EARLY INFRARED ASTRONOMY

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Abstract: I present a short history of infrared astronomy, from the first scientific approaches of the 'radiant heat' in the seventeenth century to the 1970's, the time when space infrared astronomy was developing very rapidly. The beginning of millimeter and submillimeter astronomy is also covered. As the progress of infrared astronomy was strongly dependent on detectors, some details are given on their development.

Keywords: infrared, detector, bolometer, photometry, Sun, Moon, planet, star, William Herschel, Macedonio Melloni, Hippolyte Fizeau, Léon Foucault, Claude Pouillet, Samuel P. Langley, Ernest F. Nichols, Charles V. Boys, Laurence Parsons (4th Earl of Rosse), William W. Coblenz, Edison Pettit, Seth B. Nicholson, Gerard P. Kuiper, Peter Fellgett, Madeleine Lunel, Harold Johnson, Vassili Ivanovitch Moroz

1 INTRODUCTION

Infrared astronomy had a slow and somewhat erratic early development, which is only partially covered in the literature. Sinton (1986) and Rieke (2009) are the only modern authors to give some elements of this history, but they start in 1869 while there were interesting earlier observations, and their coverage of developments in Europe is incomplete. Developments after 1970 are well documented thanks to these papers as well as those of Jennings (1986), Price (1988), Dolci (1997), Storey (2000), Low et al. (2007) and Léna (2007, 2008), which were useful in preparing this review. Interesting information can also be found in the books by Smith et al. (1968) and Allen (1975).

The present paper includes points not discussed extensively by Sinton (1986) and by Rieke (2009), and the period covered extends only to the early 1970's in order to avoid redundancies. I include early infrared observations of the Sun which are often neglected in the literature. Finally, I briefly describe early developments of millimeter and submillimeter astronomy.

2 THE INFRARED BEFORE HERSCHEL

Officially, infrared radiation was discovered in 1800 by William Herschel (1738–1822). However, some interesting work was done earlier. In 1833, François Arago (1786–1853) wrote an obituary for Joseph Fourier (1768–1830), which contains historical information on what Fourier called the 'calorique rayonnant' (radiant heat):

> The famous academicians del Cimento [in Florence] found, almost two centuries ago, that this 'calorique' can be reflected like light; like light, it can be concentrated at the focus of a concave mirror. Replacing hot bodies by snow balls, they even proved that one can form frigorific focuses by reflection.
>
> A few years later, Mariotte, member of the French Academy of Sciences, discovered that there are different kinds of 'calorique rayonnant'; that which accompanies the solar rays [the near infrared] traverses all transparent media as easily as light; that which emanates from a heated, but still dark material, as well as that which is mixed with light rays from a slightly incandescent body [the far- and mid-infrared], are stopped almost completely by the most transparent glass plate. (Arago 1836: CIV; my translation).

Arago went a little too far, as we will see. Here is what we find in a description of experiments made in 1667 by the Academia del Cimento (Anonymous, 1684: 103):

> The Ninth Experiment of Reflected Cold. We were willing to try, if a Concave Glass [actually, a concave mirror] set before a mass of 500 l. of Ice made any sensible repercussion of Cold upon a very nice Thermometer of 400 deg. placed in its Focus. The truth is, it immediately began to subside, but by reason of the nearness of the Ice, 'twas doubtful, whether the direct, or reflected rays of Cold were more Efficacious: upon this account, we thought of covering the Glass, and (whatever may be the cause) the Spirit of Wine did indeed presently begin to rise; for all this we dare not be positive; but there might be some other cause thereof, beside the want of reflection from the Glass; since we were deficient in making all the Trials necessary to clear the Experiment.

Figure 1 is a nineteenth century representation of this experiment, which looks rather faithful. Presumably, the experimenters were so surprised by their result that they had doubts about it.

Figure 1: The experiment of reflected cold presented to Duke Ferdinand II by the Academia del Cimento, fresco by Gaspero Martellini (1785–1857) at the Tribuna di Galileo, Florence (Italy), dated 1841. The mass of ice is placed in a vessel and its radiation is concentrated by a concave mirror on a long vertical thermometer. An assistant is covering the mirror with a piece of canvas or cardboard (Wikipedia Commons).

In another account, written in French, we find the following note by Petrus van Musschenbroek (1692–1761), probably relating to an experiment made by himself:

> The heat from a charcoal fire placed out of an evacuated vessel, but nearby, passes easily through this vessel, and raises the thermometer placed at the center of this vessel. (Anonymous, 1755: 27; my translation).

Musschenbroek also cites a French experiment in which a piece of butter in a vacuum is melted when exposed to an external source of heat. As to Edme Mariotte (1620–1684), all we could find from him is the following account:

> M. Mariotte made some remarks and experiments on heat, in particular that the heat from a fire reflected by a concave mirror is noticeable at its focus: but if one inserts a piece of glass between the mirror and its focus, the heat becomes undetectable. (Anonymous, 1733a: 344; my translation).

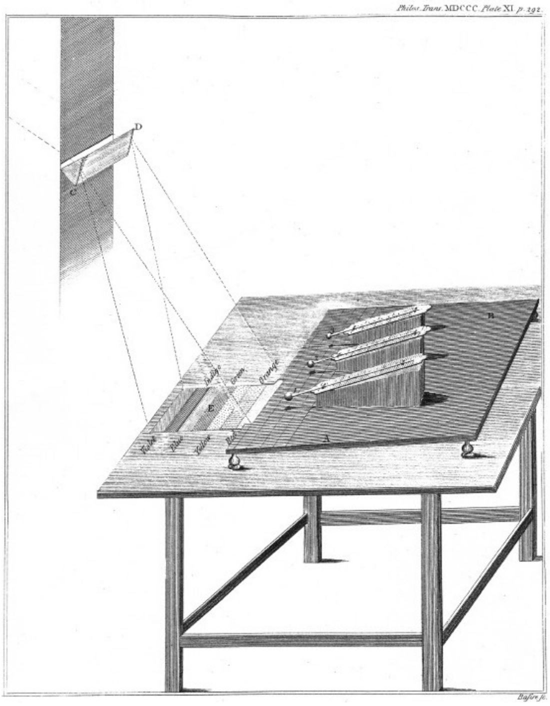

Figure 2: Herschel's experiment to study radiant heat in the solar spectrum. Three thermometers on a movable plate are placed in parallel at different places in the solar spectrum.

In 1682 Mariotte wrote a remarkable *Essay on cold and heat* (Mariotte, 1717; my English translation) in which he showed that cold does not exist by itself, but is only a lack of heat; for him, heat corresponded to an internal agitation in the heated bodies (a very modern idea, which however was not universally accepted as we will see later). A contemporary account summarizes his work as follows:

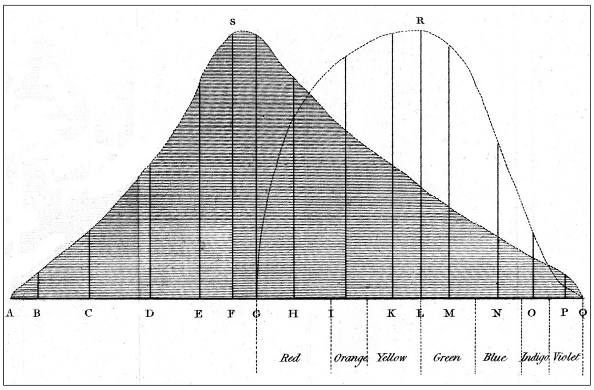

Figure 3: Herschel's attempt to display of the spectral energy distribution of light (R) and 'radiant heat' (S) in the spectrum of the Sun. The distribution of light mainly reflects the sensitivity of the eye. That of radiant heat, which would be expected to peak in the yellow, is in fact strongly displaced towards the infrared due to the variation of dispersion of the prism with wavelength: the thermometer receives a broader range at longer wavelengths.

> He did not find any positive cause for cold. A perfect cold would be a complete lack of motion in the bulk of bodies; but we think that this complete lack cannot be found in nature. (Anonymous, 1733b: 268; my translation).

It seems that Arago extrapolated what these authors have said in the light of the knowledge of his time, especially as far as Mariotte was concerned. They only produced interesting but fragmentary observations and theories, which were not placed in a coherent context. William Herschel was the first to achieve this goal.

3 WILLIAM HERSCHEL AND THE NATURE OF RADIANT HEAT

In 1800, while projecting onto a screen the spectrum of the Sun produced by a prism, Herschel had the idea of placing blackened thermometers at different places in this spectrum. He observed a strong heating in the red, which weakened when going to the violet side of the spectrum, and concluded:

> I must now remark, that my foregoing experiments ascertain beyond a doubt, that the radiant heat, as well as light, whether they be the same or different agents, is not only refrangible, but is also subject to the laws of dispersion arising from its different refrangibility ... May not this lead us to surmise, that radiant heat consists of particles of light of a certain range of momenta,[1] and which range may extend a little farther, on each side of refrangibility, than that of light? (Herschel, 1800a: 271).

Thus Herschel suspected that radiant heat and light were identical, or similar in nature. He was obviously troubled by the fact that the maximum of heat in the spectrum did not coincide with the maximum of light. Placing now his thermometers beyond the red side of the spectrum, he still saw heating and concluded that

> In this case, radiant heat will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light; that is to say, of rays coming from the sun, that have such a momentum as to be unfit for vision. (Herschel, 1800a: 272).

