. Let there be light

2.1. Greek science

Empedocles (492-432 BC) is mostly credited for the development of the concept of a universe involving four irreducible elements; water, air, earth and fire. However, we also have to acknowledge his original interpretation of light. According to Empedocles, objects emit "something" which is intercepted by luminous rays themselves emitted by the eyes. This "double emission" concept was much more complicated than the original concept of Pythagore (560-480 BC) who though that light was essentially emitted by the eyes [4].

Empedocles also taught that light takes time to travel through space, though he must have arrived at this results by reason alone for the first observational proof was not obtained until more than two thousand years later.

Ptolemy (100-170) has no relation of the Ptolemies who ruled Egypt - in fact the name Ptolemy merely indicated that he came from Egypt – but it confused medieval and some later scholars who were moved to always portray him wearing a crown!

He was much more clever assessing intrinsic properties to objects. His theory included the ideas of color as an inherent surface property of bodies as well as those of diffuse and specular reflection. His experiments on refraction, permitted him to derive laws that are analogous to those "discovered" by Snell in 1621, about 1500 years later. He used the well-known experiment of a coin lying on the bottom of the vessel but hidden by the rim that becomes visible, at the same angle of sight, when water is poured in. Ptolemy was a physicist of considerable ability encompassing subjects as music, mathematics, astronomy, geography, art, geometry, etc.

With Ptolemy, we come to the last great figures of the Greek science, and at the end of an astonishing intellectual development that was Greek in origin.

2.2. Arabian science

The history of science in Arabia is largely the history of science in Islam. Yet it is not wholly so, for science began some centuries before the time of Muhammad in the land which was to be the cradle of the Muslim civilization. For the present purposes, we mainly concentrate on the so-called golden age of Islam, from the eight century AD to the eleventh when Islamic cultures flourished in Spain, North Africa, Syria and Iran. Islam plays a crucial role in the world history, both as an important civilization in its own right, but also as an intermediary between the Antiquity and the early modern world.

Abu Yussif Al-Kindi (801 -) is sometimes referred to as the "first Arabic philosopher". Al-Kindi did not confine himself to philosophy: he took great interests in various branches of science. Among thermoptics, he was the first (as the Mohists' work was not known) to emphasize the fact that light travels in straight line.

Known to the medieval scholars as Alhazen [5], ibn al-Haytham (965-1040) can be considered as the greatest Islamic physicist. Born at Basra in Iran, he moved to Cairo to lead what was outwardly a rather disastrous career. It seems that when he arrived in Egypt, he witnessed the annual inundation of the Nile and assumed that this occurred because there was no proper control of the river. He then obtained the patronage of the caliph to finance an engineering expedition. Alas, he soon realized that if anything could have been done, the ancient Egyptians would have done it! Fearing for his life, he decided to feign madness. He remained under house arrest until the caliph died!

When once again free to pursue learning, al-Haytham was in his late fifties and most of his decisive scientific work was still to be accomplished. Though al-Haytham's optical work was based on Greek elements, particularly from Ptolemy, his analysis and treatment are absolutely genuine. Light, said al-Haytham, is something emitted from every self-luminous source. He considered a primary emission, in straight line, as well as a secondary emission, in the form of a sphere. He then introduced the basis of specular and diffuse reflection. This was original thinking indeed, really enshrining the principle of secondary wavelets proposed six centuries later by Christian Huygens.

Al-Haytham described colours as being real and distinct from light although always "blended" with it. He also studied reflection, refraction, diffraction. He also introduced the ideas of pencil of light. Finally, he strongly rejected the idea that light was emitted by the eye. And, although he did not talk about the formation of an image inside the eye, he discussed the optic nerve and its connection with the brain.

He concluded that light refraction was caused by different speeds of propagation in different materials. His law of refraction were used in the seventeenth century by both Kepler and Descartes.

Nowadays, who cites the papers of an author published nearly a thousand years before.

Without his failure at the source of the Nile, we may have had to wait for a long period for such clever scientist in what we know today as radiative transfer.

2.3. Chinese science

Until the 1960's, little was known in the west about the history of the development of Chinese science. [4].

It is worth noting that they had a metric system very early on and were also among the first when it came to problems of statics for the Mohists were already making worthwhile contributions to this in the fourth century BC. It was the Mohists, moreover, who began the study of optics in China discussing shadows and early appreciating that light travels in straight lines. They also experimented the "camera obscura", and knew how the image of a distant scene is turned upside-down when light passes through a pinhole. Flat and concave mirrors were also objects of study and the Mohists knew the concepts of "real" and "virtual" images given by the latter. In all of this, they seem to be have been ahead of the Greeks, who, as mentioned earlier, had false ideas about light and vision at the same period.

