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Beyond the infrared: a centenary of Heinrich Rubens's death

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Abstract Heinrich Rubens (Wiesbaden, 1865, Berlin, 1922) was the first scientist to study the large gap between the conventional infrared range and the electrical wave regime, better known today as the terahertz gap. To this end, he produced numerous original instruments and was almost single-handedly responsible for all research on this region up to the 1920s. His research, motivated by Hertz's demonstration of the electromagnetic theory of light, led him to contribute seminal works on blackbody radiation and interferometric spectroscopy that have been almost forgotten in modern expositions of these topics. On occasion of the centenary of his death, this work aims to critically assess his legacy, as well as to revitalize this important figure for a newer generation of spectroscopists.

1 Introduction

When Heinrich Rubens died on July 1922, he was the subject of a profuse collection of affectionate obituaries on both sides of the North Sea [3,19,28,29,45,46,59,82]. Contemporary opinion regarded him as an exceptional scientist, as evidenced by his numerous accolades and honors, including the Rumford medal of the Royal Society [45]. His name appears on the first paragraph of one of the most revolutionary papers of modern science [57], when his confirmation that the far-infrared emission by a blackbody was linear in temperature led Max Planck to refine the blackbody law, kick-starting the quantum revolution. Over a 30-year career, he extended the limit of optically generated waves by almost two orders of magnitude in wavelength, pursuing an eventual unification with electrically generated Hertzian waves, a goal that he acknowledged as his main scientific drive but would never achieve [37]. His numerous contributions to the novel field of far-infrared science and technology are evident in any historical introduction to this topic [9,49,55]. According to Palik's compilation of early far-infrared research literature, Rubens contributed about 90% of the papers on the subject up to his death [54]. Many of his students and collaborators, including British and American scientists, enjoyed very successful careers, either in the field of infrared research or outside its limits. Yet, a century after his death, his legacy has faded much faster than that of many of his contemporaries of similar stature, and he is perhaps most often remembered as the inventor of his eponymous tube, a popular teaching device for introductory acoustics [21].

Many questions arise from a revision of a figure like Rubens (Fig. 1). He was the leading infrared spectroscopist by the turn of the twentieth century, and the first one to launch investigations on long optical wavelengths [8,55]. Some authors have placed him on a preferential location in the history of spectroscopy, as a missing link between Albert Michelson and the modern formulation of Fourier-transform spectroscopy, starting in the 1950s [12,13]. He was also well positioned as part of the intellectual elite and was considered one of the greatest experimental physicists of his time, as evidenced by his participation in the first Solvay conferences. While many of his fellow participants have deservedly enjoyed lasting fame and been the subject of numerous historical studies, biographical material on Rubens is scarce and dated. Outside the aforementioned obituaries, few records of his life are available [41,47,83], with the notable exception of the works by Hans Kangro in the 1970s [37–40], which are still required references on the early history of blackbody radiation research. This clearly clashes with the prestige enjoyed by Rubens during his lifetime. Thus, this work attempts to provide context to this contradictory legacy by critically assessing his scientific contributions and influence, one hundred years on.

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Fig. 1 Portrait of Heinrich Rubens. Credit: AIP Emilio Segrè Visual Archives, Landé collection

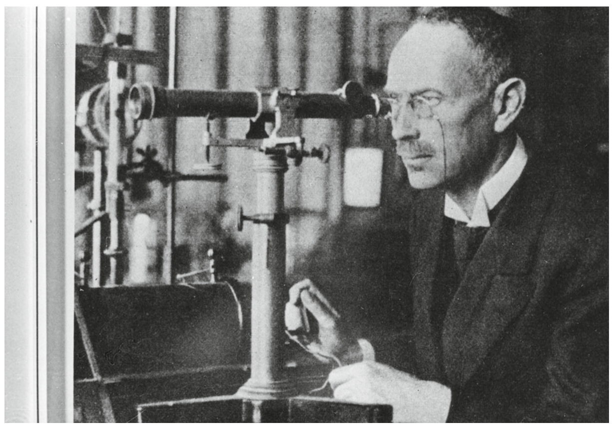

Fig. 2 Heinrich Rubens with laboratory equipment. Credit: AIP Emilio Segrè Visual Archives, gift of Ludwig Genzel

