Radiometry Before World War II: Measuring Infrared and Millimeter-Wave Radiation 1800-1925

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Infrared motion detectors and millimeter-wave automobile collision-avoidance radars are only two of the latest technologies to exploit the region of the electromagnetic spectrum that lies between visible light and radio waves. In contrast to these utilitarian applications, astrophysical researchers use orbiting infrared telescopes and space probes, such as the Wilkinson Microwave Anisotropy Probe, to investigate the earliest moments of the universe. The early history of infrared and millimeter-wave measurement technology shows the complex interdependence between experimental science and advances in engineering technology. Historians of science and technology take different views of how technical knowledge and activities advance. For some, science leads and everything else follows. Others view modern science as vitally dependent upon the engineering and technological advances that put instruments of discovery into the hands of scientists.

This tension between engineering and scientific activity can be traced in the lives of those who discovered and developed measurement techniques for these wavelengths of radiation. They range from the pure scientist, William Herschel, to that hero of empirical invention, Thomas A. Edison, among others. Herschel discovered infrared radiation more than sixty years before James Clerk Maxwell (1831-1879) wrote his famous equations describing electromagnetism, in the 1860s. By the late nineteenth century, instruments were available that could detect the radiation from a single candle several hundred yards away. And in 1924, scientists successfully made spectroscopic measurements that covered the entire range from far infrared to millimeter wavelengths. The development of the microwave radiometer as a byproduct of World War II radar research has unjustly obscured the long and rich history of the science of radiometry, which predates that time. As we will see, certain techniques developed in the 1800s are still used today in commercial instruments.

In this article, I sketch some of the highlights of this neglected history. The only unifying theme is the measurement of infrared and millimeter-wave radiation, with an emphasis on the personalities involved. Although there were virtually no strictly commercial applications of radiometry during the period (unless one counts the making of scientific instruments), many of the investigators also tried their hands at applied research and inventions, with mixed results. However, the first researcher we will consider was a good example of the eighteenth-century "gentleman scientist:" William Herschel.

1. Herschel and the Discovery of Infrared Radiation

William Herschel (1738-1822) (Figure 1) came to astronomy at a time when science was the pursuit of a few leisured wealthy gentlemen and a small number of full-time professionals who benefited from royal patronage. Herschel's first career was as a talented musician. In pursuit of better outlets for his musical talent than his native Germany could provide, he left for England at the age of nineteen, where he eventually became Director of Public Concerts at the fashionable resort town of Bath. One of the notables he met in the course of his work was England's Astronomer Royal, Nevil Maskelyne, who encouraged Herschel's budding interest in astronomy. Herschel built several telescopes himself, and began to make increasingly precise astronomical observations, such as the indirect measurement of the height of mountains on the moon.

His career changed to astronomy for good when, in the year 1781, he discovered a new planet. To honor King George III,

Figure 1. William Herschel (from W. W. Bryant, *A History of Astronomy*, 1907).

Herschel named the orb "Geōrgium Sidus," which translates as "George's Star" (the astronomical community eventually decided instead on "Uranus"). In the following year, Herschel received a special appointment as the King's Astronomer. This appointment allowed him to pursue his astronomical avocation full time. Throughout his researches, he was assisted by his sister, Caroline, who made several important discoveries in her own right [1].

Around 1794, Herschel turned his attention, and his telescopes, toward the sun [2]. The science of photography was some forty years in the future, so Herschel chose to view the sun directly by eye, in order to realize the full resolving power of his largest telescopes, one of which had a nine-inch aperture [3]. To reduce the intolerable glare produced by his instrument without losing resolution, he experimented with a number of colored glasses interposed in the light path. In his earliest attempts, the intense concentrated solar heat often cracked the pieces of glass. During this investigation, he noted that some colors of glass cut down the light intensity well, but he "found that the eye could not bear the irritation, from a sensation of heat, which it appeared these glasses did not stop" [3, p. 274]. This effect led him to conduct an investigation of the "heating Power of coloured Rays" [3, p.256].

To do this, he used a glass prism to disperse a sunbeam into its constituent colors, and placed thermometers at various places along the resulting spectrum. (Thermometers were then a standard tool in experimental research, having been developed by Gabriel Fahrenheit around 1720.) His first experiments showed that the red rays heated the blackened bulb of a mercury thermometer more than three times as fast as violet rays [3, p. 261]. Perhaps recalling his sensation of heat through a glass that passed little light, he next devised an experiment to discover if there were invisible rays beyond the red end of the spectrum that could nevertheless convey heat. He was pleased to find that "there was a refraction of rays coming from the sun, which, though not fit for vision, were yet highly invested with a power of occasioning heat..." [4]. In the spring and summer of the year 1800, he published descriptions of these experiments in the *Philosophical Transactions of the Royal Society of London*, accompanied by elegant illustrations (Figure 2) showing how he separated the heating effects of various colors with the aid of a prism, a magnifying glass, and a thermometer [5]. Another motivation for Herschel's investigation of invisible rays of radiant heat may have been his belief that the sun was probably inhabited. To the objection that the sun was probably too hot for life to exist, he countered that it was not solar radiation by itself, but radiation encountering a "calorific medium," which gave rise to heat [2, p. 64]. He reasoned that if the purported solar residents were not composed of a calorific medium, their continued existence was at least a logical possibility.