His next research paper contains the famous plate describing his experiment, reproduced here as Figure 2. Herschel (1800b: 291) was still hesitant about the nature of radiant heat:

> To conclude, if we call light, those rays which illuminate objects, and radiant heat, those which heat bodies, it may be enquired, whether light be essentially different from radiant heat? In answer to which I would suggest, that we are not allowed, by the rules of philosophizing, to admit two different causes to explain certain effects, if they may be accounted by one.

A third paper by Herschel (Herschel, 1800c) is titled "Experiments on the solar, and on the terrestrial Rays that occasion heat; with a comparative View of the Laws to which Light and heat, or rather the Rays which occasion them, are subject, in order to determine whether they are the same, or different." It shows that the radiant heat from the Sun, from a candle, from a piece of iron red hot or sufficiently cold to stay dark (the 'invisible culinary heat'), etc., are all reflected by a mirror. In his fourth and fifth papers, Herschel (1800d; 1801) studies quantitatively the transmission, reflection and diffusion by a variety of substances of total sunlight, of sunlight dispersed by a prism, and of the different sorts of radiant heat described in the previous paper. This is a beautiful work, but there are no new conclusions about the nature of radiant heat. Paper 4 contains a plate comparing in a semi-quantitative way the spectral distribution of radiant heat and of light in the solar spectrum (see Figure 3). It is one of the very first attempts to display data using a graph instead of a table.

This figure must have perplexed Herschel and his contemporaries. Was the difference due to different refractive indices of the prism for light and radiant heat? Looking at this graph, it is hard to believe that radiant heat and light are one and the same thing, and that the difference is due to the sensitivity of the eye. No one, with the exception of Thomas Young (1773–1829), understood that radiant heat is the prolongation of the optical radiation. For example, Jean-Claude Delamétherie (1743–1817), relating Herschel's discovery in his *Journal de Physique*, flatly pretends that Herschel concluded that "… light differs from heat." (Delamétherie, 1801: 8; my translation). Joseph Fourier (1768–1830) speaks of "… rays of invisible heat mixed with the light of the Sun …" (Fourier, 1823: LXXV; my translation). To complicate the matter, Johannes Wilhelm Ritter (1776–1810) in Germany and Francis Wollaston (1731–1815) in England independently discovered in 1801 that the Sun also emits 'invisible rays', also called 'chemical rays', that darken silver chloride. Scientists were very puzzled.

In 1835, André-Marie Ampère (1775–1836), with considerable insight, proposed a new concept (cited by Melloni, 1835: 503; my translation):

> It consists in considering radiant heat as a series of undulations excited in ether by the vibrations of the hot bodies. These undulations would be longer than the waves which make light if the calorific source is dark.[2] But in the case of those sources that are at the same time calorific and luminous, there would always be a set of waves which possess simultaneously the two properties of heating and illuminating. Thus, in this view, no essential difference would exist between radiant heat and light.

However, in spite of his numerous experiments on reflection, refraction and polarisation of radiant heat, the greatest specialist of the time, Macedonio Melloni (1798–1854), the 'Newton of heat' (Langley, 1880: 501), still believed two years later that light and heat are of a different nature, although they have much in common (Melloni, 1837). For him, as for many of his contemporaries, radiant heat was comparable to the 'calorique', that kind of fluid which propagates slowly inside bodies, the very heat studied by Fourier. However, in 1842, Melloni changed his mind and rallied to Ampère's support (Melloni 1842: 454; my translation):

> Light, heat and chemical reactions [i.e. in fact the ultraviolet which produces these reactions] are three manifestations of the undulations of ether which make solar radiations. The dark undulations responsible for chemical or calorific actions are perfectly similar to luminous undulations; they only differ from them by wavelength.

This was confirmed five years later, for the near infra-red, by the superb experiments of interference and diffraction of Hippolyte Fizeau (1819–1896) and Léon Foucault (1819–1868) (Fizeau and Foucault, 1847). Room is lacking here to describe these rather complex experiments, and we will only show the spectral distribution of solar radiation that they obtained in the same way as Herschel, but now with a good wave-length calibration (Figure 4). An interesting feature of their device is that they used, apparently for the first time, a permutation method in order to eliminate the effect of the temperature variations in the enclosure containing the detector, in this case a thermometer: the signal was periodically chopped by an obturator, and they read the temperature difference between the 'on' and 'off' positions of this chopper.

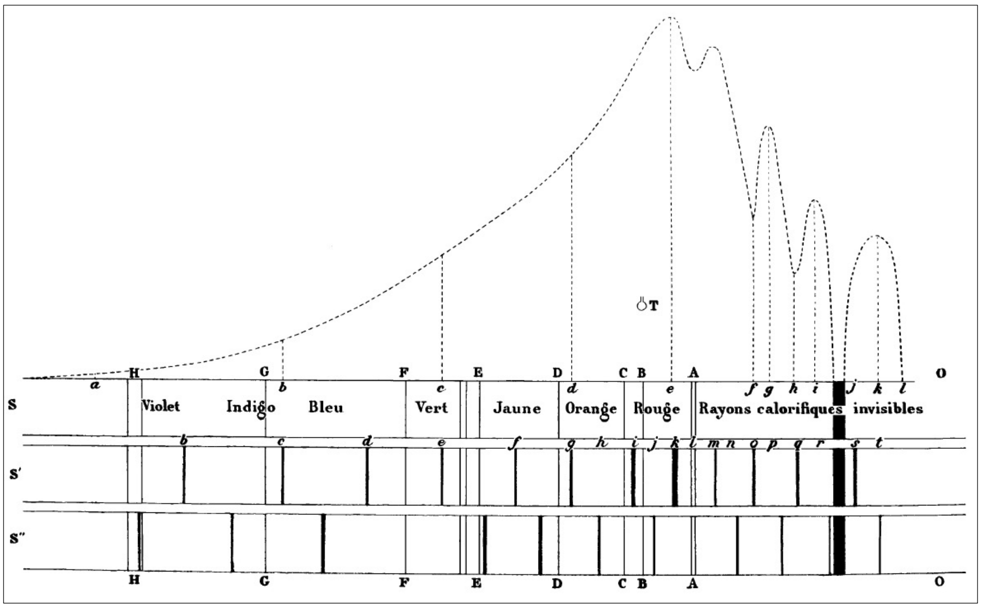

Figure 4: The spectrum of the Sun from the violet to the near infrared obtained by Fizeau and Foucault in 1847 with a glass prism. As for Figure 3, the spectrum, which would be expected to peak in the yellow, is in fact strongly displaced towards the infrared due to the variation of dispersion of the prism with wavelength. Fizeau and Foucault observed the infrared absorption bands due to the Earth's atmosphere, but they were not recognized as such by them. The vertical lines in S are the main Fraunhofer lines. The broad infrared bands were already suspected in 1843 by John William Draper (1811–1882) and also by John Herschel, but with no wavelength measurements.[3] In S′ and S″, the bold vertical lines mark the positions of interference fringes obtained using chromatic polarization, which are equidistant in wavelength. For the first time, they allowed the establishment of a wavelength scale in the near infrared.

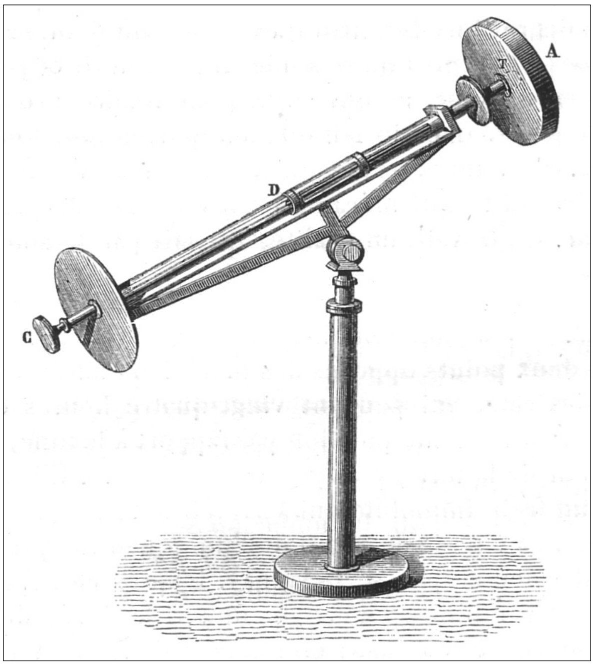

Figure 5: Pouillet's pyrrheliometer. A blackened surface A is directed normally to the direction of the Sun, using its shadow which has to be centred on the disk on the rear. It covers a metal box full of water, silvered on the outside to minimize radiative heat exchange. This box can be rotated upon itself in order to equalize the water temperature. This temperature is measured with the thermometer TD. The measurement consists in noting the temperature increase due to solar radiation during a given time (5 minutes). The temperature change in 5 minutes before and after the measurement is also noted in order to correct for it.

However, it seems that these experiments have been largely ignored. They are not mentioned in the lectures in physics given in the 1860s at the École Polytechnique by Jules-Célestin Jamin (1818–1886), who is still speaking of the "… *probable* identity of heat and light". (Jamin, 1858-1866; my translation and italics).