The concave mirrors were used to set up fires and large metal mirrors were common, but glass mirrors were unknown. Although they used crystal lenses of various shapes, they were not lead to invent the telescope or to wear spectacles. As Mohists were not diffusing their knowledge, we still do not know much about Chinese science.

2.4. Medieval science

The science of radiation was reborn in Occident with the work of Robert Grosseteste (1168-1253). Grosseteste [6] lived in times where philosophy and theology were about to be separated of science. Science, he said, began with man's experience of phenomena. Its aim was to discover the "reasons" for the experience, the "casual agents". Then, the next step was to analyse the causes, breaking them down to principles or component parts. After, the observed phenomenon had to be reconstructed form the principles on the basis of hypothesis which were to be verified or disproved. He was then a rigorous experimentalist.

Although the idea of a "law of nature" rather than a "law of God" was revolutionary, Grosseteste brought English Franciscans to study mathematics and natural science and he became the bishop of Lincoln in 1235. Although the idea he was promoting could have been challenged, he always managed to keep an immense influence and profound effect on Christian philosophy.

His work in optics (fig. 2) focussed on diffraction by spherical lenses and on reflection (he was stimulated by translations of al-Haytham's work). For him, light was the first form of prime matter to be created. He provided an interestingly scientific interpretation of the creation text in the first chapter of the Genesis, Let there be light.

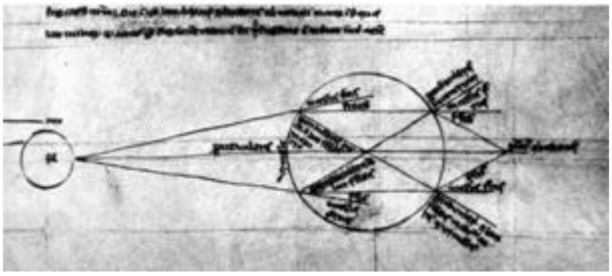

Fig.2: Diffraction of light, schematic by Grosseteste [4]

Although Grosseteste seems to have carried out astronomical observations, we have to wait until Roger Bacon (1220-1292) to obtain the principle of the telescope. "For we can so shape transparent bodies and arrange them in such a way with respect to our sight and objects of vision, that the rays will be bent in any way we desire, under any angle we wish… so we might cause the Sun, Moon in appearance to descend here below [7]

Bacon [7] was the most gifted student of Grosseteste but his inflexible temper send him to jail as he proclaimed that reason was prevailing over revealed knowledge. He also claimed that natural science led not only to a knowledge of things, but also to a knowledge of their creation, both forming a unity under the guidance of theology. But did he really believe in God? This particular time of pre-Renaissance must have been hard for such minds. His work concerned with radiative transfer was focussed on optics and, more specifically, on the human eye (fig. 3). He also worked with shadows, eyes, spectacles, etc. Indeed, this is the first text to describe thermal radiative transfer and to propose a measurements of radiative intensity (Photismi de lumine, published in 1567). But we have to wait for another 233 years for an official discovery of infrared radiation.

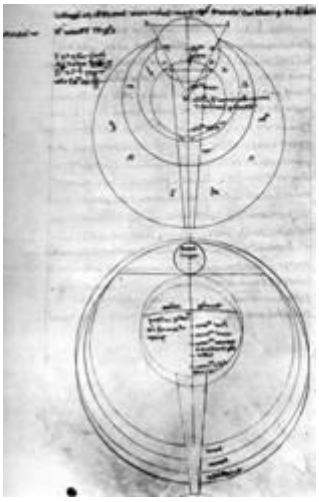

Fig.3: Study of the structure and optics of the eye by Bacon (1268) [4]

2.5. Renaissance

One of the major figure of the 17th century science was Isaac Newton (1642-1727). What is mostly surprising of his contribution to radiative transfer is that Robert Hooke (1635-1703) was, for his whole life, fiercely opposed to the ideas of the young Newton [8]. We had to wait for 30 years for the publication of his work on optics (fig. 4). And this publication, the Principa, has been made possible by Edmund Halley [9] who persuaded Newton and paid for the publication of the Principia. It is worth noting that the plague of London played a dominant role on the theory of optics as the young Isaac was confined outside the city and spend several months wandering about light on the properties of his parents.