Herschel got some other things wrong about the sun as well, but his discovery of invisible rays beyond the red end of the spectrum marked the first time that anyone had successfully measured invisible electromagnetic radiation. Throughout most of the nineteenth century, radiation having a wavelength longer than visible light would be measured primarily by its power to generate heat in an absorbing medium. Thus, in order to detect weaker emissions, such as those from stars, the challenge scientists faced was to devise more sensitive means of detecting small changes in temperature. The first such advance involved the new science of electricity, and an Italian physicist named Leopoldo Nobili.

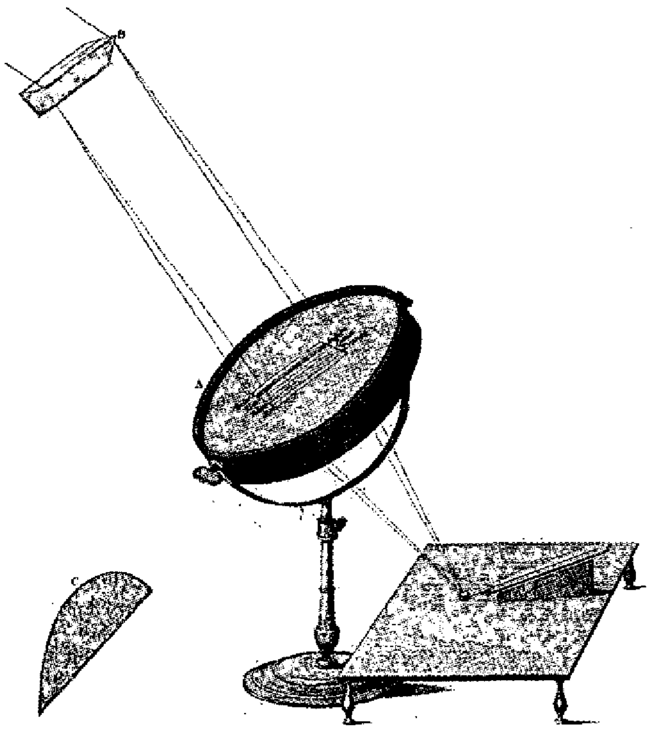

Figure 2. One of William Herschel's experiments to investigate the different heating powers of the colors comprising sunlight (from Plate XIV of [5]).

2. Seebeck, Nobili, and the Thermopile

The first two decades of the 1800s saw a flurry of electrical discoveries. In the same year (1800) that Herschel discovered infrared radiation, Alessandro Volta (1745-1827) announced his discovery of the voltaic pile, which was the first reliable source of continuous electric current. In 1820, Hans Christian Oersted (1777-1851) published the results of his investigations into the connection between electricity and magnetism. But even as late as the 1820s, there was much confusion regarding the fundamental nature of electricity. In particular, it was not clear whether the means by which electricity was produced affected its basic character. The issue was whether "voltaic" electricity from a voltaic pile was the same kind of thing as static electricity from a Leyden jar (an early type of capacitor), or electricity produced directly from heat.

Two years after Oersted showed that an electric current in a wire deflected a compass needle, Thomas Seebeck (1770-1831) constructed what we would now call a thermocouple. He bent a copper bar into the rough shape of a semicircle, and soldered a piece of bismuth metal across the gap to form a closed conducting loop. When he heated one of the two copper-bismuth junctions in the flame of an alcohol lamp, leaving the other junction at room temperature, the loop produced a magnetic field strong enough to deflect a compass needle to an angle nearly perpendicular to the Earth's field. At first Seebeck did not believe electric current was involved, and thought his "thermomagnetic" effect converted heat directly into magnetism [6]. When later research proved that an electric current was responsible, it became clear that the needle deflection was the same phenomenon observed by Oersted, and the production of electric current from heat in the manner described became known as the Seebeck effect. An Italian physicist then turned Seebeck's discovery into a practical means of measuring heat radiation.

Leopoldo Nobili (1784-1835) came to his position of Professor of Physics at Florence, Italy, after a university education and a short military career. His university training included the new theories of André Marie Ampère (1775-1836). Ampère regarded electric currents as the source of magnetic forces, and claimed it did not matter how the currents were produced. In the late 1820s, this theory was opposed by the followers of Volta, who proposed a more mechanical relaxation-of-tension explanation of electric current, based upon electrochemical processes in Volta's battery. Nobili weighed in with a theory of his own, which was that all electric current, whether produced by Seebeck's thermoelectric method or Volta's "hydroelectric" scheme, was basically one thing: the flow of heat in the form of the invisible fluid called "caloric" [7]. The caloric theory of heat was generally accepted at the time, so for a few years Nobili gained a considerable hearing for his theory of electricity. Ultimately, caloric landed on the scrap pile of the history of science, but Nobili's insistence that electrical current was something different than static electricity helped clear the way for Maxwell's more comprehensive ideas about the nature of electricity and magnetism, some forty years later.