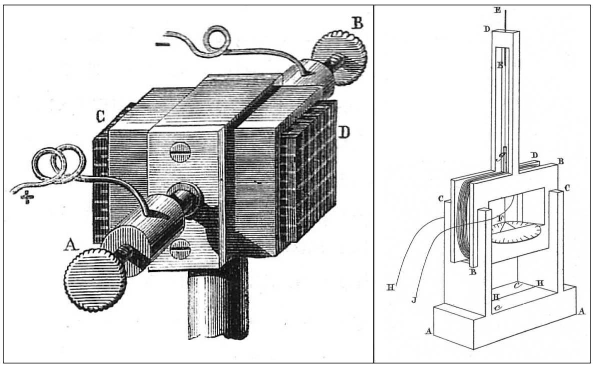

Figure 6: Left: the 'thermomultiplicateur' of Nobili and Melloni (ca. 1835); right: a 'multiplicateur' built by Christian Œrsted (1777–1831) in 1822 or 1823. The thermomultiplier is made of 36 antimony-bismuth thermocouples in series, separated by thin insulating foils. The front surface is covered with carbon black, and the device measures the temperature difference between the front and the back. It is connected to a 'multiplier', a galvanometer consisting of a magnetized needle inside a number of turns of conducting wires. The name of the multiplier comes from the fact that the first galvanometers had only a single loop, and that using several turns of wires multiplies the effect accordingly. Similarly, the infrared detector used several thermocouples instead of one, hence its name.

4 THE FIRST DETERMINATION OF THE SOLAR CONSTANT

Attempts to measure the total power received from the Sun per unit surface perpendicular to its direction at a distance of 1 A.U.—the solar constant—were made by Horace Bénédict de Saussure (1740–1799), then by William Herschel. Both were unsuccessful. The first successful measurement was that of the French physicist Claude Pouillet (1790–1868) (Pouillet, 1838). For this, he built a simple instrument that he named a 'pyrrhéliomètre' (see Figure 5).

Pouillet assumed that the black surface of his instrument entirely absorbed the incoming radiation. He also assumed that he could correct his result for absorption in the Earth's atmosphere using a method due to Pierre Bouguer (1698–1758): observing the Sun under stable conditions at different zenith distances, calculating the thickness e of the atmosphere for each direction, and supposing that the absorption is proportional to a^e, a being a transmission coefficient; an extrapolation to zero thickness allows one to calculate the incoming radiation at the top of the atmosphere. However, the carbon black on the surface did not fully absorb the radiation, and Bouguer's method was only valid if the absorption was unsaturated, which was not true for the main atmospheric absorption bands in the near-infrared. Both assumptions led to an underestimate of the solar constant, although by a relatively small amount. Pouillet obtained 1,230 watts per square meter, while the modern value measured by satellites is 1,367 watts per square meter.[4] This is a remarkably good result given the difficulties of this apparently simple experiment.

Pouillet's pioneering work was probably forgotten because the solar constant was measured again at the beginning of the twentieth century in the USA by Samuel P. Langley (1834–1906), who made a mistake in his reduction, then by Charles G. Abbot (1872–1973), whose result is not much better than the value obtained by Pouillet.

If Saussure did not succeed in measuring the solar constant, he was the first to observe in detail around 1780 the greenhouse effect using his 'héliothermomètre', a wooden box with a black bottom and a lid made of four successive glass layers. He even suggested that, like glass, the Earth's atmosphere could retain heat. This was confirmed and elaborated on by Fourier (1824). However, the main causes of atmospheric absorption in the infrared, hence for the glasshouse effect—water vapor and carbon dioxide—were only recognized spectroscopically in 1861 by John Tyndall (1820–1893) (Tyndall 1861).

5 THE FIRST INFRARED DETECTORS AND THEIR ASTRONOMICAL APPLICATIONS

The blackened thermometer is not a very sensitive infrared detector, and it is not surprising that no astronomical observation other than those of the solar spectrum and solar constant could be performed successfully with it. For example, Arago tried in vain to detect limb darkening of the solar disk in 'calorific rays' by letting the solar image produced by the lens of the Observatory's mèridienne (a gnomon) cross a thermometer. Fortunately, better detectors could be built using the thermoelectric effect discovered in 1821 by the physic-cist Thomas Johann Seebeck (1770–1831).

In Italy, Leopoldo Nobili (1784–1835) soon came up with the idea of placing in series numerous thermocouples, and Melloni connected this device (Figure 6) to a galvanometer, building what he called a 'thermomultiplicateur'. The device was sensitive enough to detect the radiation of the hand at a distance of one meter. Melloni made many experiments with it,[5] including a new spectral decomposition of solar radiation with a prism made of rock salt (natural sodium chloride), which, unlike glass, absorbed little in the infrared.

Father Angelo Secchi (1818–1878) from the Vatican Observatory succeeded where Arago failed by using the thermomultiplicateur to measure limb darkening of the Sun in the infrared (Secchi, 1875-1877). Various versions of this detector were in use until the beginning of the twentieth century.

Photographic techniques were also applied to the infrared, by staining photographic plates with various phosphorescent dyes. But the sensitivity remained low although wavelengths as long as 9,200 Å were commonly reached before 1912.[6] At this date, only the spectrum of the Sun could be photographed in the infrared. The first infrared photographs of stellar spectra up to 9,000 Å were obtained in the 1930s in the USA by Paul Willard Merrill (1887–1961).

In the 1880s, four new detectors appeared. The most famous of them is the 'bolometer' invented in 1880 by Langley (1900a). One of the several versions of this instrument, which uses the variation with temperature of an electrical resistance, is displayed in Figure 7. It was considerably more sensitive than the previous thermocouples, especially when connected to of the excellent galvanometers made by William Thomson (Lord Kelvin, 1824–1907).

In 1875, William Crookes (1832–1919) invented the 'radiometer', a well-known device in which the action of light on blackened surfaces moves a little mill in a partial vacuum. Initially, Crookes believed that radiation pressure was doing the job, but it was soon demonstrated by George Johnstone Stoney (1826–1911), an Irish scientist, that the pressure on the black surface was due to momentum transfer from the molecules of the gas heated by this surface. James Clerk Maxwell (1831–1879) and Osborne Reynolds (1842–1912) produced the complete theory of this apparatus.

Ernest Fox Nichols (1869–1924) built on this principle a very sensitive radiometer (Figure 8) that he used for laboratory and astronomical measurements (Nichols et al., 1901). This instrument had a very stable response but could not be moved, thus the radiation of the observed astronomical object had to be sent to it via a siderostat.

The third new detector was invented around 1878 by Thomas Edison (1847–1931): the 'tasimeter' (see Eddy, 1972). This device, which derives from his carbon telephone transmitter, consisted of a strip of some material sensitive to heat whose expansion changed the pressure on a carbon button. The resistance of the carbon was modified accordingly and was measured by a Wheatstone bridge and a galvanometer. The tasimeter was very sensitive but also was very unreliable (see for example Raynard, 1878), and it soon faded into obscurity.

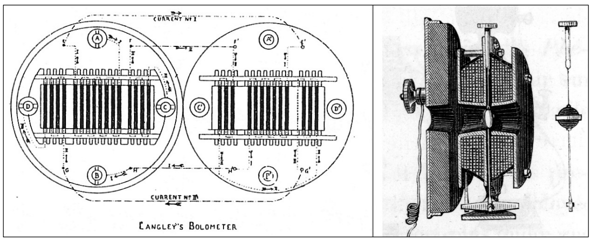

Figure 7: Left: a version of Langley's bolometer (after Rosse, 1895: 10); right: a Thomson galvanometer. The bolometer is composed of two superimposed gratings of very thin (4 µm) blackened metal, here represented deployed; each strip is 0.5 mm wide and the two planes, here represented side by side for clarity, are separated by 1 mm. For each grating, the strips are connected in series. The central gratings of 6.5 x 6.5 mm, formed of seven strips each, are inserted electrically in the two sides of a Wheatstone bridge, for a differential measurement of their resistance. The radiation is sent on the upper grating, with a chopping device. The lateral gratings of three strips each are parts of another circuit in order to detect accidental disturbances. The whole detector is placed in an enclosure where water circulates for thermal stability. It was generally connected to a Thomson galvanometer, which consists of a small magnet glued to a mirror, inserted in a coil; a pencil beam of light falls on the mirror, the deflection is read on a screen.

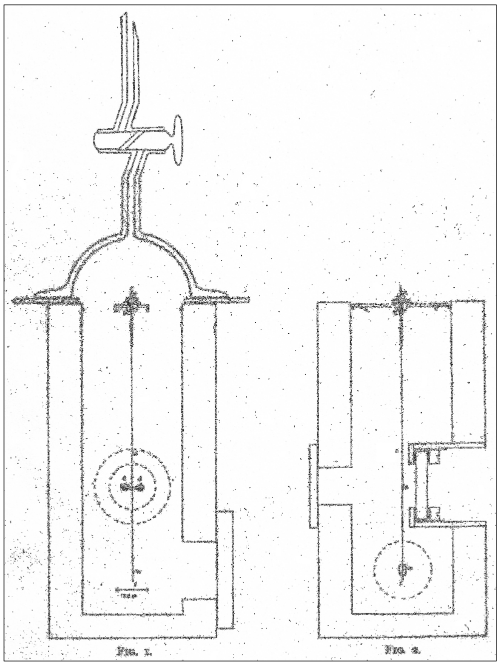

Figure 8: Nichols' radiometer (1898). Two 2-mm diameter mica disks blackened on one face are supported by a light cross-arm on either side of a thin glass rod, supported by a very thin torsion fiber of quartz in a partial vacuum. For astronomical observation of an object, both disks are submitted to the radiation of the sky through a fluorite window at the focus of a concave mirror illuminated by a siderostat, and the image of the object is focused on one of these disks. The rotation of the system is measured by reflection on a small flat mirror attached to the bottom of the rod.

