Melloni's Experiments and the Search for the Nature of Infrared Radiation

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Abstract
We repeated the historical infra-red radiation experiments performed by Melloni, to investigate why, at the end of his life, he came to the conclusion that radiation from light and heat rely on the same basic principle, what has been translated as the so called unitary formalism. In doing so, we profited from a Master thesis on heat radiation and Melloni's related effort, organized by our museum. We also investigated how Melloni fits into Kuhn's structure of scientific revolutions, and concept of paradigm shift, with Melloni's experimental work in mind. We conclude that Melloni did not come to this opinion on the unitary principle of the phenomenon of light and heat on the basis of any philosophical considerations, but on facts and observations and similarities between both phenomena.
Keywords: Macedonio Melloni, Leopoldo Nobili, infrared radiation, heat radiation, light emission, polarization, unitary theory of heat and light, pluralistic theory, metaphysical explanation

INTRODUCTION

The Ghent University Museum for the History of Sciences holds a large collection of historic scientific instruments, mainly originating from the university's rich academic past. These instruments refer as well to the academic as to the educational activities of Ghent University and comprise, amongst others, the scientific collection related to the Ghent physicist Joseph Plateau (1801-1883) (Wautier, Jonckheere, & Segers, 2012). This collection not only refers to his studies on the after-effects of light and on surface tension, but also to his educational activities as reflected by the so-called 'Cabinet de Physique' he purchased for demonstration in his courses. One of the key items in this educational demonstration cabinet is a specimen of Melloni's bench.

As part of the museums on-going efforts to restore its substantial collection of scientific instruments and extend its knowledge, Melloni's bench was recently restored, studied and tested, within the framework of a Master thesis in the Department of Physics and Astronomy. The results of these efforts are presented here.

The purpose of this paper serves several topics:

a) An educational part: In contemporary modern physics courses, nothing is mentioned on Melloni as a scientist in the study of heat radiation. In this paper we will elucidate the

person Melloni and his scientific work performed in the period well before the formulation of the electromagnetic theory by Maxwell (1831 – 1879) (Maxwell, 1873). From then on it was clear that electromagnetic radiation with different wavelengths existed and that light and heat radiation was of the same nature.

b) To better understand the elaborate and delicate experimental work of Melloni in the search of the nature of heat radiation we repeated the experiments and complemented them with modern experimental techniques.

c) In addition, we will spend some further thinking on the intellectual importance of Melloni's effort, related to Kuhn's theory on scientific revolutions and the paradigm concept. We will investigate why Melloni, at the end of his life, pronounced himself in favor of a unitary theory between light and heat. This explains why we attach so much importance to the polarization of heat radiation.

Macedonio Melloni – A Short Biographical Sketch

Macedonio Melloni was born at Parma in 1798. In 1824 he became a professor at the university there but had to escape to France after his contribution to the revolution in 1831.

He started his main work on infrared radiation in 1831, and continued it in exile in France, where he stayed till 1839 to study radiation by means of the thermopile, aiming at discovering the similarity or difference between heat and light (we will use the words unitary and pluralistic in this context). He then returns to Naples to become the director of the oldest volcano-graphic institute in the world, the Vesuvius Observatory (the Osservatorio Vesuviano) and stayed there until 1848.

He became famous for his experiments on heat radiation, performed with his "Melloni bench", a kind of optical bench used for the investigation of infrared radiation. He investigated the heat transmission through different materials, considering as well reflection as polarization. The details of his work are described in the next paragraph.

He had a close collaboration with Leopoldo Nobili (1784-1835), living in the neighborhood, who was a famous instrument maker at that time, and who was instrumental for the galvanometer construction.

After Melloni, the infrared science moved back to Germany, to continue the optics research tradition, mainly for the practical purpose of its application in the Auer light bulbs.

It is well known today that the detailed examination of the radiation laws has led to the discovery of quantum mechanics in an effort to bridge long and short wavelengths of the electromagnetic spectrum.

During his life, Melloni received many honors: the Rumford medal of the Royal Society (1834); Correspondent of the Académie des Sciences (1835); Foreign member of the Royal Society (1839); Foreign member of the Royal Swedish Academy of Sciences (1845). He died of cholera at Portici near Naples in 1854.

Despite the importance of his work, considered in the historical context, Melloni seems to have escaped most of the historic accounts. A German overview of infrared research, with the invention and development of quantum mechanics as the culminating point, simply mentions Melloni on the first page in no more than one sentence (Schaefer, & Matossi, 1930). He was in correspondence with Faraday, leaving no trace, and he is not mentioned in Maxwell's far-reaching monograph on electricity and magnetism. These observations will be considered later in this paper.

Melloni's Bench – A General Description Of The Original

Melloni became best known for his experiments on heat radiation, performed with his bench. This was an optical bench that served to align the thermocouple with the heat source. The

thermocouple signal was recorded by the improved galvanometer that was developed in close collaboration with Nobili.