2 A brief biographical profile

Heinrich Leopold Rubens (Fig. 2) was born on March 30, 1865, in Wiesbaden, capital of the Duchy of Nassau. He was the son of Barend Eliazer Rubens, a jeweler from Amsterdam that would later settle in Frankfurt am Main, and Berta Kohn, from Speyer (Palatinate). He was born Jewish, although he would convert to Lutheranism around 1890 [41]. A year after his birth, his native duchy was annexed by the Kingdom of Prussia, and merged with the Electorate of Hesse and the Free City of Frankfurt to form the Prussian Province of Hesse-Nassau in 1868. These lands would eventually be integrated into the new German Empire after its official unification in 1871. The young Heinrich would pursue his secondary education in the nearby Frankfurt and later inscribe at the Darmstadt Polytechnic (*Technische Hochschule Darmstadt*) in 1884, to study the brand new degree of electrical engineering (*Elektrotechnik*), which was not available anywhere else at the time. He spent little time there, however, moving to Berlin after only a semester, where he also switched to physics. After moving again to Strasbourg, he finally found focus under the supervision of August Kundt[1], who was then offered Helmholtz's position at the Physical Institute (*Königliches Physikalisches Institut*) of the University of Berlin. Rubens moved back to Berlin with his supervisor and soon after defended his PhD thesis on March 1889 [60].

After receiving his doctorate, Rubens became an assistant at the Institute and soon obtained his habilitation to teach at the University of Berlin in 1892. In contrast with the standard path to habilitation, in which a second dissertation was expected, Rubens followed the more unusual alternative, passing his exam using his published journal papers [41]. Hermann von Helmholtz, who was a member of the jury, was particularly impressed with

[1] Kundt would also supervise some of Rubens's collaborators (Leo Arons, Henri du Bois), as well as his main early-career rival and fellow Rumford medal winner, Friedrich Paschen [39]. Kundt's innovative vision of experimental physics, which he regarded as a precision science in close contact with the latest theoretical developments [11], proved to be influential on Rubens.

Fig. 3 First Solvay Congress 1911. Rubens is standing, third from the left and opposite Planck. Credit: Photographie Benjamin Couprie, Institut International de Physique Solvay, courtesy AIP Emilio Segrè visual archives

his recent study on the infrared dispersion of crystals [61]. In 1896, Rubens would be appointed extraordinary Professor (*nicht etatmäßiger Professor*) at the Technical University (*Technische Hochschule*) at the nearby town of Charlottenburg (later incorporated into Berlin with the Greater Berlin Act of 1920), while also taking charge of its Physical Laboratory [37]. He was given a full professorship in 1900, but he would move back to the University of Berlin in 1906 to take over Paul Drude's chair on Physics, connected to the directorship of the Physical Institute, after his unexpected death by suicide. Throughout his career, Rubens collaborated as a guest researcher with the *Physikalisch-Technischer Reichsanstalt* (PTR) in Charlottenburg, where most efforts regarding the study of blackbody radiation were taking place [35,40]. Founded in 1887 after intense lobbying by the industrialist Werner Siemens, the PTR was the first national metrological institute, an innovative institution centered on precision measurements built on a patriotic spirit to serve the scientific and technical needs of German industry and the State [10]. These three institutions connected to Rubens still stand today, serving as a living memory of the heyday of Berlin physics [30,31].

For the next decade and a half, Rubens moved into a role more typical of a senior Professor, supervising doctoral theses and collecting awards and honors, while never leaving hands-on experimental research. He would receive the Rumford medal of the Royal Society in 1910, and be invited to the initial Solvay Conferences of 1911 (Fig. 3) and 1913. He became a member of the Berlin and Göttingen Academies of Sciences, honorary member of the Royal Institution of Great Britain, and doctor *honoris causa* at Leeds and Cambridge [45]. He lived long enough to enjoy fame and prestige during his lifetime, as evidenced by an episode in autumn 1921 at a conference in Jena, where he presented definite experimental proof of Planck's law and was received by outstanding acclamation [45].