Finally, Charles V. Boys (1855–1944) in England invented the 'radiomicrometer' (Boys, 1890), a combination thermocouple-galvanometer inserted between the poles of a permanent magnet (Figure 9). This instrument was used for high-resolution infrared spectroscopy by Exum Percival Lewis (1863–1925), who encountered severe difficulties in operating it (Lewis, 1895).

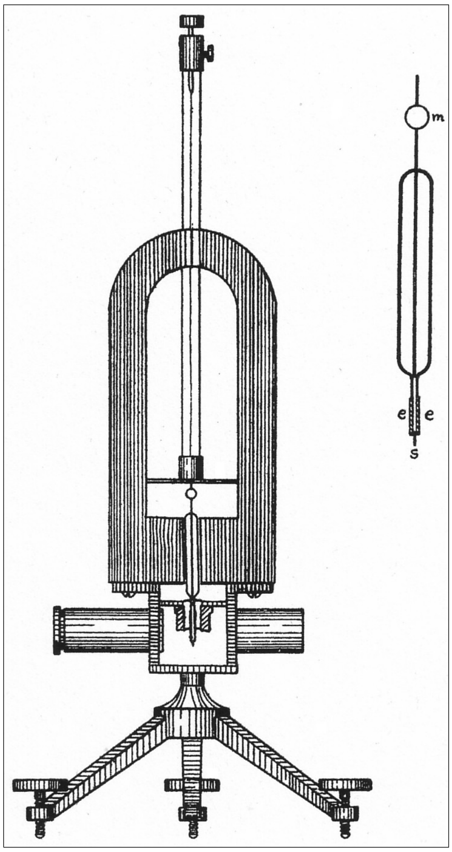

Figure 9: The radiomicrometer of Boys (after Lewis 1895: 9). Two blackened thermocouples *ee* are connected in opposition to an elongated rectangular electric circuit consisting of one or several loops. This ensemble is suspended from a torsion wire and placed between the poles of a permanent magnet. The heating of one of the thermocouples by the incoming thermal radiation produces a current in the circuit which is then deflected by the magnetic field. The small mirror *m* allows the observer to measure this deflection by reflection of a light beam. This set-up derives from the mobile-coil galvanometer invented in the early 1880's by Arsène d'Arsonval (1851–1940) and Marcel Desprez (1843–1918).

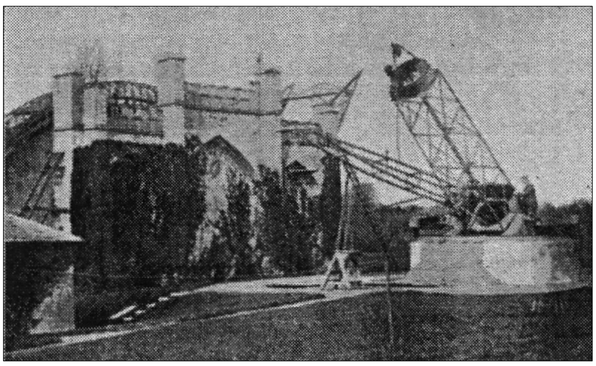

Figure 10: The 3-ft telescope of Lord Rosse at Birr Castle (Ireland), with the focal device illustrated in Figures 11 and 12.

Various detectors were used in attempts to detect the thermal radiation of the solar corona. The nature of the corona which was seen to surround the disk of the Sun during total eclipses was then a complete mystery, and it was hoped that detection of its thermal emission would help astronomers understand it. It is no surprise that the first attempts were made during total eclipses. Luigi Magrini (1802–1868), a pupil of Nobili, claimed to have detected the heat of the corona with a 'Rumford thermoscope' during the eclipse of 9 July 1842, but since he could not detect the heat of the full Moon with the same apparatus doubts were expressed about this observation (e.g. Hale, 1895: 327). During the eclipse of 29 July 1878, Langley made an unsuccessful attempt with an inadequate thermopile, while the thermal radiation from the corona was saturating Edison's tasimeter, at least if we can believe his account (see Fernie, 2000)! George Ellery Hale (1868 –1938) was optimistic about the possibility of a detection even outside eclipses, using a bolometer and a sensitive galvanometer (Hale, 1895). Langley and Abbot, and Henri Deslandres (1853–1948), were first to definitely detect the corona, during the total eclipse of 28 May 1900. Langley and Abbot used a bolometer and no filter (Langley, 1900b), while Deslandres employed a Melloni thermopile and a glass prism spectroscope which eliminated radiation outside the range 1.0-1.8 μm. Deslandres (1900) also succeeded in detecting infrared radiation from the corona outside of eclipse using another thermopile built by Heinrich Rubens (1865–1922). None of these researchers was able to draw a conclusion about the nature of the corona, which was generally believed at this time to be some electric phenomenon similar to a glow discharge. Since this discharge radiated very little heat, the faintness of the infrared radiation was considered an argument against it being thermal emission. However, in 1908 Abbot observed near-infrared emission from the corona during another eclipse and concluded that it was probably not an electrical phenomenon (Abbot 1908). He proposed that this emission was due to scattering of the solar emission by dust particles, an explanation confirmed later by polarization studies of the corona; the thermal emission of these particles starts to dominate in the mid-infrared.[7]

As can be expected, the next target for infrared astronomy was the Moon. Attempts to observe radiant heat from the Moon date from the seventeenth century.[8] The goal of these observations was obviously to see if the Moon is able to radiate some heat to the Earth at night. There are claims of a detection of lunar thermal radiation in 1685 by Geminiano Montanari (1633–1687), a member of the *Academia del Cimento* in Florence where the thermometer was developed, but this is probably spurious since subsequent attempts were unsuccessful. In 1845 or 1846, Melloni placed his thermomultiplicateur at the focus of a 1-m diameter Fresnel lens and made the first definite detection (Melloni, 1846). He used a Fresnel lens instead of an ordinary lens, a good idea because the glass thickness is considerably less and its absorption is limited; but the glass wavelength cut-off makes it impossible in this way to detect anything other than reflected solar radiation.

Confirmations were obtained in 1856 in Teneriffe by Charles Piazzi Smyth (1819–1900), the godson of Giuseppe Piazzi (1746–1826) who discovered the first asteroid. At the focus of a mirror, Charles Piazzi used a thermomultiplier "… with the ordinary cone of polished metal …" to concentrate the radiation. In 1869, Hippolyte Marié-Davy (1820–1893) in Paris also detected lunar heat with Edmond Becquerel's 'pile thermo-électrique', a bismuth-antimony/bismuth-cadmium thermocouple; he used permutation by alternatively covering and opening the objective of his 9-inch refractor (Marié-Davy, 1869). Another detection was made at the same time in France (Baille, 1869).

The most extensive set of infrared lunar observations is due to Laurence Parsons, the 4th Earl of Rosse (1840–1908), and his assistants. Laurence was the son of William Parsons, 3d Earl of Rosse (1800–1867), who built the famous reflecting telescope nicknamed 'The Leviathan', but also the more manageable 3-foot diameter reflector used by his son for the lunar observations (Figure 10).

For his first observations of 1868-1873, Rosse used a thermopile of four elements directed alternately towards the Moon and the nearby sky, but he soon replaced it by the differential device displayed in Figures 11 and 12. The whole disk of the Moon was imaged on one of the thermopiles, directly or through a sheet of glass which was known to absorb infrared radiation. In this way, Rosse could obtained by subtraction the infrared flux from the Moon. The electric signal was detected with a Thomson galvanometer (see Figure 7). Rosse (1973) observed the Moon at different phases, reducing the observed flux to outside the atmosphere using Bouguer's method. He found this flux to follow the optical flux (the 'phase-curve') rather well, and reached the following conclusions about the radiation:

> As the phase-curve descended on each side almost to zero on approaching New Moon, it was clear that little or none of the heat we were measuring came from the interior of the Moon. It was heat derived directly from the Sun ...
>
> From the fact that 8 to 17 per cent. of the heat (being greatest towards Full Moon) was transmitted by the glass, while some 90 per cent. of the sun's rays passed through the same sheet of glass, it was, we think, clearly established that the heat, which we had already concluded, as stated above, to be directly derived from the Sun was not reflected sun-heat, but heat absorbed and afterwards emitted by the lunar surface.

Rosse compared his lunar deflections with those from blackened cans containing water at different temperatures. This was the only wise thing to do given the knowledge at this time: Josef Stefan (1835–1893) published his fourth-power of the absolute-temperature law only in 1879, and little was known about atmospheric extinction. After some attempt to correct for this extinction, Rosse obtained a temperature of the full Moon in reasonable agreement (by chance!) with the present value.