Besides his theoretical contributions, Nobili was among the first to build what became known as a "thermopile." Since each pair of dissimilar metals in a thermocouple produced a constant voltage for a constant difference of temperature, Nobili found that if he "daisy-chained" an alternating sequence of thermoelectrically dissimilar metals, such as copper and bismuth, in series – much as Volta had constructed his battery – and placed them so that alternate junctions were either hot or cold, he could build up the millivolt-level potential of one junction into a substantial voltage that could be easily measured. Later developments of the Nobili thermopile included the apparatus shown in Figure 3, which was designed to measure small amounts of heat radiation. A set of twenty-five pairs of junctions was enclosed in the box on the left, and the opposite ends of the junctions were exposed so that a small difference in temperature (or incident radiation) produced a voltage that was measured by the sensitive glass-enclosed galvanometer on the right. For most of the nineteenth century, such instruments represented the state of the radiation-measuring art for routine laboratory purposes. Today, the conversion of electromagnetic energy into heat, which is then measured with a thermocouple or other sensitive temperature-measuring device, is still the basis for many precision power meters and reference standards, covering the microwave range down to infrared wavelengths.

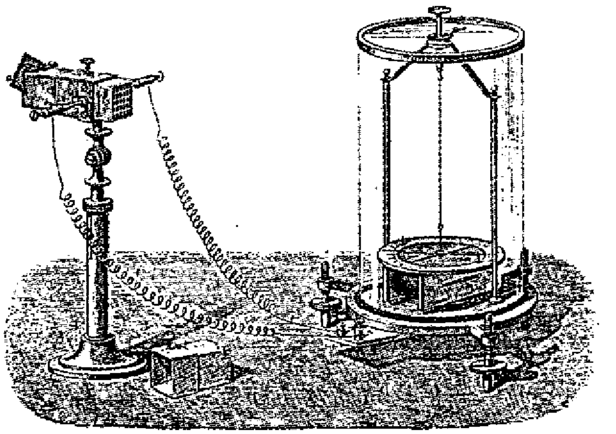

Figure 3. Leopoldo Nobili's thermopile was later adapted for use as a sensitive detector of heat radiation. This illustration shows a 25-junction thermopile (left) connected to a sensitive galvanometer (from Amédée Guillemin, trans. S. P. Thompson, *Electricity and Magnetism* (1891), used by permission of Macmillan Ltd.).

Figure 4. William Crookes (from E. E. Fournier d'Albe, *The Life of Sir William Crookes*, 1924).

By the time of Nobili's death, in 1835, the notion of invisible radiant energy was becoming accepted in the scientific community. But things were not so settled as to forestall an intense controversy about the nature and effects of radiation. The cause of the controversy was an audacious claim by an Englishman named William Crookes.

3. Crookes and the Radiometer

Like Herschel, William Crookes (1832-1919) (Figure 4) first became famous through a discovery. But the different natures of their respective discoveries reveals the different natures of the personalities involved. Herschel's gaze was directed skyward when he found a new planet; Crookes found what he was looking for in the ground: specifically, the messy tailings from a German selenium mine in which he discovered traces of a new element he named thallium, in 1861. Trained by outstanding experimentalists, such as Michael Faraday, Charles Wheatstone, and George Stokes, Crookes became a meticulous experimenter in his own right. But unlike Faraday, Crookes consciously sought fame, reputation, and financial profit from his scientific and industrial work. The same skills that enabled Crookes to discover thallium led him to develop practical industrial processes in areas such as mining and public health [8]. One would think that such an industrious, practical individual would discount the presence of subtle or spiritual influences. But Crookes was a many-faceted Victorian dynamo, whose diverse interests reflected the paradoxes of his age. For example, along with many other prominent Englishmen of his time, Crookes developed a strong interest in the quasi-religion called spiritualism, and attempted to obtain empirical scientific proof of life after death.

But in the late 1860s, most of Crookes' spiritualist research lay in the future. Around that time, he became interested in the measurement of atomic weights of thallium and other elements. These measurements required him to weigh small quantities of purified chemicals with unprecedented precision. Since the buoyancy of air slightly reduces the apparent weight of a sample of material, Crookes decided to eliminate this source of error by weighing his samples in a vacuum. He constructed an iron vacuum chamber, and used sophisticated pumps of his own invention to obtain the highest vacuum possible at the time. But instead of stabilizing his mass measurements, as he expected, the vacuum setup gave rise to odd, erratic readings that were influenced by the temperature of the material being weighed. Hot objects seemed to be repelled by nearby cold objects. Under certain conditions, the force involved was large enough to move a delicately suspended ball of pith (a kind of plant product). The effect seemed to be the same as one exploited by certain German instrument-makers at about the same time in their construction of what they called a "light-mill" [9]. Crookes built several light-mills of his own to further investigate the phenomenon. Because the force appeared to be roughly proportional to the intensity of radiation incident on the vanes of the mill, Crookes termed his device a "radiometer." An engraving of Crookes' radiometer appeared in a contemporary article in *Scientific American*, which was then a kind of inventors' newspaper, and is shown in Figure 5. It consisted of a number of vanes (usually four), colored white on one side and black on the other, suspended on a pivot that was free to turn. Either light or heat could create enough of the mysterious radiometer force to spin the vanes, with the white side leading. Inexpensive versions of this apparatus have occupied a prominent place on the shelves of science-museum gift shops ever since.

By 1875, when Crookes was engaged in his radiometer investigations, Maxwell's electromagnetic theory was gradually making its influence felt as other physicists worked out some of its implications. One important corollary of Maxwell's equations was the fact that the incidence of light radiation on an object should be accompanied by a small pressure. This so-called "radiation pressure" was extremely small, but, in principle, measurable. Was Crookes directly measuring the mechanical equivalent of light, in analogy to Joule's earlier discovery of the mechanical equivalent of heat? At first, Crookes thought so. In an abstract of a paper he submitted to the Royal Society of London in March of 1875, he described over a dozen different experiments he had performed using various solid materials for the vanes, different gases before evacuation, and so on. He claimed that they all tended to show a fundamental radiation-pressure effect, although the presence of increasing quantities of gas eventually obscured the effect [10].