In his 1850 work "La thermochrôse ou la coloration calorifique" (Melloni, 1850), concluding his lifelong research, Melloni describes extensively his thermo-multiplier and experimental setup. For his investigations of the transmission of heat radiation through various materials, Melloni used 4 kinds of heat sources, given hereafter. Figures 1, 2 and 3 show the bench and the first 3 heat sources together with the galvanometer.

1. Leslie cube with boiling water

A copper cube is filled with boiling water and kept boiling. This happens with a small flame, allowing to keep the recipient at a constant temperature of 100°C. The recipient is known as the Leslie cube and has three sides in raw metal copper, the other painted in black. By turning the cube, Melloni could also investigate two "qualities" of heat radiation, including black radiation.

2. Hot metal plate

An alcohol light is placed behind a vertical, black painted metal plate of 0.3 mm thick and approximately 20-cm² size. The temperature of the metal rises until an equilibrium is reached between the heat from the flame and energy losses to the air. Melloni could test the constant temperature with his thermo-multiplier. A heat source of 360°C to 400°C was obtained this way. He estimated the temperature with the "mixing method", based on a calibration method of heating of a defined quantity of water by a calibrated heat source. A simple approximation of the second source temperature is obtained by adjusting the ratio of the temperature differences of the water.

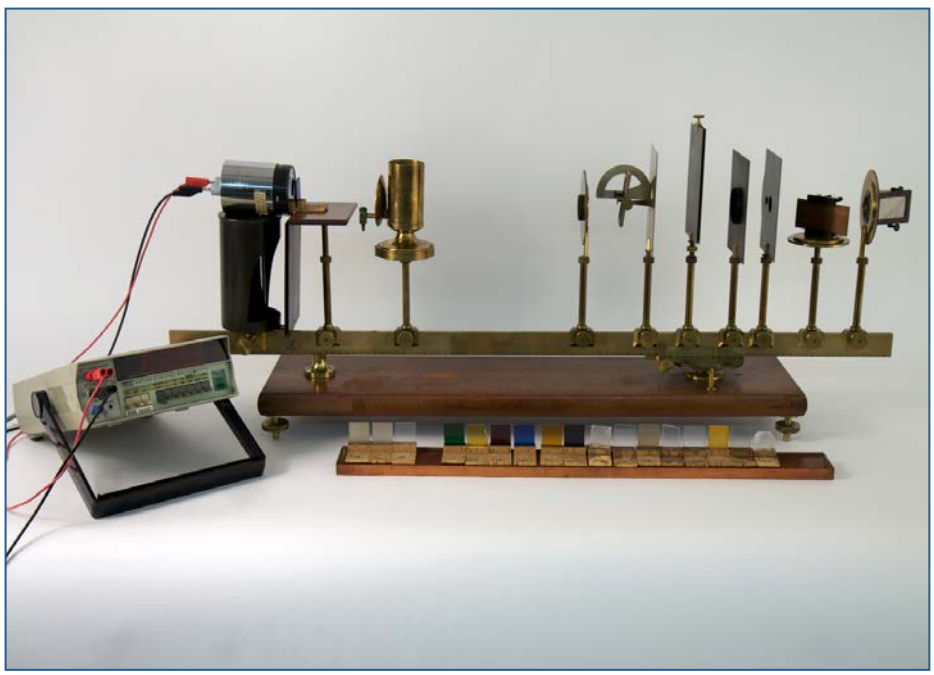

***Figure 1**. Experimental setup. Bench of Melloni (original) with Locatelli's lamp, the filters, thermopile and digital voltmeter. The thermopile and digital voltmeter shown here are modern instruments*

3. Glowing platinum wire
   The alcohol lamp is used to bring a platinum wire to white glowing. The flame has to be as stable as possible, the reason why small flames were applied. Melloni describes his flame as being approximately 15 mm high and 8 mm wide. The platinum wire (0.5 mm diameter) is bend as a spiral in a cone form compatible with the flame. The platinum wire is attached to a vertically movable bar, to allow the last coil to be at the height of the alcohol flame.
4. Lamp of Locatelli
   Here too Melloni uses the alcohol light whereby the fuel in now kept in a small cylindrical container. The fuse is placed in the focal spot of the polished copper reflector. To keep the flame sufficiently constant the fuse is made compact, thick and impregnated with salt to fix all kind of heterogeneous particles. One knew at that time that the combustion of such carbon particles produced very clear light.