Rosse, or rather the German astronomer Otto Boeddicker (1853–1937) whom he put in charge of his observatory, also observed two total eclipses in 1884 and 1888, and found that there was, as expected, some delay in the heat radiation with respect to the light in the eclipses (Anonymous, 1892a; Rosse, 1895). In both cases the flux took 1h 40m after the last contact to reach the original level. These were the last observations, and although Rosse (1905) later proposed a network of stations to observe lunar eclipses this was never realized.

One of the weak points in these observations was that they only measured the global flux of the Moon. The first to explore several points of the lunar disk was the American astronomer Frank W. Very (1852–1927) (Anonymous, 1892b), who in 1889 used Langley's bolometer. Langley himself also made many observations of the Moon.

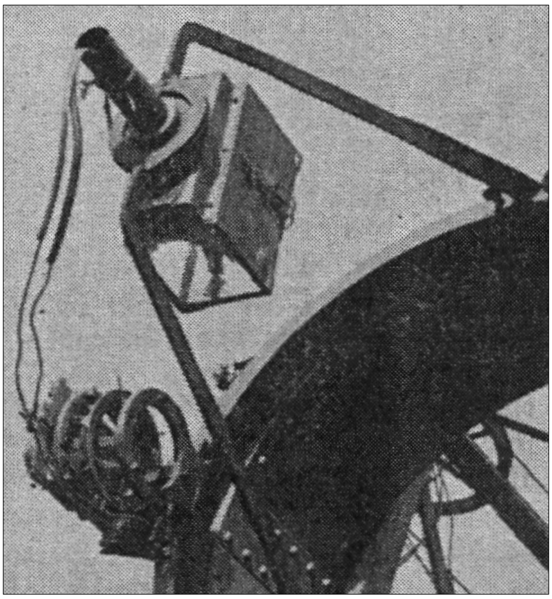

Figure 11: The focal equipment at the focus of the 3-ft telescope shown in Figure 10.

Observing the radiant heat from the stars and planets turned out to be considerably more difficult. Claimed detections in 1869 of the heat from bright stars by Sir William Huggins (1824–1910) (Huggins, 1878) and Edward James Stone (1833–1897) (Stone, 1870), who used a differential technique similar to Rosse's, were later shown to be spurious. Nor was Boys able to detect infrared radiation from stars when he carried out observations with his radiomicrometer[9] in 1888-1890. The first detections were secured in 1898 by Nichols and two collaborators who used a radiometer that was twelve times more sensitive (Nichols et al., 1901): Arcturus, Vega, Capella, Altair and a number of other stars were detected, although somewhat marginally. Nichols also obtained for the first time a detection for Jupiter and Saturn; in this case, it is obvious that he could only observe solar radiation scattered by the atmospheres of these planets, since they were too cold for their own radiation to be detected easily from the ground, especially through the fluorite window used by Nichols, which cuts the radiation off at 9 μm.

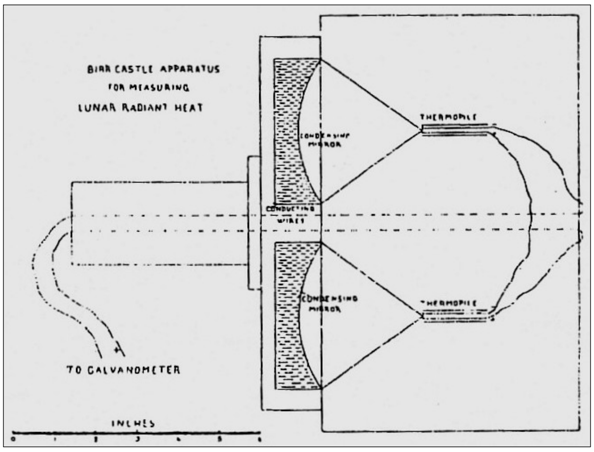

Figure 12: Principle of the infrared detection system at the focus of the 3-ft telescope (see Figures 10 and 11). Two detectors of four thermocouples each, mounted in opposition, are placed in a box at the foci of two small concave mirrors for a differential temperature mea-surement.

6 TOWARDS QUANTITATIVE MEASUREMENTS

All the measurements discussed in the previous section were qualitative: the signals were generally quite weak, no photometric system existed in the infrared, and the observers only compared the galvanometer deflections with those given by a candle at some specified distance. For example, in reporting on new observations by Nichols, Hale (1899) writes:

> In view of the smallness of the deflections, and the uncertainty which arises from rapid fluctuations in the atmosphere, Professor Nichols does not greatly rely upon the quantitative value of the results.

Atmospheric absorption was very important, even for the candle, and almost impossible to correct for, in spite of the investigations made with a rock-salt prism by Langley and Very (1889), who unfortunately used an incorrect wavelength scale. Anyway, the spectral range of the observations was either poorly-defined or not defined, with the notable exception of Deslandres' observations of the solar corona. All this made any reasonable astrophysical interpretation of the measurements impossible, a fact honestly acknowledged by the observers themselves. The 'ball' was now in the camp of the physicists, who were actively exploring the mid- and far-IR and were trying to bridge the gap between the optical-infrared range and the radio waves discovered by Heinrich Rudolf Hertz (1857–1894) in 1889.

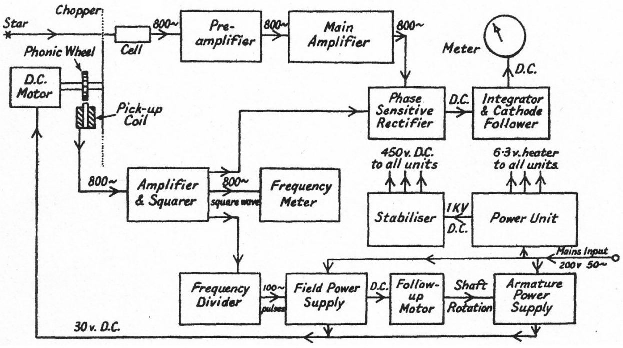

Figure 13: The electronics of Fellgett's infrared photometer. The synchronous detection (here at 800 Hz) is typical for all ground-based infrared detectors after WWII.

The first thing to do was to measure wavelengths. Most spectroscopic observations being done with glass or rock salt prisms, so it was necessary to calibrate their dispersion, either using a grating as Langley or Friedrich Paschen (1865–1947) did, or by modulating the spectrum by an interference pattern (Rubens), the method invented by Fizeau and Foucault but now attributed to Henri Becquerel (1852–1908)! In 1896, the wavelengths could be calibrated up to 9.4 µm, a range soon to be extended to much longer wavelengths.[10] Langley (1900a: 183) obtained a spectrum of the Sun up to 5.5 µm, discovering many spectral lines and obtaining simultaneously the position of the main absorption bands of water vapor. Other work on atmospheric absorption was done in 1898 by Rubens and his assistant Emil Aschkinass (1873–1909) who extended the measurements of absorption by H_2O and CO_2 to 24.4 µm (Rubens and Aschkinass, 1898). They concluded:

> The observations now communicated show that the Earth's atmosphere must be wholly opaque for the rays of wave-length 12^{μ} to 20^{μ} as well as for those of wave-length $24^{\mu}.4$. In fact Langley's observations on the spectrum of the Sun and Moon only extend to ... an extreme wave-length of from 10^{μ} to 11^{μ}.

All this was the basis of the quantitative theory of the 'greenhouse effect' of the terrestrial atmosphere, developed by Svante Arrhenius (1859–1927) after 1896.

In 1900, Max Planck (1858–1947) announced his theory of blackbody radiation. By a superb series of experiments, Rubens and Ferdinand Kurlbaum (1857–1927) in Berlin verified Planck's formula for blackbodies in a large range of temperatures and wavelengths (Rubens and Kurlbaum, 1901). It then became possible to interpret observations in the infrared in terms of temperature of the emissive body; all previous attempts were completely unreliable.

Now infrared astronomical observations could become quantitative. Most of them were done in the USA. In 1914, at the Lick Observatory, William W. Coblentz (1873–1962) made the first attempt to measure stellar radiation at all wavelengths accessible from the Earth (Coblentz, 1914). He then extended his measurements at a higher altitude site, the Lowell Observatory in Flagstaff, Arizona (Coblentz, 1922). With a very sensitive, tiny thermocouple in a vacuum, he detected twenty-seven stars, the radiation being blocked above various wavelengths by combining red glass, quartz and a water cell. Coblentz believed that he had also detected radiation from some of these stars between 4 and 10 µm, but this was probably spurious. He also observed Venus and Mars. From his measurements, he was able to determine the effective temperatures of stars:[11]

> In this manner the distribution of energy in the spectra of sixteen stars was determined, and thus was obtained for the first time an insight into the intensities of radiation in the complete spectrum of a star ... It was found that in the stars of type B and A the maximum intensity of radiation lies in the ultra-violet (0.3 µ to 0.4 µ) while in the cooler stars of types K and M the maximum emission lies at 0.7 µ to 0.9 µ in the infra-red. From this it appears that the black-body temperature (i.e., the temperature which a black body would have to attain in order to emit a similar distribution of relative spectral energy) varies from 3000°C. for red M stars to 9000° or 10,000°C. for blue B stars. (Coblentz 1922: 21).