Heinrich Rubens died on July 17, 1922, of leukemia [45]. It is possible that the disease originated from manipulation of radioactive materials in the laboratory, such as the thorium-oxide-based Welsbach gas mantle, a light source that he often used in his experiments. Nevertheless, sources close to him allegedly blamed the blockade of Germany during and after the First World War, and the subsequent widespread famine, on his debilitation and eventual demise [45]. He was survived by his wife Marie (*née* Hirschfeld) and their son Ernst Berthold [41]. Like her husband, Marie had Jewish origins, despite her family having converted to the Protestant faith, and she would commit suicide in 1941 to avoid persecution [50,83]. The resting place for the couple would be the famous Alter St.-Matthäus-Kirchhof cemetery in the Berliner neighborhood of Schöneberg, where the spectroscopist Gustav Kirchhoff had been buried in 1887, among many other renowned personalities.

Rubens was a moderate conservative who distanced himself from the increasing radicalism of some of his contemporaries. In particular, he declined to endorse nationalistic war propaganda and explicitly rejected annexationist proposals at a time when the German intellectual elite became divided on the issue, a period known as the War of the Spirits (*Krieg der Geister*) [84]. Over time, his public image became linked to the stereotype of the liberal Jewish intellectual associated with the school of Berlin physics [17]. His status as a so-called *baptized Jew* meant that, irrespective of his conversion, he was never fully considered an equal by some of his peers (namely, non-Berliners such as the cousins Max and Wilhelm Wien) [85]. The Jewish issue was compounded by the fact that, even though very few physicists with Jewish backgrounds received professorships at the time (all of them baptized), their proportion was relatively higher at the University of Berlin, where there were also Jews at lower positions [17,86].

Testimonies by his contemporaries suggest that Rubens was an easy-going person, revered by his students and with many friends among both Germans and foreigners [45,46,55,82,83]. He forged strong bonds with many scientists, particularly with Max Planck, with whom he co-supervised several doctoral theses in the 1910s [48]. However, the trauma of the First World War cast a dark shadow over his later years. Aside from the physical effects of food rationing and scarcity, he also suffered emotionally from the hostility between scientists on each side of the conflict, and the collapse of the Imperial German state in 1918–1919 [82]. He died in the midst of the hyper-inflationary spiral that struck the early Weimar Republic, and thus could not witness his country's recovery in the Golden Twenties, nor the devastation that followed.

3 Infrared research at the turn of the twentieth century

Nineteenth-century physics started with the twin discoveries of infrared (William Herschel, 1800) and ultraviolet radiation (Johann Wilhelm Ritter, 1801). The concept of "invisible light", as Herschel put it, was so alien to the physicists of the time that they devised a three-term scale for radiation, assuming that each type of radiation had a significantly different nature: caloric, luminous, and actinic (chemical) radiation [5]. A confusing period ensued, in which modern ideas about the nature of heat and light (including the wave theory) began to take shape [27]. Investigations were limited by the rudimentary nature of the available instrumentation, such as blackened thermometers, so more quantitative work on these new radiations was tied to instrumental development.