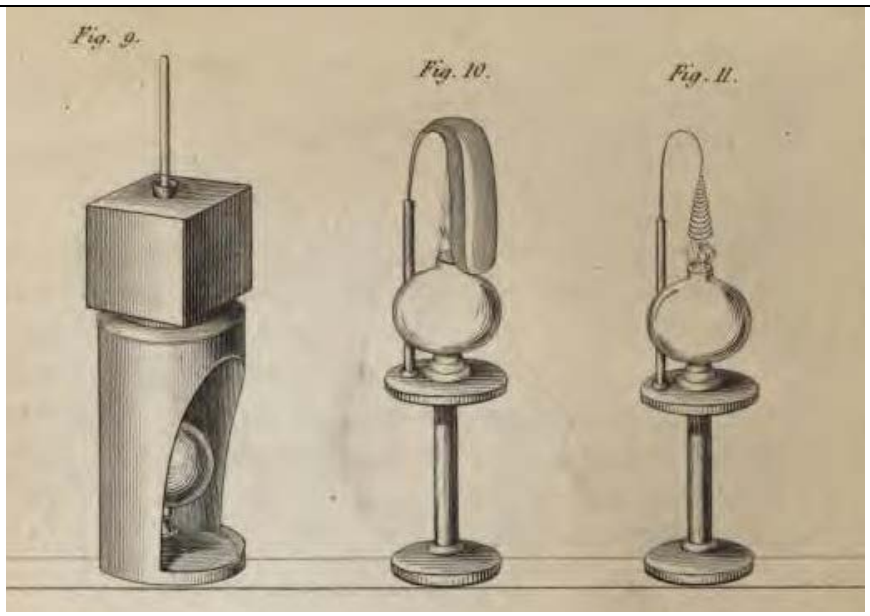

***Figure 2**. Heat sources – Leslie cube, metal cap and incandescent platinum wire; the lamp of Locatelli is not given.*

***Figure 3**. Galvanometer.*

In general, the heat sources must be easily reproducible and must be sufficiently invariant during the experiment. This last requirement can be controlled by the galvanometer reading. Melloni made the remark (Melloni, 1850) that this last condition is not evident. Especially with the platinum wire he noticed a constant deviation of the galvanometer. He also remarks that the platinum wire does not glow uniformly: the upper wirings of the spiral looked less pronounced than the lower windings.

To measure temperature differences, Nobili applied the Seebeck effect, discovered by Johann Seebeck (1770 – 1831) in 1831: in an electric circuit, junctions of different metals on different temperatures, produce a thermo-electric tension (Schettino, 1989). Melloni adapted the prototype development to a very accurate measurement instrument, the thermo-multiplier. The voltage measurements also depend on the nature of the materials used, but is optimized using bismuth and antimony. This setup constitutes an extremely sensitive device.

Based on the many experiments (Melloni, 1833) Melloni optimized different parameters. He used many thermocouples in series, resulting in an increased voltage difference between the room temperature and the radiation.

Because Melloni wanted to use his equipment to prove the polarization with tourmaline, he limited the extension of the elements to optimize the response time (Cromphout, 2011). The different thermocouples were put in series in a cube form, taking care of sufficient separation between the thermocouples, unless in the connection points (Melloni, 1850).

To effectively measure the temperature difference, the current was measured with the galvanometer. The current generates a magnetic field that has to be substantially higher than the earth magnetic field, to move the needle. Because Melloni's experiments dealt with very weak currents, he made some adaptations to overcome the inconveniences: first an adaptation of the copper wire to balance the wire resistance and the magnetic field of the coiled wire, and second, the use of a double needle working in balance and the free hanging of the coil. This resulted in an increased sensitivity of a factor three to four thousand (Melloni, 1850). In this way he laid the basis for further galvanometer development, and these improvements are still applied in modern galvanometers.

To minimize the heating up of the equipment, Melloni avoided as much infrastructure as possible. He also equipped his thermopile with a conic reflector to collect the heat radiation coming from large surfaces at a distance. This version was also found in our museum, but did not work anymore.

Melloni mentions that his thermo-multiplier reacts 20 to 50 times faster and that the sensitivity is 40 to 50 times higher than the equipment in use at that time (Schettino, 1989).

The exact response of Melloni's thermo-multiplier to a temperature difference was not described, but research with a similar well conserved thermo-multiplier shows a value of 40 µV/°C in the interval between 20 and 100 °C (Schettino, 1989).

Melloni knew about different side effects that could not be excluded. He explicitly mentions the temperature changes of air and absorber materials. To more or less correct for this, he made several measurements and relied on the mean value. He doubted too that galvanometer deviations could be due to the human body radiation during the experiment, and even tries to correct for it. No numerical values could be found on magnitude in neither his main work nor his reports (Melloni, 1833; Melloni, 1850).

In this way, experiments were made on 36 different absorber materials of each 2.6 mm thickness, exposed to heat radiation of the four heat sources. A listing of Melloni's absorber materials is given in table 1 (Melloni, 1850). The positioning of the heat sources is defined by a galvanometer deviation of 30° for free passage of the radiation.

For his research of heat transmission through different absorber plates, Melloni put the heat source on one side, and the thermo-multiplier on the other side. Behind the heat source was a screen with circular opening of variable diameter. All flags can move over the bench, and fixed with screws, and height adjusted. The thermo-multiplier can be adjusted so as to have its axis coinciding with the axis of the heat radiation. To measure the background radiation, a metal screen was placed in front of the heat source.