Other physicists, including Osborne Reynolds and Arthur Schuster, disputed Crookes' claim. For one thing, the magnitude of the force was much larger than what Maxwell's equations predicted. Also, if direct ballistic reflection of light particles was the cause of the radiometer effect, the force should have been greater on the lighter – and thus more reflective – sides of the vanes than on the darker, absorptive sides, since the momentum transferred by reflection was more than that transferred by absorption. This would make the vanes turn with the darker sides leading, but, in fact, the device turned the opposite way. It was Schuster who eventually proved that Crookes' "radiation pressure" had to be produced by secondary effects of residual gas, and not by the direct impact of light or heat radiation on the radiometer vanes. To do this, he arranged a clever experiment in which he suspended an operating radiometer so that the entire apparatus, bulb and all, was free to turn. His reasoning went as follows: If the rotation of the vanes was due to an external impartation of momentum directly from incident light, the motion of the vanes would eventually convey itself through the pivot to the radiometer body itself, and cause the bulb to rotate in the same direction as the vanes. But if the vanes' motion was due to internal interactions with residual gas molecules excited by differential heating, the system was therefore isolated mechanically, angular momentum would be conserved, and the bulb would begin to rotate in a direction *opposite* to that of the vanes. When Schuster performed this *experimentum crucis*, he found that the torque exerted on the bulb opposed the torque on the vanes, thus confirming his belief that the effect was an internal effect due to residual gas. Despite Crookes' contention that his vacuum was the highest possible, there was obviously some gas remaining, and Crookes eventually accepted Schuster's explanation. A quantitative theory of the effect took considerably more effort to devise, effort that was expended primarily by Reynolds and by Maxwell, who was also well known for his work in statistical mechanics. One of the last scientific works Maxwell published before his death from cancer, in the fall of 1879, was a detailed explanation of the rarefied-gas dynamics that led to the radiometer effect, as well as other low-pressure phenomena. While a complete explanation of the radiometer effect is outside the scope of this paper, it basically involves interactions between surfaces of differing temperature that are separated by a distance that is on the order of the mean free path of the gas molecules. (Reynolds wrote a theoretical treatment of the problem and submitted it for publication, and Maxwell was selected as one of the reviewers. Maxwell's public comments on Reynolds' as-yet-

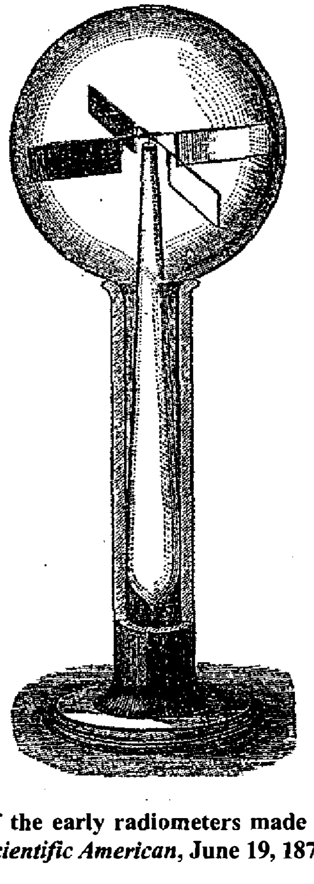

Figure 5. One of the early radiometers made by Sir William Crookes (from *Scientific American*, June 19, 1875, p. 392).

unpublished work led to a protest by Reynolds, muted only by Maxwell's untimely death in the meantime: see [9, pp. 110-122].)

By the time the true explanation of the radiometer effect was found, Crookes had gone on to other things: his development of the high-vacuum "Crookes tube," which led indirectly to the discovery of X-rays; his research into the new science of radioactivity; and, after his interest in spiritual matters occupied more of his time, his presidency in 1897 of the Society for Psychical Research. But about the time Maxwell was helping to settle the controversy of radiometric pressure, a very different type of electrical specialist, on the other side of the Atlantic, was planning one of his rare ventures into pure science.

4. Thomas Edison and the Microtasimeter

In 1878, Thomas Alva Edison (1847-1931) was in the midst of what was arguably the most fertile period of his inventive life. Already well known as an inventor of useful new systems for automatic telegraphy, he had just completed work on a carbon telephone transmitter, and was in the midst of investigations that would lead to the strikingly original invention of the phonograph. Small vibrations and the recording of delicate, almost insensible motions were on his mind. He was also embroiled in a public controversy over whether he or British inventor David Hughes was the first to devise the carbon telephone transmitter [11].

Edison, always aware of the value of publicity in raising investment funds for his more ambitious projects, such as the electric light, encouraged and welcomed the attention of both the press and the scientific community, as long as he received what he felt was proper credit for his inventions. In October of 1877, the well-known astronomer Samuel P. Langley had asked Edison to think about ways of making a highly sensitive heat-measuring device for use in astronomical research [12]. In Edison's work on the carbon transmitter, he had used the fact that the electrical resistance of a volume of carbon granules was extremely sensitive to changes in pressure on the granules' enclosure caused by sound waves impinging on an attached diaphragm. For the same reason, early versions of the transmitter were also very sensitive to small changes in temperature that altered the dimensions of its hard-rubber enclosure [13].