Progress advanced more rapidly around mid-century, with a proliferation of new instruments and intriguing experimental results. An introduction to the main protagonists is given by Barr [5]. The first breakthrough came in 1829 with the Nobili–Melloni thermopile, based on the recently discovered Seebeck effect [80]. Nobili produced a combination of bismuth/antimony thermocouples, which Melloni later refined into the first functional non-contact thermal detector. This instrument allowed all kinds of experiments to characterize this radiant heat, and by the 1870s, it was common knowledge that infrared radiation obeyed the same physics as visible light [22,80]. Then, in 1878, Samuel Langley developed the bolometer, a much more precise measurement device based on the changes in electrical resistivity of a platinum strip. His most famous result using this instrument was a painstaking map of the solar spectrum and its absorption lines (Fig. 4), a feat that was one of the first milestones in astrophysics and led to many attempts to determine the temperature of the Sun and the nature of the radiation function peak [56]. An in-depth exploration of Langley's mapping efforts and his role within the evolution of spectroscopy as a visual science, based on new representation techniques and advances in printing technology, can be found in Hentschel's book [26]. Interestingly, the use of the Sun as the source of radiation led Langley to ponder in 1885 whether the longest wavelength possible to produce with an optical source was around 2.7 μm, the limit of solar radiation as measured by him [53]. It is ironic that waves more than 100 times longer would be produced and detected by Rubens and his collaborators less than 30 years after this unprophetic remark.

The development of adequate instrumentation allowed the birth of infrared spectroscopy as a research field. Spectroscopy itself was a very young discipline, which had been started in 1859, when Gustav Kirchhoff and Robert Bunsen devised the first spectroscope, which they later applied to discover the new elements cesium and

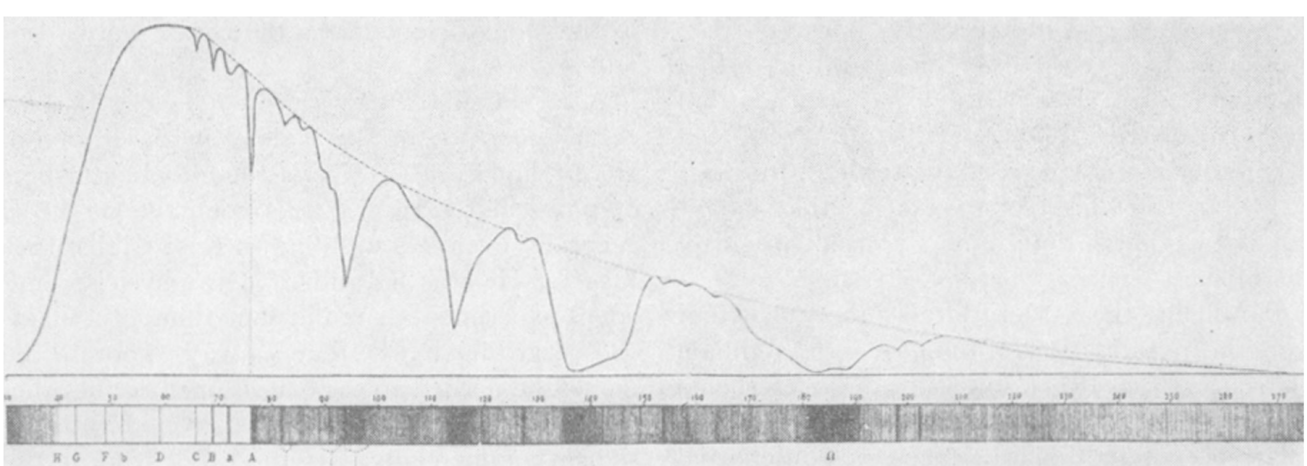

Fig. 4 Langley's grating curve for solar radiation up to 2.8 μm, measured in 1883. Reproduced from [5]

rubidium. In recognition of their role as fathers of spectroscopy, the cornerstone of the modern theories of matter and radiation, Abraham Pais named them the grandfathers of quantum theory [53]. At the same time, Kirchhoff used thermodynamic considerations to describe the most efficient radiator, for which he coined the word *blackbody*, which must also be a perfect absorber, and postulated the universal nature of this new blackbody radiation, which could only depend on frequency and temperature. He also gave a description on how to realize this blackbody in practice, as a large isothermal cavity which only had a small hole through which radiation could escape. Following Kirchhoff's postulation of the universality of thermal radiation, many scientists tried to find a relation between emission, wavelength, and temperature. The standard prehistory of the blackbody problem is well documented, starting with Stefan's empirical postulation of the T^4 law, and the later derivation of it by Boltzmann [15,44]. During this stage, the crucial nature of the spectral distribution function remained elusive, and its study would prove much more insightful than Kirchhoff had envisioned.