Reconstructing Melloni's Bench and Testing

In order to be able to perform the work planned for the master thesis (Cromphout, 2011), including a repetition of Melloni's famous historical experiments with modern electronic instruments (present-day thermopile and digital voltmeter), we used the Melloni bench of the museum that was made operational. Because solid materials form the basis for Melloni's further research (Melloni, 1850), we concentrated on the heat transmission through solid materials. In the museum only 18 filters were available, as given in table 2. The filters

available in the museum do not all have the same thickness: 10 filter thicknesses vary between 2.50 mm and 3.00 mm, another 7 show variations between 3.55 mm and 4.40 mm and 1 filter has a thickness of 6.25 mm. The relative uncertainty on all the values is 0.05 mm. Comparison of the relative absorption will allow an adjustment of this thickness difference.

Table 1. *Melloni's table of absorbing materials with transmission values* (Melloni, 1850)

TABLEAU I.

Numéros d'ordre	Noms des substances interposées réduites à une épaisseur commune de 2, 6 millimètres	Transmissions calorifiques (en centièmes de la radiation incidente) pour la lampe de Locatelli	pour le platine incandescent	pour le cuivre à 400°	pour le cuivre à 100°
1	Sel gemme (limpide)	92,3	92,3	92,3	92,3
2	Soufre de Sicile (jaune)	74	77	60	54
3	Spath fluor (limpide)	72	69	42	33
4	Sel gemme (louche)	65	65	65	65
5	Béril (jaune verdâtre)	54	23	13	0
6	Spath fluor (verdâtre)	46	38	24	20
7	Spath d'Islande (limpide)	39	28	6	0
8	autre espèce (limpide)	38	28	5	0
9	Verre (limpide)	39	24	6	0
10	autre espèce (limpide)	38	26	5	0
11	Cristal de roche (limpide)	38	28	6	3
12	Cristal de roche (enfumé)	37	28	6	3
13	Chromate acide de potasse (orangé)	34	28	15	0
14	Topaze blanche (limpide)	33	24	4	0
15	Carbonate de plomb (limpide)	32	23	4	0
16	Sulfate de baryte (louche)	24	18	3	0
17	Feldspath adulaire (louche)	23	19	6	0
18	Améthyste (violet)	21	9	2	0
19	Ambre artificiel (jaune)	21	5	0	0
20	Aigue marine (vert bleuâtre)	19	13	2	0
21	Agathe (jaune louche)	19	12	2	0
22	Borate de soude (louche)	18	12	8	0
23	Tourmaline (vert foncé)	18	16	3	0
24	Gomme commune (jaunâtre)	18	3	0	0
25	Spath pesant (louche veiné)	17	11	3	0
26	Sélénite (limpide)	14	5	0	0
27	Acide citrique (limpide)	11	2	0	0
28	Carbonate d'ammoniaque (louche strié)	12	3	0	0
29	Tartrate de potasse et de soude (limpide)	11	3	0	0
30	Ambre naturel (jaune)	11	5	0	0
31	Alun (limpide)	9	2	0	0
32	Colle forte (brun jaunâtre)	9	2	0	0
33	Sucre candi (limpide)	8	1	0	0
34	Spath fluor (vert foncé veiné)	8	6	4	3
35	Sucre fondu (jaunâtre)	7	1	0	0
36	Glace (limpide)	6	0,5	0	0

The heat radiation falls on the absorber material and further reaches the thermopile. This causes a deviation on the galvanometer. In order to check whether this deviation is due to the transmission or to the heating of the material (becoming a radiator itself), we checked if the lateral deviation was equal to zero. After this check the thermopile is put back along the axis of the radiation to make a second measurement, expecting the same result. To shield the setup as much as possible from other heat sources and airflow, metal screens were placed along the bench.

We used identical heat sources as were used by Melloni himself, being the lamp of Locatelli with the alcohol flame, the lamp of Locatelli with a black cap in front, lamp of Locatelli with glowing platinum wire, the cube of Leslie.

Measurement geometries were arranged to have the heat source, absorber plate and detector aligned, to result in a distance between source and detector of around 10 cm, with in between them the table to position the absorber plates. This setup was maintained as the standard configuration. The distance between filter and detector was approximately 0.6 cm.

All transmission measurements on the 18 absorbers were performed 3 times.

The cube of Leslie was not available any more, but we made a copy, based on Melloni's description: a copper cube of 6 cm side, one side painted in black, like the original and a wall thickness of 2 mm. A comparison was made of the thermocouple measurements, facing the black side and the raw metal side of the Leslie cube, when filled with boiling water and kept boiling using a simple candle underneath. We found 0.247 mV and 0.060 mV on the black, respectively copper side. The results give a mean factor 4.11 difference between both sides.

Concerning the other heat sources, Melloni mentions an alcohol lamp, without mentioning what fuel was used, but we used methanol. In a first approximation the lamps can be considered as black radiators and precise knowledge of the fuel is not so important to estimate the wavelength dependency of the heat intensity.

As the available thermopile did not work anymore and could not be repaired, it was replaced by a commercial CA1 thermopile from Kipp & Zonen (Netherlands).