To address Langley's problem, Edison combined the two phenomena of heat-induced expansion and pressure-induced resistance change in an instrument that he dubbed the "microtasimeter," from the Greek *τασισ* (*tasis*), meaning "tension." In a meeting with US government officials and scientists in Washington, DC, in April of 1878 – the main purpose of which was to demonstrate his new phonograph – Edison also announced that his new microtasimeter could measure temperature changes as slight as 1/50,000th of a degree [12, p. 116]. A sketch, reproduced in Figure 6 from one of Edison's notebooks dated June 23, 1878, shows a rod (presumably made of hard rubber) suspended between a stationary mounting bracket on the left and a modified carbon telephone transmitter on the right. A battery and ammeter complete the system. Edison planned to bring this simple yet delicate apparatus along on a scientific expedition to Wyoming to observe an eclipse of the sun on July 29.

Edison was probably the most well-known of the public figures involved in this expedition, and to his fame we owe the substantial journalistic records available that describe this adventure.

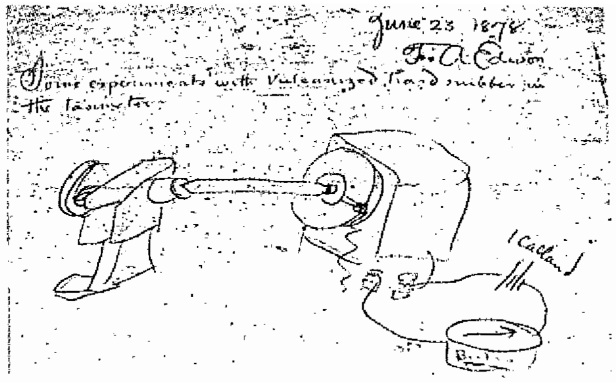

Figure 6. Edison's "microtasimeter" for measuring small changes in temperature. As the hard-rubber rod changed length under the influence of temperature changes, the pressure exerted on the carbon-microphone button on the right changed, causing the instrument's resistance to change and varying the current through the crude ammeter shown at the lower right (from Edison Papers Project Microfilm, reel 7, no. 893).

The expedition set up in Rawlins, which was then an unincorporated village in the Territory of Wyoming, a region that had witnessed Custer's disastrous encounter with the Sioux Indians at Little Big Horn just two years before. Edison's closest encounter with the wild west on this trip was a chance meeting with a drunken cowboy, who banged on Edison's hotel door late one night to demonstrate to the famed inventor his prowess with a pistol [13, p. 69-70].

The day after their arrival in Rawlins, Edison searched for a suitable location to set up his apparatus. Winds were high, so he found an abandoned chicken coop, had the roof removed, and set up a four-inch telescope and his microtasimeter in the semi-sheltered location. On the night before the eclipse, Edison apparently attempted to calibrate his instrument by observing the star Arcturus and noting the relative heat reading it gave. The next day, despite storms and high winds, Edison pointed his telescope at the solar corona one minute after totality, and obtained a reading fifteen times higher than the Arcturus reading [13, p. 71]. Edison published these results, but according to J. B. Hearnshaw, a historian of astronomy, they did not make much of an impression on the scientific community [14]. Edison had neither the time nor the inclination to perform the exacting work needed to obtain an absolute calibration of his instrument against known physical standards. Because of the unstable nature of carbon granules, microtasimeter readings were not repeatable enough to allow the instrument to sustain long-term calibration. Although Edison tried to commercialize his invention and offered it for sale through scientific-instrument makers, it attracted few buyers [11, p. 162]. As later researchers were to find, extreme sensitivity is only one of several virtues required of a radiometer: stability and ease of calibration are just as important.

Although newsworthy, Edison's scientific trip out West was more of a vacation than a vocation, and made little lasting difference to the science of radiometry. The scientist Langley, whose inquiry inspired Edison's microtasimeter in the first place, devoted a large part of his career to the measurement of visible and invisible radiation. His only notable failure was in the area where Edison succeeded: practical invention.

5. Langley and the Bolometer

Samuel Pierpont Langley (1834-1906) was one of the best of the generation of largely self-educated American scientists who matured in the middle of the nineteenth century, when opportunities for higher education in the United States were rare. After completing high school in Boston, he studied independently in the public libraries there, and at the age of 33 obtained an appointment as Professor of Physics at the Western University of Pennsylvania (now the University of Pittsburgh). Langley's practical bent showed itself in his decision to furnish time signals based on astronomical observations to the burgeoning railroad industry. He charged a fee for these signals, communicated by telegraph, and used the money to build up his Allegheny Observatory, and to fund his research into the nature of solar radiation [15].

One of Langley's long-term research goals was to make absolute measurements of the intensity of solar radiation for as many wavelengths as possible. The usefulness of this data for geophysical as well as astronomical research was obvious. Langley knew that one of his first tasks in the pursuit of this goal was to devise an instrument sensitive enough to detect the heat resulting from the small amount of radiation that filters through the narrow slit of a spectroscope. It was this need that inspired his query to Edison about sensitive heat-measuring instruments. While Edison dodged bullets in Wyoming, Langley, back in Pittsburgh, considered another approach to the problem. By 1880, Langley had perfected a new device that he termed the "bolometer," from the Greek *βολη* (*bole*), meaning "beam of light."