In parallel with these developments, John Tyndall started in 1859 to use the thermopile to systematically study the properties of infrared radiation and, in particular, its absorption by gases. This lead to an extensive body of work on not only infrared radiation, but also atmospheric optics and early molecular physics [22]. The topic of the absorption characteristics of gases would remain at the forefront of infrared studies for decades into the early quantum period, with the electromagnetic and quantum theories providing links between molecular structure and absorption bands. Nevertheless, the conventional starting date for infrared spectroscopy is dated later in 1881, when Abney and Festing, inspired by Tyndall, recorded photographs of infrared absorption spectra of organic liquids and associated their bands with certain groups of atoms [1].

Finally, the story of far-infrared radiation cannot be told without accounting for the monumental discovery of radio waves by Heinrich Hertz, which took place in several steps around the year 1888 and set Maxwell's theory of electromagnetic radiation on firm experimental ground. Even though the wavelengths produced by this method were many orders of magnitude longer than those at optical frequencies, the electromagnetic hypothesis predicted that it should be possible to bridge these two extremes in a continuous fashion, thus providing a direct stimulus to research optical waves of increasingly longer wavelengths.

The previous lines have briefly exposed the general state of affairs in which Rubens found the study of infrared radiation when he started his scientific career. However, many more important developments would take place in parallel to his first investigations. In particular, the nature of the blackbody radiation function continued to intrigue scientists. Motivated by this puzzle and by the need to standardize light measurement procedures, the Optical Laboratory of the PTR focused on creating and evaluating blackbody radiation sources [10,39]. Despite the more scientific inclinations of individual researchers, the industrial motivation was essential to ensure the viability of the blackbody research program [10]. However, a clear shift in priorities toward fundamental physical research as the main goal of the light research division had taken place by 1899 [32]. Wilhelm Wien and Otto Lummer would succeed in creating the first realization of a blackbody as an isothermal cavity in 1895, which Wien used to formulate his empirical formula in 1896 (not to be confused with his more famous displacement law), with which he though he had settled the debate surrounding the nature of the universal function suggested by Kirchhoff. Lummer and Ferdinand Kurlbaum would later develop an electrically heated improvement, which could reach temperatures up to 1600 °C (Fig. 5), an instrument that would eventually be used by Rubens and Kurlbaum to put an end to speculation on the nature of blackbody radiation.

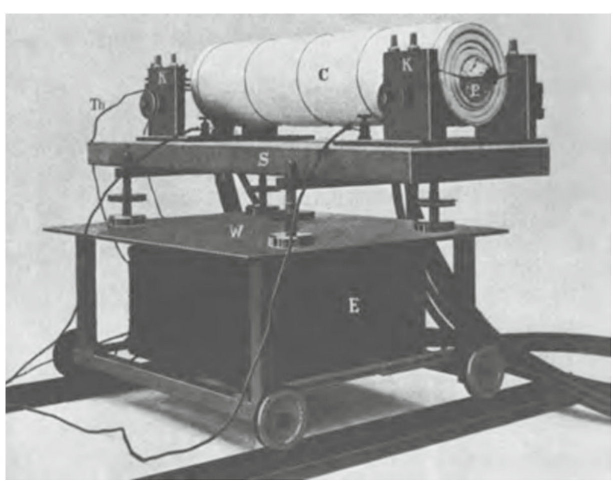

Fig. 5 Lummer and Kurlbaum's realization of an electrically heated blackbody cavity, manufactured by the Royal Porcelain Manufactory in Charlottenburg. Reproduced from Hollandt [35]