Fig.4: Decomposition of light by Isaac Newton

Another scientific who came to optics by accident was Augustin Jean Fresnel (1788-1827). Fresnel was a brilliant royal engineer when Napoleon came back. Forced to exile, he started his series of experiments and later presented his work to Arago (1786-1853). The scientist was impressed. After the fall of Napoleon, Fresnel was rehabilitated in his original position but he pursued his work till the end of his life. His work on diffraction are schematically described in figure 5. It is worth noting that the discoveries of Fresnel about wave propagations in 1815 were already known to Young (1773-1829) for 14 years, and just on the other shore of the Channel [10]. Could we imagine today several scientists working on a subject and not being aware of the work of anyone else?

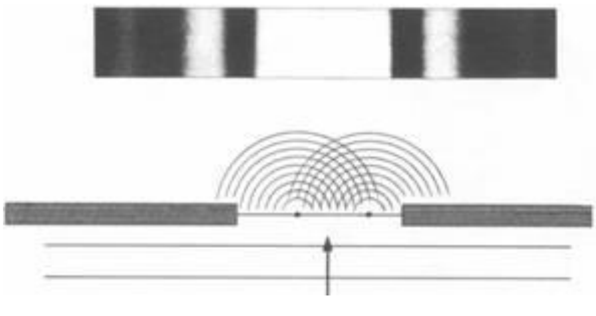

Fig.5: Schematic of Fresnels's work (1815) [10]

3. The discovery of infrared

Studies of radiation interchange in a system have been conducted for many years, as evidenced by François D'Aguillon's paper written in 1613. However, Pierre Bouguer (1698-1758), who was Royal Professor of Hydrography at the age of fifteen, was the first scientist to show on a quantitative basis how light intensities could be compared: he essentially derived an expression for the attenuation of light in a participating medium that is still used today.

The infrared region might well have been discovered by the Italian Landriani (fig.6) who seems to have been the first (may be about 1777) to examine the solar spectrum by passing a simple thermometer through it [11]. Rochon and Senebier made similar experiments. They likewise let the official discovery elude them: their work passed without notice!

Fig.6: Marsilio Landriani (1698-1758)

The discovery of the infrared region was finally made (or acknowledged) in the spring of 1800 by Sir Frederick William Herschel (1738-1822) mostly known for his discovery of Uranus. The young William [12], along with his nine brothers and sisters, became oboist in the Hanoverian guard has his father saw to it that his children became musicians. He moved to London and earned his living by giving music lessons. Astronomy was for him at first just a plain hobby! He eventually started to make telescopes and finally was able focus on astronomy after his marriage to a wealthy widow.

Herschel's (fig.7) first paper (with a delightful concise title): *Investigations of the Powers of the prismatic Colours to heat ad illuminate Objects: with Remarks*, that prove the different Refrangibility of Radiant Heat. To which is added an *Inquiry into the Method of viewing the Sun advantageously, with Telescopes of large Apertures and high magnifying Powers*, described his efforts to find a suitable color for a glass filter to be used for solar observations, so that it would transmit most light and least heat.

Fig.7: Sir Frederick William Herschel (1738-1822)

In the paper Herschel enthusiastically wrote: "*It appears that the maximum of the full red falls still short of the maximum of heat; which perhaps lies even a little beyond visible refraction. In this case, radiant heat will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light!*".

In his second paper, he summarised his intensity measurements in the curves shown in fig.8. It can be noticed that he divided the visible spectrum in the domains earlier proposed by Newton himself and that he spotted the maximum of visible light in the yellow-green region. In this figure, the shaded areas clearly indicate the maximum of heat is beneath the visible spectrum.

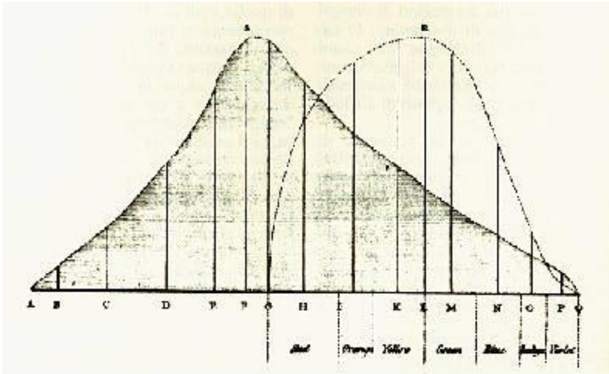

Fig.8: Herschel's distribution of the solar spectrum: A) "relative heating effect"; B) "relative luminosity"

André Marie Ampère (1835), and James David Forbes (1835) later provided confirmatory evidence that visible light and infrared radiation were identical in nature [1].