Langley described his bolometer in a paper submitted to the American Academy of Arts and Sciences in 1880. Figure 7, from that paper, shows a detailed drawing of the heart of his instrument [16]. In designing his bolometer, Langley drew upon the work of William Siemens, whose resistance-temperature device (RTD) used the variation of a metal's resistance with temperature for precise temperature measurements. Between two discs of hard rubber with rectangular cutouts, Langley mounted a grid of metal strips made of platinum rolled to a thickness of less than 10 microns. The grid was divided into two sections: a central measurement section, exposed to the radiation to be measured, and a reference section, shielded from radiation and symmetrically positioned on either side of the measurement section. The two sections formed two arms of a precisely balanced Wheatstone bridge. Ambient temperature variations equally affected the measurement and compensation arms of the bridge, leaving the bridge in balance. In this way, any unbalance of the bridge would be due exclusively to the effect of radiation on the measurement grid. When Langley mounted his bolometer at the business end of a spectroscope or other optical instrument, he took care with a series of baffles to illuminate only the measurement section with the radiation he wished to measure. His balanced circuit allowed him to use an extremely sensitive galvanometer to measure the differential output current of his device. Like Edison, he confidently claimed that his instrument could accurately measure extremely small temperature changes, on the order of 10^{-4} degree Celsius. But unlike Edison, he published tables of comparisons with other calibrated instruments, such as the thermopile. In this way, he backed up his assertion about accuracy with quantitative data, traceable to generally accepted scientific standards.

Langley's development of the bolometer was only a means to his ultimate scientific end of measuring the "solar constant," which is the value of the total amount of radiation energy at all wavelengths received from the sun. Because he wished to reduce the effect of or compensate for atmospheric absorption at infrared wavelengths, he had a scientific need to observe the solar spectrum (including the important infrared wavelengths) at two widely separated altitudes. So, in 1881, he organized an expedition to Mt. Whitney, the highest peak in what is now the lower 48 states of the US. If Langley encountered any cowboys or Indians, he failed to mention them in his official report, although he did describe the difficulties of lugging hundreds of pounds of delicate instruments over rugged mountain trails [17]. His efforts on this expedition were rewarded by the discovery that the sun's radiation includes substantial energy in the longer infrared wavelengths, above one micron.

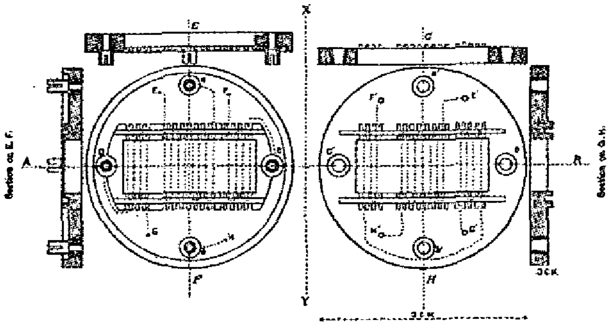

Figure 7. Langley's bolometer, consisting of two sets of extremely thin platinum strips, one of which was illuminated by the radiation to be measured (from [16, p. 351]).

In contrast to these valuable scientific contributions, Langley's later efforts in the field of commercial inventions were not as successful. In 1887, Langley accepted the post of Secretary of the Smithsonian Institution, and moved to Washington, DC. In 1891, he announced that it was then possible to contemplate mechanical flight with the latest high-efficiency engines powered by steam or gasoline. Having put his scientific reputation on the line, Langley then felt obliged to develop several small model airplanes, which he flew successfully over the Potomac River. By 1903, the same year that the Wright Brothers flew their full-size man-carrying craft for nearly a minute at Kitty Hawk, Langley was still experimenting with smaller-scale models. His aircraft experiments came to an unfortunate conclusion in 1906, when he finally built and launched a machine capable of carrying a man (not Langley personally, by the way) in a highly publicized demonstration on the Potomac. Figure 8 is a photograph of Langley at the time he was working on this project, with his engineer and pilot, Charles Manly. Among other problems, the launching gear proved defective, and when the plane crashed (fortunately without loss of life), Langley's career as an aviation pioneer crashed along with it. Unlike Edison, Langley was not adept at the manipulation of public opinion. Except for isolated demonstrations, Langley had kept the popular press in the dark about his aviation research, and when his 1906 demonstration failed, the newspapers were in no mood to be charitable. The ridicule he received discouraged Langley from pursuing the project any further [15, pp. 20-21]. Just as Edison's rare venture away from invention into the pure science of astronomy was not notably successful, Langley's attempt to invent a commercially valuable airplane failed, as well.

Langley's aeronautics research is memorialized by the eponymous NASA Langley Research Center in Hampton, Virginia, whose roots go back to the National Advisory Committee for Aeronautics, established in 1915. Langley's work in infrared radiation and spectroscopy formed part of the experimental back-

Figure 8. Samuel Pierpont Langley (l) shown with his chief mechanic and pilot, Charles Manly (from NASA Web site http://grin.hq.nasa.gov/ABSTRACTS/GPN-2000-001298.html).

ground that led Max Planck (1858-1947) to formulate his famous law of radiation. The long-wavelength infrared spectroscopy research pioneered by Langley continued into the twentieth century in a number of laboratories around the world, especially in Germany and the US. The German-American connection was especially important to the last researcher whose achievements we shall review: Ernest Fox Nichols.