For many years, observations of stars in the infrared stopped at 4 µm. Independently of Coblentz, in the 1920s Abbot (1929) obtained at the coudé focus of the Mount Wilson 2.5 m telescope the spectral energy distribution of eighteen stars and of two planets (Mars and Jupiter) from the visible to 2.2 µm. He used a flint prism as a disperser and a radiometer in a low-pressure hydrogen enclosure, whose sensitive elements were blackened flies' wings, but difficulties with this equipment prevented him from obtaining accurate results. This was first achieved by Edison Pettit (1889–1962) and Seth B. Nicholson (1891–1963), who observed with their excellent vacuum thermocouples (Pettit and Nicholson, 1922) 124 stars from 1922 to 1928, also at the Mount Wilson Hooker telescope, but this time at its Newtonian focus (Pettit and Nicholson, 1928). They determined the effective temperature and the bolometric absolute magnitude for a number of these stars, and separated dwarfs from giants. Other systematic near-infrared observations of a larger sample of 347 stars, obtained at the Loomis telescope of the Yale University Observatory, were published in 1934 by

John Scoville Hall (1908–1991). He used, probably for the first time in astronomy, a caesium oxide photoelectric cell, cooled to −40°C to reduce the dark current.

Another important result was obtained in 1924 by Pettit and Nicholson: this was the detection of thermal radiation from the dark hemisphere of Venus in the 8-14 µm atmospheric window (Pettit and Nicholson, 1924). Their observations were carefully calibrated against stars they had measured and set as standards. The temperature of Venus was correctly estimated to be about 0°C. This is actually the temperature of the top of the thick clouds which surround the planet. Coblentz and Carl Otto Lampland (1873–1951) also extensively observed planets, particularly Venus, but little of their work was published (for details see Sinton 1986: 247-248). Finally, Arthur Adel (1908–1994) conducted observations of atmospheric transmission in the 8-14 µm window and discovered another window around 20 µm (Adel, 1942; details are in Sinton, 1986: 248-250).

Most of this pioneering work was largely ignored by other astronomers, even in the USA. More could have been done with the existing detectors, but more promising ones were appearing. The lead sulfide photoconductive cell was the first of these new detectors, developed by the Germans for military purposes during and after World War II.[12] It was first used in astronomy by Gerard P. Kuiper (1905–1973), one of the pioneers of infrared astronomy, who discovered, through their infrared bands, CO_2 and CH_4 in the atmospheres of Mars and Titan respectively (Kuiper, 1947). Equipped with a chopper, it was also used for photometry by Albert Edward Whitford (1905–2002) in order to extend the interstellar extinction curve to 2.4 µm, the longest wavelength accessible with a PbS cell (Whitford, 1948a). Whitford (1948b) also made with this cell the first photoelectric infrared survey, of the Sagittarius region. Soon after, Peter Fellgett (1922–2008) used an uncooled PbS cell with a preamplifier, chopper and synchronous detector (Figure 13) to measure 51 stars in two infrared colors, reviving in this way infrared astronomy in the United Kingdom (Fellgett, 1951). Similar innovative work was carried out in France a few years later by Madeleine Lunel (1926–1998), who was careful to use filters selecting the atmospheric transparency windows and made good corrections for atmospheric transmission (Lunel, 1960). Unfortunately, there was no interpretation in these two papers, and they remained relatively unnoticed.

Still, they marked the beginning of a new era in infrared astronomy. But there was no standardization in the photometry until Harold Johnson (1921–1980) in 1962 introduced a stellar photometric system for the near- and mid-infrared. The availability of square interference filters was of crucial importance for this work and all the future efforts. Johnson (1962) added to the classic bands UBVRI[13] three new bands, JKL, corresponding to atmospheric windows with respective effective wavelengths of 1.3, 3.6 and 5.0 µm. Eric Becklin later introduced a fourth one, H. at 2.2 µm. Johnson's observations were made first with PbS cells, then with an InSb photovoltaic detector cooled by liquid nitrogen. His photometric system was later extended to 20 µm with three other bands, MNQ, as it was known since the work of Adel in 1942 that observations were sometimes possible in very good sites up to 24 µm, and an excellent spectrum of the Sun was obtained in 1951 between 16 and 24 µm by Marcel V. Migeotte (1912–1992) and L. Neven at the Jungfraujoch (Migeotte and Neven, 1952). For observing near 10 µm, two new detectors were used: a mercury-doped germanium photoconductor cooled by liquid hydrogen by Robert L. Wildey (1934–1998) and Bruce C. Murray (Wildey and Murray, 1964), and a bolometer cooled by liquid helium by Frank J. Low (1933–2009) (Low and Johnson, 1964). These were to give another new impulse to infrared astronomy; moreover, thanks to the success of radio astronomy, astronomers were slowly opening their interest to new wavelength ranges and to new techniques. However, as remarked by Low et al. (2007), the new start in infrared astronomy was led almost entirely by experimental physicists, not by astronomers.

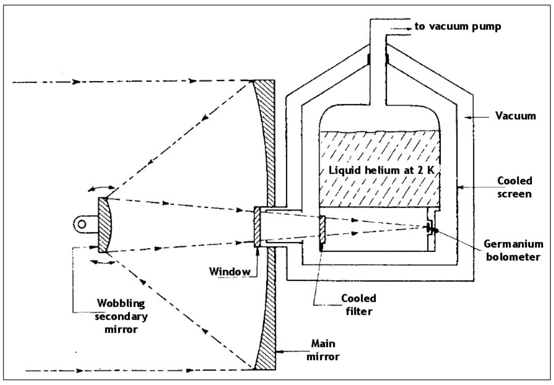

Figure 14: Low's bolometer (1961) at the focus of a Cassegrain reflector. The bolometer itself is a piece of doped germanium connected with two fine wires which carry the current and act as heat leaks. It is inside a liquid helium dewar.

7 THE GLORIOUS SIXTIES

The doped germanium photoconductive detector was classified and unavailable to astronomers; however, it was possible to purchase the material from the Eagle Picher Company and to stick contacts on it, but this was not too easy. As to the cooled bolometer, Low's own company, IR Laboratories Inc., produced it from 1968 in quantities quite insufficient to meet demand. This made it difficult, especially for non-Americans, to work in infrared astronomy, except with PbS cells. In order to remedy this situation some efforts were made in Australia, England, France and Germany to build competitive instruments, in particular helium-cooled bolometers, but these were not available before the 1970s. Impressive infrared work was done in the USSR by Vassili Ivanovitch Moroz (1931–2004) and his collaborators, with PbS and germanium cells obviously developed for military purposes (e.g. see Moroz et al., 1968). Their observations of the Crab Nebula (Moroz, 1964) were particularly interesting. However their work was largely overlooked by the rest of the world.

It was fully understood for a long time that cooling the detectors and their surroundings would give great advantages in increasing their response and reducing thermal noise (see Jones, 1934), so why one had to wait until the 1960s to see a cooled bolometer is difficult to explain. The first one, Low's bolometer (Figure 14), is perfectly designed and all later ones were in one way or another derived from it.

Thanks to these superb instruments, the time was finally ripe for infrared astronomy: evidence of this is the Liège colloquium titled "The Infrared Spectra of Stars" (English translation), the proceedings of which were published in Volume 9 of the *Mémoires de la Societé Royale des Sciences de Liège*. Most astronomers active in infrared research were present, and although many speculations were presented at this colloquium there were few results.

After that, discoveries occurred at a rapid pace. It is impossible to list all of them, and I give only a few examples. Murray, Wildey and James Wesphal (1930–2004) at Caltech and at the Mount Wilson and Palomar Observatories observed for the first time thermal emission from the dark Moon and from Jupiter and its satellites (Murray et al., 1964a; 1964b), while Low (1965) observed Saturn, Jupiter and Mars in the mid-infrared. Near- and mid-infrared emission from galactic sources buried in molecular clouds and located at the Galactic Center was discovered by Eric E. Becklin and Gerald Neugebauer at Caltech (Becklin and Neugebauer, 1968). D.E. Kleinmann and Low found a low-temperature nebula in Orion, the first protostar ever observed (Kleinmann and Low, 1964). Observations of various objects like the Crab Nebula and the quasar 3C 273 (Low and Johnson, 1965) were also reported, showing in both cases that synchrotron emission was responsible for their infrared radiation. They were strong indications that some galactic and extragalactic sources emit most of their energy beyond 25 μm (Figure 15), pointing to the need for observations made above the atmosphere (see Low, 1969).

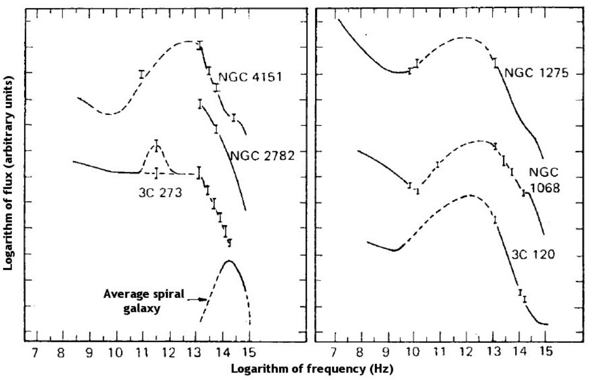

Figure 15: The spectral energy distribution (SED) of some active galaxies and quasars obtained by Low and collaborators from ground-based observations before 1969. The bars are observations, and the dotted lines are interpolations in the far-IR/submillimeter range. The tentative SED for an 'average spiral galaxy' is wrong, because it contains only the radiation from the stars: later observations have shown that the far-infrared radiation of interstellar dust is also very strong so that the SED has another peak around 2×10^{12} Hz.