Thin metal strips (thickness 5 μm) were painted in black, absorbing radiation. Each strip consists of manganin (82-85% copper, 12-15% manganese, 2-4% nickel) and constantan (55-70% copper, 30-35% nickel, 1% manganese), that forms a thermocouple with low heat capacity and a thermal electro-motive force of 36 μV/°C. In the CA1 thermopile 20 of these metal strips are in a serial connection to form a thermopile, with a sensitivity of 720 μV/°C. Apart from that, 2 times 10 thermocouples are in series with a voltage compensation outside the radiation field. In this way, the effect of heat on the strips due to heating or cooling of the thermopile is strongly reduced. The spectral sensitivity is in principle constant in the UV till IR range, which makes the detector optimal for our investigations.

The characterization of the different absorbers was made by actual methods.

A Varian Cary 500 (an IR-UV spectrophotometer device) was used to define the wavelength dependency of the transmission between 200 and 3000 nm.

Because the used heat sources also emit radiation with a wavelength above 3000 nm, we also performed measurements in the far IR with the help of the Fourier Transform Infrared spectroscopy (FTIR). In this way we could determine the transmission for radiation between 2000 and 25000 nm. The FTIR technique allows simultaneous measurements for all wavelengths, being complementary to the Cary 500 spectrophotometer (Newport, 2011).

To identify the composition of our filter materials, we used X-ray diffraction (XRD) and secondary electron microscopy (SEM). The result of this characterization effort is given in table 2. Obviously, there can be no traceability to Melloni's sample inventory, as this is different in number and specie.

***Table 2**. Identification of the filters*

Filter #	Material
1	Opaque glass with traces Chlorine and Magnesium
2	Opaque glass with carbon, oxygen, sodium, sulphur, potassium, calcium and traces of aluminum
3	Transparent glass
4	Blue glass
5	Green glass
6	Yellow glass
7	Glass with red surface layer
8	Blue glass
9	Orange glass
10	Dark purple glass with lead and traces manganese and nickel
11	Salt crystal (NaCl)
12	Single crystal quarts (SiO_2)
13	Poly crystal quarts (SiO_2)
14	Calcite ($CaCO_3$)
15	Transparent glass
16	Amber ($C_{10}H_{16}O$)
17	Transparent glass with lead, carbon, sodium, aluminum, potassium
18	Alum ($KAl(SO_4)_2(H_2O)_{12}$)

With Melloni's bench, all filters were transmission measured by putting them in front of the detector, whereby the digital voltmeter value is recorded as accurately as possible, taking account of considerable fluctuations, that amount to approximately 43 mV, or 2.6%. Using the metal plate reduces the temperature by a factor 5, reducing the measured fluctuations and facilitating the reading, but the relative uncertainty on individual measurements remains 2.8%.

One of the problems encountered was the unequal glowing of the platinum wire, as was also observed by Melloni. Furthermore, temperature fluctuations on the platinum wire amounted to approximately 53 mV, corresponding to a relative uncertainty of 3.3%. The spiral wire moreover got deformed during the course of the experiment.

Background temperature was measured at regular intervals and found to be quite stable. The necessary corrections were done through simple interpolation. The research on the filter transmission was performed through the black painted side of the cube.

This background temperature cannot be too high, while otherwise the positioning of an absorber in the setup would perturb thermal equilibrium. The measurements were performed under a quite constant room temperature of 15-16 °C. The results for the different heat sources are given in table 3.

The aim of repeating the experiment with modern means is twofold: we could determine with modern means the heat transmission of the filters, and compare them with Melloni's results, and the exact composition of the absorbers could be determined with wavelength dependent measurements, like X-ray spectroscopy and electron microscopy.

Comparison of Melloni's Results to Our Tests

The repetition of the historical experiment of Melloni allowed us to compare our results with Melloni's, and to pass at the same time to an upgrade of our instrumentation and a better characterization of the different parts.

***Table 3**. Summary table with experimental transmission results*

Filter #	Cube of Leslie	Lamp of Locatelli + Metal Plate	Lamp of Locatelli	Lamp of Locatelli + Platinum Wire
	Transmission (%)	Transmission (%)	Transmission (%)	Transmission (%)
1	1.42±0.1	2.9±0.03	8.2±0.6	13.1±1.0
2	1.59±0.6	1.9±0.2	7.9±0.4	14.4±1.3
3	1.77±0.7	4.8±0.7	15.8±0.3	26.7±2.5
4	1.88±0.6	4.6±1.07	14.7±1.3	20.4±2.0
5	1.95±0.6	5.4±0.8	14.9±1.5	21.4±2.6
6	1.62±0.5	4.1±0.6	14.4±1.4	21.7±1.9
7	1.83±0.4	5.1±0.6	14.2±0.8	22.1±1.8
8	1.62±0.5	3.6±0.1	11.2±0.6	15.2±0.7
9	1.84±0.6	3.9±0.5	13.3±0.5	18.8±1.3
10	1.74±0.8	5.4±1.5	15.5±0.8	22.6±1.3
11	80.41±1.5	83.6±3.6	83.5±4.2	69.6±14.2
12	2.38±0.5	8.4±2.5	22.4±0.3	33.4±1.8
13	0.69±0.5	1.2±0.8	2.6±0.3	8.4±0.1
14	1.75±0.3	8.8±2.7	22.1±3.7	25.2±0.8
15	1.33±0.4	5.3±1.2	13.2±0.4	22.7±0.9
16	0.48±0.2	0.6±0.2	1.0±0.7	2.4±1.3
17	0.80±0.2	5.1±1.4	12.6±1.0	20.6±1.5
18	3.18±1.6	4.1±1.9	2.1±2.0	6.4±4.1