6. Ernest Fox Nichols and Millimeter-Wave Radiometry

The nineteenth-century physicist thought of his world largely in terms of mechanisms and forces. Experimentalists of that time strove to measure ever weaker and subtler influences, as Crookes had done in his radiometer investigations. Having no electronic means of amplification, these researchers developed extremely delicate mechanical instruments, such as the quartz-fiber torsion balance. In combination with a small mirror reflecting a beam of light onto a remote scale, this type of torsion balance could accurately measure forces as small as 10^{-5} dynes [18].

Ernest Fox Nichols (1869-1924) (Figure 9) went to college at a time when university-based research was just getting established in the United States. After he obtained an undergraduate degree from the Kansas State College of Agriculture, he pursued graduate studies at Cornell. He then made a pilgrimage to Germany, which was then the world's leader in graduate-level physics research and education. During his two years in Berlin in the mid-1890s, Nichols learned from Ernst Pringsheim how to make a torsion balance operated by a modified Crookes-style radiometer [19]. The result was much more than a toy. Nichols' device was a precise, calibrated instrument, capable of resolving extremely small differences of temperature. Upon his return to the US in 1897, he was granted the DSc degree by Cornell University, largely upon the merits of the work he did in Germany [20]. After he joined the Physics Department of Dartmouth College in New Hampshire, Nichols collaborated with astronomers at the recently established Yerkes Observatory in Williams Bay, Wisconsin, to quantify the amount of heat emitted by stars.

This was the same goal that Edison had attempted more than twenty years earlier. In the intervening years, a British astronomer named C. V. Boys had developed what he called a "radiomicrometer." It was essentially a single-junction thermocouple connected to a torsion-balance mirror galvanometer, which measured extremely small currents [21]. When Boys' device was coupled to a 16-inch telescope, it was sensitive enough to detect the heat from a candle at a distance of 250 yards. However, it gave no result when directed at even the brightest stars, such as Arcturus. When Nichols placed his improved radiometer at the focus of the Yerkes 24-inch reflecting telescope, he was gratified to see measurable deflections of his instrument from the stars Arcturus and Vega, as well as readings from the planets Jupiter and Saturn. Through the use of distant Earth-bound sources of known amounts of heat, he was able to calibrate his astronomical measurements to an absolute standard. Following this triumph, Nichols moved to another challenge: the direct measurement of the pressure of light radiation.

As we have seen, Crookes had erroneously believed that his radiometer effect was due to the direct pressure exerted by light, the effect that was predicted by Maxwell's equations. Subsequent research showed that the radiometer effect was much stronger than the true radiation-pressure effect, which required much more delicate apparatus to observe. Nichols' light-pressure radiometer, which he devised for the express purpose of measuring the direct pressure of light radiation, is shown in Figure 10. The entire apparatus was enclosed in an evacuated glass bell jar. Two round silvered mirrors near the bottom of the apparatus were suspended on

Figure 9. Ernest Fox Nichols (from [20]).

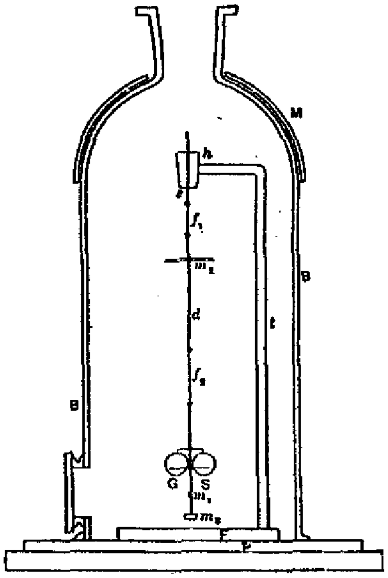

Figure 10. Nichols' improved radiometer for the measurement of direct radiation pressure. The round mirrors *G*, *S* suspended near the bottom of the vacuum jar were silvered on one side. When only one was illuminated, the slight rotation due to differential pressure turned the small readout mirror, *m*, at the lower end of the quartz torsion fiber (reprinted with permission from E. F. Nichols and G. F. Hull, "A Preliminary Communication on the Pressure of Heat and Light Radiation," *Phys. Rev.*, 13, 1901, p. 312, Copyright 1901 by the American Physical Society).

a quartz fiber, and received the intense radiation from a carbon arc lamp (not shown). A small rectangular indicating mirror below the radiometer mirrors was used to measure the torsion balance's deflection. Nichols was unable to obtain a vacuum greater than 0.06 mm of mercury, so his raw data were contaminated by the Crookes-type radiometer effect. Nevertheless, through a clever series of balancing techniques and dynamic measurements, he was able to isolate the true electromagnetic radiation pressure from other influences, and in 1901 he presented results that agreed within an error of 22% with Maxwell's theoretical prediction [18, p. 318]. A Russian physicist named Lebedew also reported similar measurements of comparable accuracy at about the same time, so Nichols could not claim an unequivocal "first" [20, p. 109].

Nichols' later years were increasingly occupied with administrative duties, first as President of Dartmouth, from 1909 to 1916, and later as President of the Massachusetts Institute of Technology for a short time in 1920, before health concerns forced him to step down. Although the nature of the illness is not clear from the record, it is possible that a heart attack or similar cardiovascular problem occasioned his resignation from MIT, since it came upon him suddenly and required a long period of recuperation. A few months before he was called to MIT, Nichols had previously agreed to become director of pure science research at the Nela Park Laboratory near Cleveland, Ohio, and he moved to Ohio after recuperating from his illness [20, pp. 117-119]. Nela Park was a creation of the General Electric Company, which was itself descended through myriad business twists and turns from the old Edison Electric Company. The Park was one of the first examples of a deliberately planned rural research campus constructed by a large corporate enterprise [22]. Nichols took advantage of the resources available in his well-funded corporate environment to realize one of the dreams of his lifetime: to perform continuous spectral measurements extending all the way from the far infrared range to the short radio-wave range.