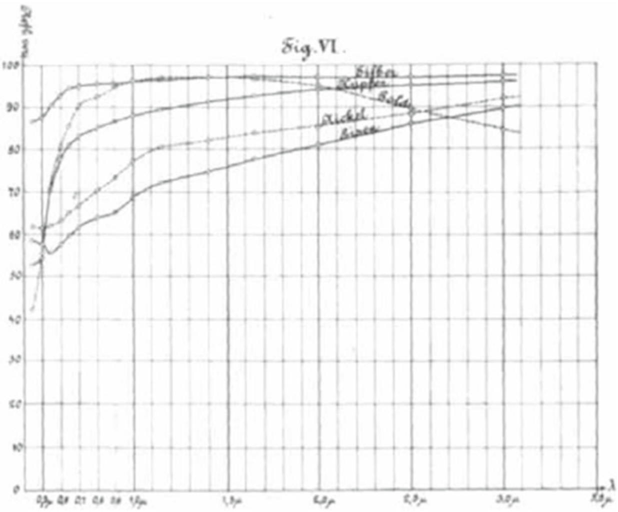

Fig. 6 Results of Rubens's thesis: reflectivities of silver, copper, gold, nickel, and iron, respectively. The decreasing reflectivity of gold in the infrared is due to an experimental error. Reproduced from Rubens [60]

4 Early career (1889–1900)

Heinrich Rubens formally started his scientific career with the publication of his *Inauguraldissertation* in *Annalen der Physik* in 1889. The period from then to his professorship in 1900 can be described as his early career, where he made his first forays into the far-infrared region and laid the foundation for most of his subsequent work. This date also coincides aptly with his most consequential contribution, on the long-wavelength limit of the blackbody distribution function [72]. Rubens's career was notably consistent in time and he distinguished himself as an excellent experimentalist from early on; nevertheless, this periodization is useful from a narrative standpoint. The period covered in this section is also featured in the works of Kangro [37,39].

4.1 Dissertation and habilitation work (1889-1892)

Rubens undertook his first steps in research with the help of August Kundt, who had recently relocated from Strasbourg to Berlin. He defended his dissertation under Kundt on 1889, barely a year after the momentous demonstration by Hertz of the possibility of generating electromagnetic waves. In his dissertation, under the title *Die selective Reflexion der Metalle*, he proved that the reflectivity of metals increased in the infrared and also located some plasma resonances in the ultraviolet (Fig. 6) [60]. As with most of his subjects, he would later revisit these findings in his investigations on the dispersion of metallic optical constants with Henri du Bois and Ernst Hagen.

Although Kundt's influence would prove to be long-lasting, it was clear that young Rubens was most immediately interested in the brand-new phenomenon of electric waves. His first independent experiments were devoted to the study of their polarization and velocity in various media. He maintained correspondence with Hertz himself, whose suggestion to apply the bolometer to these new waves he promptly implemented [40]. It soon became evident that his research would be directed towards bridging these waves with the near-infrared radiation he had experimented with during his dissertation.

Unfortunately, performing measurements deep in the infrared required special equipment, with dedicated gratings and powerful light sources. Noting these stringent instrumental requirements, Rubens proceeded to develop a more sophisticated setup, combining a prism with a simple interferometer, to reliably study wavelengths up to 5 μm [61]. He reported dispersion data for solids and liquids and noticed important deviations from the Cauchy equation, which motivated him to perform additional absorption measurements. It was this rigorous and extensive article the main merit considered by the commission tasked with evaluating his habilitation [41]. From then on, Rubens would dedicate himself to pushing the limits of the infrared as far as possible.

4.2 Breaking through: consolidation and far-infrared experimentation (1892–1900)

During the period from 1892 to 1900, Rubens consolidated his position as the leading reference in infrared spectroscopy in Germany and abroad. He was initially challenged in that goal by Friedrich Paschen, another prolific former student of Kundt. Accounts of their rivalry during the mid-1890s, where they often tried to outperform