The first point noticed by Melloni (Melloni, 1850) is the high transmission value of rock-salt (table 1 – sample 1), being constant for all the heat sources. He concludes that the heat radiation from the different heat sources is not essentially different, and that the difference in transmission through various media is nothing more than a characteristic of the medium, namely an analogue quality as the one producing the different colors in visible light. According to Melloni glass and other transparent substances allow the passage of different portions of "heat colors", and rock-salt is a "non-colored" material allowing the transmission of all colors of the heat radiation.

The quality of materials and of heat radiation that have a comparable effect as color was called "thermochrose" and in a similar way the quality to have no "heat color" was called "athermochrose" (Melloni, 1850). Melloni clearly expresses himself to introduce these concepts according to analogy with light, and not as a simple hypothesis: "We do not adopt here no hypothesis, but we state a simple closeness between two orders of facts that seem to be gifted by a sort of analogy (Nous n'adoptons ici aucune hypothèse, mais nous posons un simple rapprochement entre deux ordres de faits qui nous paraissent doués d'une certaine analogie)".

He looks for a relationship between the transparency of materials and their heat capacity, and observes that the relative order of transparency changes according the source used. Melloni finds even more remarkable the inversions that happen in the transmission in comparing different materials (Melloni, 1850).

As an example, the transmission of heat with yellow at "soufre de sicile" (table 1 – sample 2) and with transparent fluor spat (table 1 – sample 3) is approximately the same for the Locatelli lamp, but for the other sources the transmission for "soufre de sicile" is different. In comparing beryl ("béril jaune") with fluor spat (table 1 – samples 5 and 6) he observes that the transmission of heat radiation coming from the lamp of Locatelli, is higher for beryl, but

for the other three sources the transmission through fluor spat is higher, beryl becoming opaque for heat radiation of this last source.

From these observations he concludes (Melloni, 1850) that there should exist a difference in "quality" between the different kinds of heat radiation, and that this quality is a measure of the degree of heat transmission. The fact that the transmission remains constant for different sources, as with rock salt, is mentioned as a 'very remarkable and unexpected' phenomenon.

By comparing transparent media with colored ones, Melloni remarks that the order of heat transmission is independent of the light transparency and that dark colored media often transmit more heat than light colored ones.

As an example, we compare some findings from table 2 with data from table 1. We can see, by using Locatelli's lamp, that transparent substances (namely citric acid – filter 27, potassium- and soda tartrate – filter 29, alum - and glass – filter 36, all in table 1) transmit 3 to 6 times less heat than smoked rock salt (table 1 – filter 12), 4 to 8 times less than greenish fluor spat (table 1 - filter 6) and 5 to 9 times less than greenish beryl (table 1 - filter 5), while the latter are all colored.

In short, the transparency of substances, relative to heat radiation, is not the same as for the transmission to light rays.

This difference between light and heat radiation is also manifested, according to Melloni (Melloni, 1850), with the other heat sources, and for example uncolored alum becomes completely opaque for heat radiation for a source of 400°C and 100°C, while other colored media such as sulphur and impure rock salt still give a high transmission for these heat sources.

Therefore Melloni introduced a special term to distinguish the transparency of heat radiation from 'usual' transparency, and calls it 'diathermasie' and 'diathermique media' and an analog term 'adiathermasie' and 'adiathermique' for substances being opaque for heat radiation (Melloni, 1850).

In succeeding experiments Melloni investigates the influence of the split, texture, chemical composition, crystal axes direction, the influence of the thickness of the samples, the propagation of different heat radiation in different environments, the effect of combining various samples, and methods to recognize thermal colors.

An important experiment on this long list was the polarization of heat radiation. While the effect of polarization is very clear and instructive, we repeated this experiment and draw particular conclusions out of it, related to the interpretation of the nature of light and heat.

Polarization of Heat Radiation

Not long after Etienne Malus (1775 – 1812) discovered the polarization of light, the phenomenon was investigated for heat radiation. James Forbes (1809 – 1868) tried to polarize heat radiation with tourmaline (Forbes, 1835), and Melloni also performed the measurements in a later stage (Melloni, 1836). One knew that two tourmaline plates allow transmission of light if their axes are kept parallel, while by keeping the axes perpendicular, the light is almost 100% absorbed.