By 1924, Nichols' experiments were far enough along to summarize at a meeting of the prestigious National Academy of Sciences, held in the brand-new facilities of the Academy in Washington, DC. In his talk, illustrated by photographs projected from a large glass-plate slide projector of the time, he showed how scientists had perfected instruments to measure nearly all parts of the electromagnetic spectrum from radio waves up through visible light to X-rays, with the sole exception of a gap between the longest infrared rays (about 50 microns in wavelength) and the shortest "ultra-short" radio waves (on the order of a centimeter). (These correspond to frequencies between 6 THz and 30 GHz, respectively.) With evident pleasure, he stated that with his colleague, J. D. Tear, he had finally managed to bridge this gap, producing and measuring radiation with wavelengths between about 11 mm and 0.4 mm (400 microns).

The source of his radiation was a "Hertzian oscillator," basically a spark gap between thick tungsten electrodes submerged in kerosene and operating at the focus of a reflector. For his detector, he used yet another variation of the Crookes-style radiometer, which converted absorbed radiation into heat that was detected by the differential rotation of vanes in an evacuated chamber. To maximize the absorption of energy at the wavelengths of interest, Nichols evaporated small platinum dipoles onto his radiometer vanes, and designed the dipole lengths to resonate with the wavelength of the radiation to be measured. He also devised echelon-type diffraction gratings, made of stepped blocks of aluminum, to complete his spectroscopic setup [23].

In the midst of his presentation at the Academy, after referring familiarly in his talk to Academy President Albert A. Michelson, seated a few steps away on the platform, Nichols said, "I shall–," then sat down quietly on a bench at the rear, with his pointer still in his hand. For a few seconds, no one moved. Then someone, possibly Prof. Michelson, finally stepped forward and tried to gain Nichols' attention – without success. The following day, April 30, 1924, the *New York Times* carried the front-page headline, "Drops Dead Before Scientist Audience" [24]. With his dramatic death, Nichols probably attracted more public attention to his rather obscure branch of research than anything else he could have done.

7. Epilogue: The Radio Revolution

In the same year that Nichols presented his last lecture about bridging the gap between infrared and electric waves, dozens of radio entrepreneurs were bridging the gaps between continents with the newly discovered "short waves," which, in 1924, meant wavelengths below 100 meters (above 3 MHz). The age of spark gaps and torsion balances was drawing to a close. Still, experimental traditions die hard, and researchers were still publishing papers on Crookes-style radiometers as late as 1945 [25]. Around 1930, Karl Jansky, a radio engineer with Bell Telephone Laboratories, detected a noise source in the 20-30 MHz range, which he eventually showed was of extraterrestrial origin [26]. Although a very few other researchers – notably the radio amateur, Grote Reber [27] – picked up on Jansky's research to build radiometers of their own for astronomical use, Jansky's discovery was largely ignored by astronomers until the end of World War II, when advanced war-surplus microwave equipment made the construction of microwave radiometers practical. One of the earliest significant discoveries made using such equipment was the detection of emission from interstellar hydrogen by Robert H. Dicke and Harold I. ("Doc") Ewen in 1948 [28]. Around that time, the vast superiority of radio receivers over mechanical means for detecting electromagnetic radiation was clearly evident, although radiometers based on mechanical or thermal effects would continue to be used at the shorter millimeter-wave and infrared wavelengths for many years to come.

8. Conclusion

In 1800, a gentleman-scientist armed with nothing more than a prism, a lens, and a thermometer made the first discoveries in what would eventually be called the science of radiometry. At the close of World War II, nearly a century and a half later, scientists around the world were using some of the most sophisticated equipment on the planet to measure electromagnetic radiation for both scientific and practical reasons. Today, radiometers fly in satellites and interplanetary orbiters. Some point toward Earth to produce infrared images of hurricanes, while others look to the sky to probe the farthest reaches of space and time.

The choice between the active and the contemplative, the life of action versus the life of the mind, is an ancient one. It shows up clearly in the lives of those who made signal advances in the field of radiometry. Edison and Langley are perhaps the most complementary in this regard. Each was a great success in his own chosen field, but could not resist the urge to venture into the other's territory. Edison found that a meaningful advance in science takes more than a single camping trip with some fancy new equipment, while Langley learned that the scientist who ventures into the public square to show off a practical invention runs the risk of looking foolish. Nichols worked in a laboratory funded by General Electric, a corporation built with the fruits of Edison's highly practical incandescent lamp. Yet Nichols used General Electric's resources to pursue the esoteric scientific goal of uniting the radiowave and infrared spectra. And the down-to-Earth engineer Jansky almost reluctantly concluded that he had discovered something literally out of this world with his prototype radio telescope. The early history of radiometry is a kind of mirror that reflects the way science and technology at large have interacted, stimulated each other, and led to both knowledge and power of which its progenitor, Herschel, never would have dreamed. But then, someone who could believe in life on the sun may have dreamed of more than we can guess.

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