A near-infrared survey (IRC) in the K band (2.2 μm) was started in 1960 on Mount Wilson and later on White Mountain in California by Neugebauer and a Caltech physicist, Robert Leighton (1919–1997), who built for this purpose the first specialized infrared telescope, a lightweight parabolic mirror of 1.6-m diameter obtained by rotating liquid epoxy during hardening. The corresponding catalogue (Neugebauer and Leighton, 1969) contains 5,612 objects, mostly cool or strongly-reddened stars. This proved a 'gold mine' for future research, and was probably the main cause of the explosion in infrared astronomy during the late sixties.

The 1960s also saw the birth of Fourier transform spectrometry. The possibility of doing spectrometry with Michelson interferometers was first discussed by Albert A. Michelson (1852–1931) and by Lord Rayleigh (1842–1919), but practical applications had to await the development of electronic computers. The spectrum is the Fourier transform of the signal obtained by moving the reflecting mirror of one of the two arms of the interferometer.[14] Fourier transform spectrometry was developed more or less independently by Pierre Jacquinot (1910–2002) (Jacquinot, 1958), then by Pierre and Jeanine Connes (1966) in France, by Fellgett (1973) in England, by Donald M. Hunten (1968) in the USA, and also by L. Delbouille, Ginette Roland and H.A. Gebbie (Delbouille et al., 1964) in Belgium and in England. Its main advantages are:

- the high throughput which allows extended objects to be studied with a very high wavelength resolution;[15]
- the possibility of reaching this resolution with a relatively small telescope;
- the possibility of measuring wavelengths with high accuracy; and finally
- the high sensitivity resulting from the 'multiplex' property: if the sensitivity is limited by the detector noise and not by the photon noise of the signal, for a given observation time the signal-to-noise ratio in a spectrum with N independent spectral elements is $N^{1/2}$ times larger than if a one-channel spectroscopic scanning technique was used. This advantage was a feature of the detectors at this time, although it disappeared later when detectors like CCDs became limited by photon noise, and when detector mosaics could be constructed.

Fourier transform spectrographs became favorite tools for molecular spectroscopists and spectacular astronomical results were obtained. For example, observations of Venus by Delbouille et al. reached 25 μm as early as 1964, but with a relatively low wavelength resolution. In 1967-1968 very high resolution observations of planetary atmospheres (Connes et al. 1967, 1969; Maillard et al. 1973) and cool stars (Connes et al. 1968) were obtained in the near infrared at the Haute Provence Observatory, giving a new impulse to their study.

Some observations were also made with Fabry-Perot interferometers, but these instruments turned out to be more useful in space.

Finally, after the discovery of the maser and laser, several astronomers had the idea of applying heterodyne techniques to the mid-infrared, using a CO_2 laser at 11 μm as the local oscillator. Very high wavelength resolutions could then be obtained, but due to the limited wavelength range this technique was mainly of interest in the study of line intensities and profiles of Martian CO_2 (Peterson et al., 1974). M.A. Johnson, A.L. Betz and Charles H. Townes in Berkeley succeeded in building a spatial interferometer at this wavelength using two telescopes separated by 5.5 m, the common local oscillator being a CO_2 laser (Johnson et al., 1974). They obtained interference fringes on Mercury, then on several cool stars. Similar work was done in France at the CERGA Observatory near Grasse (de Batz et al., 1973; Gay and Journet, 1973). Unfortunately, the small available band at the intermediate frequency limited strongly the sensitivity in the continuum, so that only very bright objects could be observed. Consequently, this type of interferometer proved a dead end. Direct interferometry, although more difficult to implement, had a much brighter future and is presently extremely active in the infrared.

8 THE BEGINNING OF SPACE INFRARED ASTRONOMY

The Earth's atmosphere is so troublesome in the infrared that observations from space are not only much better than observations from the ground in the transparency windows, but absolutely necessary in the various water vapor absorption bands; the atmosphere is almost completely opaque in the far-infrared. It is not surprising that as soon as they became technically feasible astronomical observations were started in the infrared from high-altitude sites, aeroplanes, balloons, rockets and satellites. As an example, Figure 16 shows the best estimates obtained in 1968 of the zenithal atmospheric transmission in the submillimeter range for typical conditions in a low-altitude observatory, in a high-altitude one and from a balloon at 30 km altitude (Turon-Lacarrieu and Verdet, 1968).

Techniques were mature, thanks to recent developments in detectors and spectrometers, but also to the laboratory work done since the beginning of the twentieth century in the far-IR: lenses and mirrors, *Reststrahlen* filters using selective reflection by various materials (e.g. see Porter, 1905), grid filters, transmission filters made of various materials, beamsplitters, etc. They only had to be adapted to the conditions in space vehicles.

Balloons were particularly suited to observations in the far-infrared. The first observations from balloons were made in 1964 in the USA: the Stratoscope II observations of some stars and planets were very influential (Woolf, 1964). Our new infrared group at the Paris-Meudon Observatory used a pointed gondola to obtain for the first time the spectral energy distribution of the Sun in the 50-200 μm range (Gay et al., 1968; Gay, 1970). We used a Michelson interferometer and a Golay pneumatic detector. This detector, which is particularly robust but not very sensitive, consists of a gas container with a dark bottom absorbing the incoming radiation (for a description see Golay, 1947). The expansion of the gas so heated exerts pressure on a foil whose deformation is measured either by an optical system or, as in the system we used for the balloon flight, by the variation of a capacitance. The equipment worked well, but the result was not very accurate. Simultaneously, in the USA, a series of photometric far-infrared balloon observations was initiated at the NASA Goddard Space Flight Center, with Low's bolometer (Hoffmann et al., 1967). The most interesting result was the detection of strong far-infrared emission from the Galactic Center, due to thermal emission from interstellar dust grains (see Hoffmann and Frederick 1969; Lequeux, 1970). For many years, balloons continued to be used with success for far-infrared astronomy, especially in the Netherlands, France, Japan and the United Kingdom, and results included measurements of the solar spectrum between 12 and 24 μm (Baluteau, 1971), detection of various far-infrared sources (Furniss et al., 1972a; 1972b), and surveys of the Galactic Plane (Maihara et al., 1978; 1979). However, many flights were technical failures, so aeroplanes were often preferred when available.

At the end of the 1960s NASA decided to equip two aircraft, a Convair 990 and a Lear jet, with telescopes for astronomical infrared studies. From 1968 the Convair was used by John A. Eddy, Pierre J. Léna and Robert M. MacQueen to measure solar emission at around 300 μm (Eddy et al., 1969), but unfortunately it crashed in April 1973 with eleven persons on board. Meanwhile, Low and his collaborators used the Lear jet with great success in 1969 and 1970, confirming in particular the idea that the spectra of several galactic and extragalactic sources peak in the far-infrared; however, with the exception of the Galactic Center, the origin of this radiation had yet to be elucidated. The first far-infrared interstellar fine structure line, that of [OIII] at 88 μm, was discovered in M17 using the Lear jet.

In 1971, another aeroplane, a Lockheed C141 Starlifter, was equipped with a relatively large telescope, 91-cm in diameter. Christened the 'Kuiper Airborne Observatory' (KAO), it began scientific flights in 1975. During the twenty years it contributed to infrared research the KAO surpassed most astronomers' expectations. Amongst the early results obtained with the KAO I will only cite three: some observations of far-infrared fine structure lines (Baluteau et al., 1976); a very high resolution spectrum of Jupiter obtained at around 80 μm (Baluteau et al., 1978); and the discovery of the rings of Uranus (Elliot et al., 1977).

Amongst the first to use rockets for infrared astronomy were groups from the US Air Force and the Center for Radiophysics and Space Research at Cornell University. From 1970 to 1974 the US Air Force conducted a mid-infrared rocket survey in order to be able to distinguish Soviet missiles from celestial sources. This survey, known as the AFGL Survey and the supplementary ground-based survey, were made with doped silicon detectors cooled by liquid neon and extended to 24-30 μm; the results were published by Stephan D. Price and R.G. Walker in 1976.

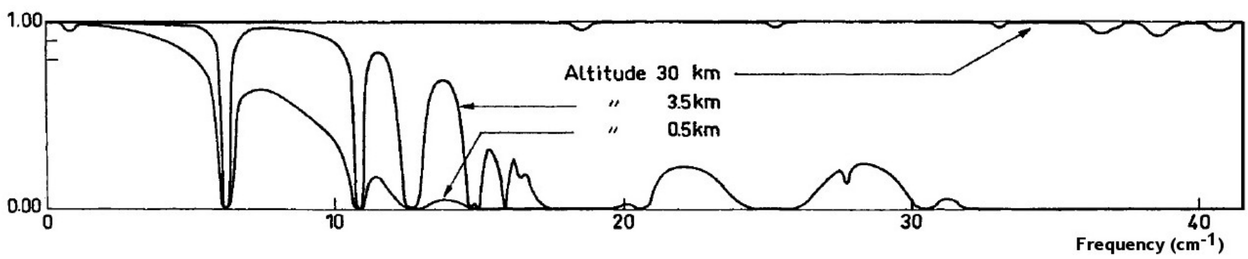

Figure 16: Estimated atmospheric transmission at the zenith in the submillimeter range for typical conditions at various elevations. This transmission is calculated from the laboratory spectrum of water vapor of S.A. Zhevakin and A.P. Naumov, and smoothed to a resolution of 0.5 cm^{-1}. Absorption by molecular oxygen is not included.