The scientific world was divided on drawing the right conclusions from the experiments. While tourmaline absorbed the highest part of the heat radiation, the intensity was insufficient to be measured by the classical thermocouples. In 1835 Forbes decided to repeat the experiments making use of Melloni's thermo-multiplier (Forbes, 1835).

Forbes made a series of trials and mistakes, and consequently misinterpretations of the experimental results, using in a first experiment an oil lamp (describing it as a lamp of Locatelli), and later correcting for the absorption of heat by the tourmaline itself by

optimizing the experimental setup (Forbes, 1835). This way he found that between 14% and 17% of the heat would be polarized. From these results he concluded that heat can be polarized by tourmaline: "I cannot, therefore, entertain any doubt on the polarization of heat by tourmaline" (Forbes, 1835).

With our setup and a tourmaline sample from the museum collection, we tried out a similar experiment. We used a lamp of Locatelli and the detector, described earlier. We used a pair of tweezers with tourmaline crystals that can rotate. The whole is fixed on a support, positioned in such a way that the tourmaline is just in front of the detector opening. The distance between source and detector was approximately 3.0 ± 0.1 cm. Six measurements were made.

The results of the polarization experiment are that we got signals in the range of 2 to 16μV, and a mean ratio parallel/crossed axes of 1%.

Just like Forbes, we observed that measurements of heat polarization are not simple. We also observed that the difference in transmission with parallel and crossed axes diminishes with time, and the same holds for the secondary radiation. In addition, there is another effect that Forbes seemed to overlook: that the filter polarization power depends on the wavelength, or in other words, the fact that tourmaline polarizes visible light, does not make this true for heat radiation as well.

We conclude that with this setup it is quasi impossible to measure the polarization of heat radiation. This is partly due to the fact that the used polarization filters do polarize visible light very well, but are less efficient in the infrared spectrum. This causes the difference in transmission with crossed and parallel axes to be quite small. Moreover the polarization filters have a high absorption. The small measurement value increases the inaccuracies and the secondary radiation masks the primary (polarized) radiation.

The experiments as performed in the museum are less accurate than Forbes'. Possibly Forbes paid more attention to improve his setup. The thickness of the tourmaline filters for example has serious influence on the results. Forbes does not mention any dimensions, but describes them as 'very fine cut'. Our filters were parts of the museum collection, originated from polarization experiments on light, and less appropriate.

Nevertheless we can put question marks on Forbes measurement results. Considering the behavior of tourmaline in the infrared, it seems very improbable to find a systematic difference of 17% on the transmission with crossed and parallel axes.

Melloni followed Forbes in a whole series of measurements, and in fact had concluded that transparent substances affect radiant heat in much the same sort of way that colored glasses affect light. Transparent substances will readily pass heat of the approximate refractive index but will progressively absorb rays whose refractive indices differ increasingly from that of the 'calorific' color of the substance.

The demonstration of the polarization of heat radiation was an important step in the process of acceptance of the theory of equality of heat and light. Since 1850, when the destructive interference and propagation speed of heat radiation were determined, it was generally accepted that light and heat radiation only differ in wavelength (Chang, & Leonelli, 2005a). In 1865 eventually came the theoretical framework: Maxwell formulated his four famous laws (Maxwell, 1873), wherefrom it became clear that heat and light are similar phenomena, in fact electromagnetic radiation, reducing the difference between heat and light to a difference in wavelength.

Melloni – Key Figure in The Study of Infrared Light?

In the history of physics the development of scientific instruments often plays an important role. Even today scientific research is driven by technological innovations. In the beginning of the nineteenth century the research on heat radiation got an increased interest through the use of the thermopile, used to measure temperature differences by application of the Seebeck effect. Until that time thermometers were based on the expansion of gases or liquids under temperature variations. Because of the relatively important inaccuracy of this method it was rather difficult to measure infrared radiation from weak sources. Most scientist considered light and heat as two totally different phenomena (Cromphout, 2011).

Melloni is often considered as the person that discovered the equal nature of light and heat, but this was a process of years wherein he balanced between the pros and contras of that statement, considering that experimenting proceeds with ups and downs. The preference for a unified theory over a pluralistic theory was based on experimental results.

Melloni was a pioneer of heat radiation research, by the development of his thermo-multiplier: he created such a sensitive instrument (going to a tenth of a degree) that it was kept in use till the end of the century without much change. By using the thermopile in the most efficient way, he was the first who collected sufficient data to make a comprehensive study of infrared radiation (Cromphout, 2011).

A lot of effort has been devoted to come to an explanation and to find arguments for Melloni's choice, mainly from the philosophical point of view, and questions were raised on many occasions related to Melloni's final choice in favor of a unified theory between light and heat phenomena. The extensive paper by Chang and Leonelli (Chang, & Leonelli, 2005a; Chang, & Leonelli, 2005b), states that there is no convincing scientific argument to prefer a unified theory to a pluralistic one.