4. The measurements of infrared

In the early 19th century, there was a crucial need for a device that could undeniably confirm that heat and light where part of the same "family", that of radiation. In these years, and for most of the 19th century, it appeared to most scientists of that time that there were three kinds of radiation, "caloric", "luminous", and "actinic". In 1872, we find John Draper stating that "*the general opinion held at the present day as to the constitution of the spectrum is this, that there exist a heat spectrum in the less refrangible regions, a light spectrum in the intermediate, and a spectrum producing chemical reaction in the more refrangible regions*".

In 1829, Leopoldo Nobili (1784-1835) refined Seebeck's thermocouple into the more sensitive thermopile. Nobili [13] was then living near Parma (at Reggio) where Macedonio Melloni (1798-1854) taught at the University. Intrigued by the novel device, Melloni eventually suggested modifications that made the "thermomultiplicateur" suitable for radiation measurements.

The "thermomultiplicateur" was capable of detecting radiation from a person at a distance of 8 to 10 meters. This instrument (fig.9), used a stack of about 30 small rods of bismuth and antimony, connected so that the hot junctions formed one face of a cube and the cold junction the other [14]. The output of the thermopile was connected with the terminals of the sensitive, two-needle “multiplicateur”. The advantage of this instrument over the thermometer is two fold: (1) fast and high response; (2) the absence of the masking effect of the glass bulb. For details, the interested reader should consult La Thermochrôse ou la Coloration Calorifique printed in Napoli in 1850 (reprinted in facsimile in 1954).

Concerning the work of Melloni, Langley said: “ …*of all the great students of our subject, who in reference to what he accomplished, made the fewest mistakes*”. His work involved measurements of reflection and absorption [1]. He also mentioned that the position of the solar radiation peak varied from day to day, and properly concluded that this was due to subtle variations in the absorption of the atmosphere.

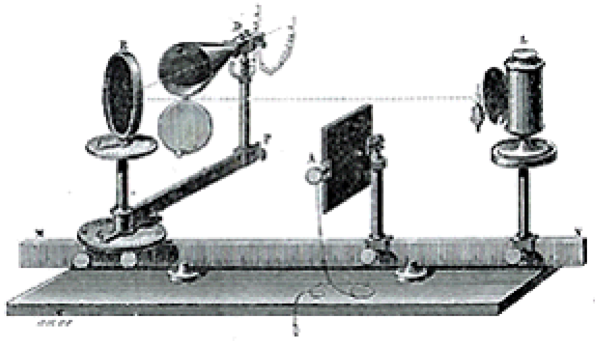

Fig.9: The Melloni thermomultiplicateur in use.

When it comes to light de composition, the spectroscope of Fraunhofer (1787-1826) (fig. 10) and that of Kirchoff (1824-1887) (fig. 11) must be mentioned here as the relevant instruments to improve the global understanding of the electromagnetic spectrum. It is by building out the Young-Fresnel theory that the young Fraunhofer [21] has been able to measure the darkest wave-lengths of the spectrum.

Fig. 10: The spectroscope of Fraunhofer [15]

The decade 1880-1890 saw the introduction of three high-sensitivity devices for infrared radiation: Langley's bolometer (fig. 12), Pringshiem's radiometer, and Boy's radiomicrometer [1].

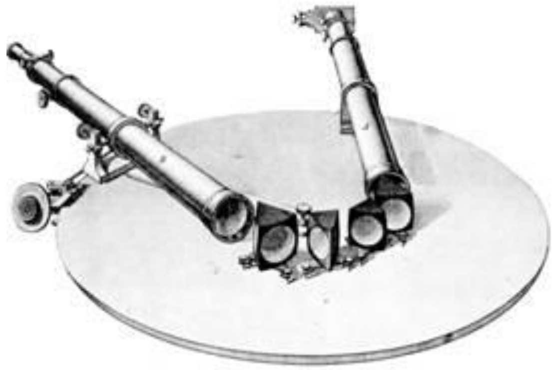

Fig.11: The spectroscope of Kirchoff [16]

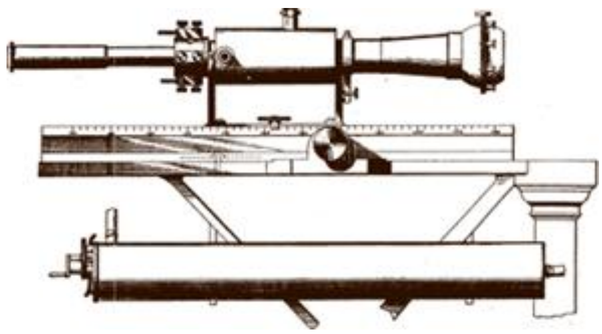

Fig.12: The bolometer of Langley [17]

What could be considered as the last series of tests that confirm the identical nature of light and infrared was proposed by Fizean (1819-1896) and Foucauld (1819-1868). With very fine thermometers, for which telescopes were required for observation, they were the first to detect fringes interference in the infrared region. They were also able to confirm the conclusions of Melloni who claimed that electromagnetic waves were absorbed by the atmosphere.