The Cornell group used a helium-cooled, rocket-borne telescope and an InSb bolometer and detected an unexpectedly high diffuse flux of about 5 10^{-9} W cm^{-2} sr^{-1} between wavelengths of 0.4 and 1.3 mm in various regions of the sky, some remote from the Galactic Plane (Shivanadan et al.; 1968; Houck and Harwit, 1969). This raised considerable interest and a lot of controversy until it became clear that this high flux was spurious (Houck et al.; 1972). During these flights, Harwit and his collaborators discovered thermal emission from interplanetary dust in the mid-infrared (5-23 µm).

Satellites for the mid- and far-infrared were more difficult to build because they must have giant helium dewars containing the cooled telescope, optics and detectors. After earlier activity by the US Air Force, NASA, the UK and the Netherlands finally collaborated to launch IRAS in 1983, and this space telescope proved a great success. The first European mid-infrared spectrometer with passive cooled detectors was on board the Soviet probe Vega 1, launched in 1984, and gave many valuable results when it was directed at Comet 1P/Halley (e.g. see Combes et al., 1986). This period also saw the appearance of infrared detector arrays. A new era was opening in infrared astronomy, but this is another story.

9 EARLY MILLIMETER AND SUBMILLIMETER ASTRONOMY

During the development of radio astronomy in the 1950s, there was a natural impulse to observe at increasingly shorter wavelengths. Some of the relevant techniques at millimeter waves were available long before, thanks to scientists like Jagadis Chandra Bose (1858–1937) in Calcutta (Emerson, 1998), but the main problems were the observing sites and the detectors. Several studies of high-altitude sites were conducted in the 1960s in order to evaluate the atmospheric transmission at submillimeter wavelengths, for example in the 350 µm window (e.g. see Biraud et al., 1969). The conditions for millimeter waves were less restrictive, and most of the early observations were performed in existing mid-altitude observatories, with optical telescopes. The first specialized millimeter-submillimeter radio telescopes appeared in the sixties: in 1965 two 4.9-m radio telescopes were erected, one at the McDonald Observatory of the University of Texas and the other one at the Aerospace Corporation in the USA. In 1968, the 11-m infrared telescope at Kitt Peak (Arizona) was turned to radio astronomy by NRAO. For their part, in 1959 Soviet astronomers started to carry out observations at 8 mm wavelength with the 22-m diameter radio telescope at Pushchino near Serpukhov, followed in 1966 by a similar one at Simeis in Crimea. The Kitt Peak instrument was by far the most productive of these. Then around 1976 several 14-m radio telescopes and a number of smaller instruments were constructed around the world. The first millimeter interferometer, an experimental instrument devoted to solar studies at 8 mm wavelength, was constructed at the Bordeaux Observatory in France at the end of the 1960s (Delannoy et al., 1973).

Initially, the observers used broad-band detectors like Golay cells, Low's germanium bolometer or InSb bolometers cooled at liquid helium temperature. With them, the millimeter and submillimeter thermal emission from the Sun and the Moon was observed as early as 1954 in the USSR (Salomonovich, 1958; Salomonovich et al., 1958),[16] then in the USA (Low and Davidson, 1965)[17] and finally in England (Bastin et al., 1964). However, these detectors were not suited to spectroscopy or to interferometry.

At the beginning of the 1960s, radio astronomers started to build heterodyne receivers at millimeter wavelengths. This was a difficult task because the mixers were not very reliable and required a lot of power for the local oscillator, which could only be obtained as harmonics of a cm-wave klystron (e.g. see the observations of the Sun by Tolbert and Straiton, 1961). After radio line emission from interstellar molecules at centimeter and decimeter wavelengths was discovered in 1963, many efforts were devoted to the construction of such receivers because more molecular lines were expected to be observable at millimeter and submillimeter wavelengths. The best was that built by Arno A. Penzias and R. Wilson at the Bell Telephone Laboratories, and in 1970 it allowed them to discover several interstellar molecules with the Kitt Peak radio telescope.[18] This opened a new era in radio astronomy.

The submillimeter range was even more difficult to observe. Spectroscopic observations could be carried out with the InSb bolometer, but the bandwidth was rather narrow, of the order of 1 MHz, which allowed the profile of a spectral line to be explored by tuning the bolometer through a change of magnetic field. The real progress came when Tom G. Phillips and K.B. Jefferts (1973) at the Bell Telephone Laboratories developed an heterodyne receiver with a InSb bolometer as a mixer, requiring little power from the local oscillator. This allowed the Caltech group to discover the interstellar line of atomic carbon at 610 µm using the KAO (Phillips et al. 1980). Since then, progress has been spectacular, leading to the heterodyne instrument on board the Herschel satellite, launched in 2009.

10 CONCLUSION

Infrared astronomy is an older science than is usually believed: good detectors were directed at the sky as early as 1845, while the first measurement of the solar constant dates to 1838. Better detectors became available at the end of the nineteenth century, but apart from the Sun and the Moon the targets were too faint even for these instruments and progress initially was slow. Lack of interest from the astronomical community contributed to this. Solid-state, cooled detectors and helium-cooled bolometers which appeared after WWII offered good possibilities, opening a new era in infrared astronomy. The same occurred for millimeter and submillimeter heterodyne detection. Interest in infrared and submillimeter astronomy grew rapidly, fostering the construction of specialized telescopes and space vehicles, and culminating recently in the Herschel and Planck space missions.

11 NOTES

1. As with most of his contemporaries, Herschel adhered to the corpuscular theory of light developed by Newton, in which light was supposed to be made of particles with a mass.
2. Ampère was one of the strongest proponents of the undulatory theory of light, which had then almost

replaced the corpuscular theory thanks to Augustin Fresnel and Arago.
3. For details, see Lewis (1895).
4. Pouillet and his successors, including Father Secchi, expressed the solar constant through the thickness of ice that the solar radiation would melt in a year. Note that the equivalence between heat and work was poorly known in 1838.
5. Some of Melloni's experiments are described by Jamin (1858–1866).
6. For a detailed history see Burns (1912).
7. With considerable insight, William Thomson (Lord Kelvin) proposed in 1860 that "… the hot dust around the Sun must produce radiant heat of such colour as that of a hot stone or metal not at bright red heat …", but his suggestion apparently remained unnoticed (Hale, 1895: 328).
8. For historical information see Volpicelli (1869) and Zantedeschi (1869).
9. The validity of the claimed detections by Huggins and by Boys is discussed by Nichols et al. (1901: 102). These authors also mention a detection of Arcturus by Edison with his tasimeter, but they do not seem very confident of the result.
10. For a detailed history see Lewis (1895; 1896).
11. This was not the first determination of the effective temperatures of stars. Previous ones were made independently in Postdam (Wilsing and Scheiner, 1909) and in Paris (Nordmann, 1909), by comparing visually the fluxes of the stars at several wavelengths with that of black bodies.
12. A German laboratory developing PbS cells was moved to the Paris Observatory after WWII, complete with equipment and people! I carried out my military service in this laboratory from 1957 to 1959.
13. In 1945 Joel Stebbins (1878–1966) and Whitford added the R (red) and I (near infrared) bands to Johnson's original UBV system.
14. Other devices, like the Mock interferometer, also give the Fourier transform of the spectrum and were used effectively in astronomy, particularly by Laurence Mertz and his associates (1962).
15. This also allowed poor images and hence a low-quality telescope to be used. In Meudon, Pierre Connes started to build a large-diameter, low-quality mosaic telescope for Fourier transform spectroscopy, but this was never completed.
16. Whether their detector, a 'modulation radiometer', was an ordinary radiometer or an heterodyne receiver is not clear.
17. Combined observations in the mid-IR and at 1.2 mm yielded for the first time a good picture of the heating and cooling of the lunar surface.
18. See the many papers published by them and their collaborators in 1970 and 1971 in the *Astrophysical Journal*.
19. This paper is of particular interest for astronomy students as it gives an extensive description of the equipment and observing procedures.
20. This special issue contains many interesting papers in French on interference spectroscopy and astronomical applications.
21. This very interesting paper gives many details on the state-of-the-art infrared techniques useful for astronomy.

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Dr. James Lequeux started research in radio astronomy as a student in 1954, and spent most of his career as a radio astronomer. In parallel, he became interested in the infrared during his military service in 1956-1959, which was carried out in a military infrared laboratory, and in 1966 he and a few colleagues founded the first infrared laboratory at the Paris-Meudon Observatory. He was active in the scientific preparation of the Infrared Space Observatory (ISO) and was an Associate Scientist for this European satellite. His post-retirement interests turned to the history of astronomy. He produced several research papers and three books in this field. James is now affiliated with the LERMA Department at the Paris Observatory.