In an effort to clarify the reason for this decision, we critically explored Melloni's own writings, and especially the conclusion laid down in his final work "La Thermochrose" (Melloni, 1850), that intended to be a summary of his lifelong experiments, together with the various opinions spread over his many more publications.

In the summary of his final work (Melloni, 1850), Melloni states that "the light of flames and incandescent light is accompanied by a great quantity of obscure heat radiation".

He describes how this heat radiation behaves: "it is composed of many elements, analogue to prismatic colors, susceptible like them to cross a vacuum, with going as them along straightforward directions in negligible time lapses, and feeling no influence from the state of rest or movement of the particles of the medium. Obscure calorific radiation contains more elements that follow the same propagation laws as luminous radiations. Nevertheless, the amount diminishes with the temperature of the radiating source" (Melloni, 1850). He finally called this phenomenon "la thermochrôse" to identify it as thermal color.

Since 1840 Melloni got more and more convinced of a unified theory, that was growing by the many experiments concerning transmission, diffraction and especially polarization of heat radiation (Melloni, 1836). Melloni is the first to suggest that the difference between heat and light is something analogue as the difference between lights of different colors (Melloni, 1850).

The convincing argument that polarization is the key element for Melloni to decide in favor on the unified theory is the attention he paid to this phenomenon (Melloni, 1836), despite the difficulty of the polarization experiments. Heat radiation has shown all characteristics of light radiation, such as interference, diffraction and polarization. They only have longer wavelengths. A comparison with sound, well known at Melloni's time, also exhibits the characteristics of waves, with the exception of polarization, because of the different nature of the waves.

As was mentioned by Chang and Leonelli (Chang, & Leonelli, 2005a) the fact that Melloni's companion scientists Herschel and Draper did not come to this same conclusion can be understood by the fact that their research did not completely cover the depth obtained by Melloni, and for which polarization was not taken into consideration.

Referring to Kuhn's paradigm concept (Kuhn, 1962), and endorsing the criticism to this structured framework as formulated by Steven Weinberg (Weinberg, 1998), we can state that Melloni's work can be considered a precursor to the establishment of two paradigms: electromagnetic theory of Maxwell, and the rise of quantum mechanics in the effort to explain the radiation laws.

This preparatory work was done during periods of "normal" science (in Kuhn's vocabulary): Melloni explored phenomena of heat radiation, and interpreted these phenomena, undergoing a lot of oscillation in making up his mind, and made clear to be a good scientist, but did not come to a satisfactory (mathematical) model for his findings. One should moreover keep in mind that there were other actors in the polarization research and that there was a continuous exchange of ideas between the different actors (Cardwell, 1971; James, 1996).

Indeed, the infrared research was continued in Germany, concentrating on radiation laws in the framework of research to optimize the Auer lamp (Schaefer, & Matossi, 1930), and eventually leading to the discovery and development of quantum physics by Planck and others like Lummer, Rubens and Pringsheim, bridging the Wien and Rayleigh radiation laws, and going towards a real paradigm shift.

And in the meantime Melloni hardly survived the riddles of history.

CONCLUSION

a) For what concerns the educational part: Who was Melloni and what kind of research did he do? How important was his research? Is Melloni important in the history of science? Did he influence Maxwell?

It is clear that nowadays, Melloni is barely known. In modern physics books no mention is made of Melloni's research. Even in Maxwell's book on electricity and magnetism no mention is made of Melloni. Melloni was certainly involved in the preparatory research that would later lead to two paradigm shifts (Maxwell's electromagnetic theory and Planck's quantum hypothesis). However, in a 1930 overview of IR research (Schaefer, & Matossi, 1930) Melloni is mentioned by no more than 1 sentence.

In this paper, we tried to illustrate that the research performed by Melloni was very important in the evolution of the study of the nature of heat radiation. He contributed to the experimental techniques for that particular research by using a sensitive thermo-multiplier (developed in collaboration with Nobili) and by improving his galvanometer.

Despite all this, Melloni disappeared completely in the riddles of history.

b) The reproduction of the historical experiments of Melloni proved to be very interesting and gave us more insight on the high degree of complexity and difficulty of that kind of experiments. These experiments were very instructive in the framework of the research for the master thesis.

c) Melloni's conclusion in favor of the unitary theory: We performed tests with the different heat sources on the available absorber materials, and special attention was paid to the phenomenon of polarization of heat radiation.

It is clear that Melloni had first failed to detect the polarization of radiant heat. But in 1834 Forbes, who had learned of Nobili's thermo-multiplier, was able to detect the polarization of radiant heat after transmission through tourmaline. Melloni confirmed the results of Forbes, and was able to show that the laws of polarization by reflection and by refraction were the same for radiant heat as they were for light.

In considering the question how Melloni decided in favor of a unitary theory of light and heat, we claim that sufficient experimental relevance was available for such conclusion, and that any experimental physicist could not neglect the evidence in the experimental observations and facts. It might be clear that Melloni came to his choice in favor of a unitary theory on a basis of pure scientific arguments, without any interference with philosophical arguments.

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