5. The relation between temperature and radiation

In 1889, Langley said: *“Immediately before us ... there is one great problem waiting solution. I mean the relation between temperature and radiation”*. At that time, as reported by Barr [1], the only known relations were those of Gustav Robert Kirchhoff and the empirical relation of Joseph Stefan, which was theoretically validated by Ludwig Edward Boltzmann, known as the Stefan-Boltzmann law for blackbody emissive power.

Wilhelm Carl Werner Otto Fritz Franz (Willy) Wien derived the displacement law in 1891 by consideration of a piston moving within a mirrored cylinder. The interesting result about this law is that Wien spotted a peak in blackbody emissive power at about 0.8 μm at a body temperature of 6000K. *Almost exactly where Herschel found his maximum 91 years before!!*.

Measurements of blackbody radiation at various temperatures were begun by Otto Lummer with Willy Wien in 1896, but his work with Ernst Pringsheim is most famous, their experimental curves for blackbody having been reproduced many times since their first publication.

Lord Rayleigh, in 1900, and Sir James Jeans, in 1905, based their relations for the spectral distribution of radiation on the assumption that the classical idea of equipartition of energy was valid [18]. The fact that measurements and some theoretical considerations indicated that Wien's expression for the spectral distribution is invalid at high temperatures and/or large wavelengths, led Max Ernst Ludwig von Planck to an investigation of harmonic oscillators that were assumed to be emitters and absorbers of radiant energy. Various further assumptions as to the average energy, led Planck to derive both the Wien and Rayleigh-Jeans distributions.

Planck finally found an empirical equation that fitted the measured energy distributions over the entire spectrum. In determining what modifications to the theory would allow derivation of this empirical equation, Planck was led to the assumptions that form the basis of quantum mechanics.

The derivation of the approximate spectral distributions of Wien and of Rayleigh and Jeans, the Stefan-Boltzmann law, and Wien's displacement law are all seen to be logical consequences of the spectral distribution of intensity as derived by Max Planck (fig. 11). However, as discussed by Siegel and Howell [18] it is interesting to note that all these relations were formulated prior to the publication of Planck's work [19] thus confirming the opening words of this paper by Langley.

6. The engineering applications

After the turn of the 20th century, many scientists and engineers became involved in radiative heat transfer measurements and calculations and a review, even pretending being exhaustive, cannot encompass all the contributions. Therefore, this review will end up at the turn of the 20th century.

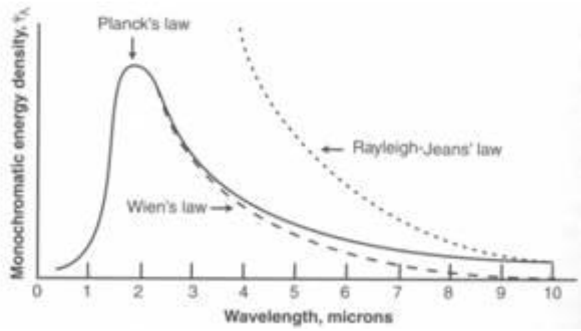

Fig.11: The spectral distributions of Wien, Planck, and Rayleigh-Jeans [18]

7. Conclusion

The objective here certainly was to carry out a review of the research on radiative transfer over the centuries. Nevertheless, the review is still incomplete, details could be added, others may be withdraw.

But here the author mostly wanted to highlight several elements of the destiny of the investigators that made possible the discoveries of theories put forward at specific moments of the development of radiative transfer science.

Some of these details tend to demonstrate that science evolves like a crowd that is going out of a stadium. In fact, every single individual follows his own path, apparently not related to that of a neighbour. But the historian, describing the event "a posteriori" can only conclude that the stadium is empty as if the whole movement was carefully planned and organized.

As a result, there is a major difference between the motivations, the errors, the contradictions of scientists and the report we later find in textbooks. And to exemplify that, was one of the goals of this paper.

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