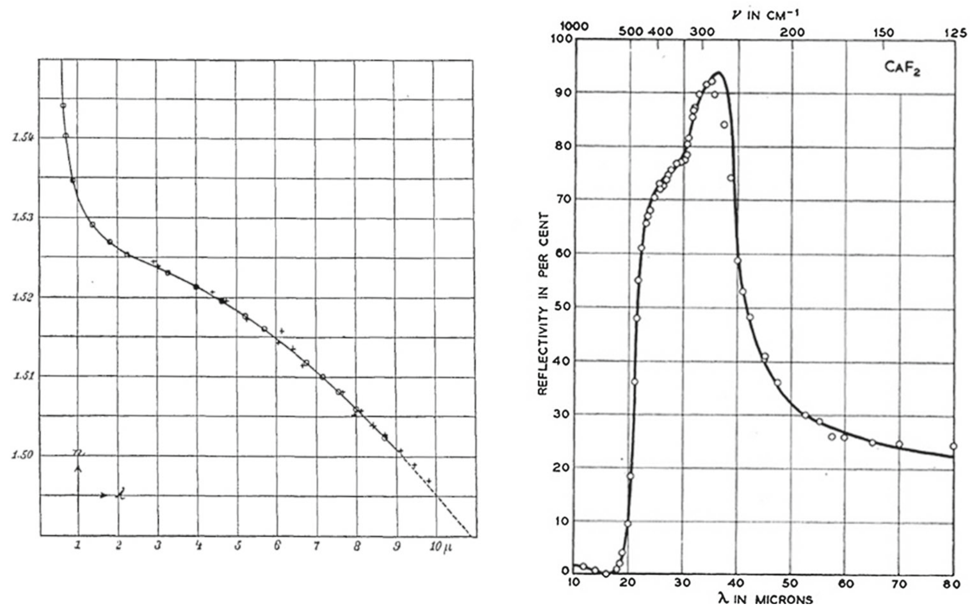

Fig. 7 Infrared dispersion of ionic crystals. Left: Ruben's measurements of the refractive index of NaCl up to a wavelength of 9 μm, accurately fitted by the Ketteler–Helmholtz dispersion theory. Reproduced from Palik [55]. Right: a more modern illustration of the *reststrahlen* effect in CaF_2, showing a main resonance at 35 μm and a secondary mode at 25 μm. Reproduced from Kaiser et al. [36]

each other's measurements and extend the range of their dispersion curves, feature prominently in the early history of spectroscopy [8,18,39]. Relocations and lack of funding ultimately led Paschen to redirect his research towards atomic spectroscopy, a field in which he would find great success [18]. In this respect, Rubens's position in the Berliner scene and his access to institutional support, particularly regarding PTR's experimental facilities, must be acknowledged as important drivers of his work.

Rubens's work from 1892 onwards was characterized by a large number of collaborations, including a constant flow of American researchers that would later be instrumental in the development of far-infrared technology in the USA [49]. Most of their efforts were centered in pushing the limit of detection and generation of infrared waves further than Paschen was capable of. This required development of new optical instrumentation, including newer sources, detectors, prisms and gratings. He undertook the first steps in this direction with Henri du Bois, with whom he explored the polarization properties of wire gratings [7], and the American Benjamin W. Snow, with whom he studied the dispersion of minerals with absorption bands located at longer wavelengths, such as rock salt (NaCl), fluorspar (CaF_2), or sylvine (KCl) [76]. It would not take long before wavelengths of 9 μm could be reliably measured, thereby matching Paschen's record [40]. These long wavelengths were sufficiently long to allow testing of the Ketteler–Helmholtz dispersion theory (Fig. 7, left), which implicitly relied on the existence of optical resonances in the ultraviolet and the far-infrared [62]. These theoretical resonances would prove to be of paramount importance for breaking through the far-infrared barrier.

Ernest Fox Nichols was an American scientist who had pioneered infrared absorption studies in the USA and also had the honor of writing the first ever paper in the *Physical Review* journal [52]. Frustrated by instrumental difficulties, he applied for a leave to join Rubens in Berlin from 1894 to 1896. There he would develop the radiometer that brought him fame, but he also participated in the project which would finally render accessible the realm of far-infrared radiation. Motivated by the resonances in the Ketteler–Helmholtz theory, which predicted that certain crystals would show bands of high reflectivity at long wavelengths (Fig. 7, right), Rubens and Nichols developed the *reststrahlen* (residual ray) method of filtering radiation [74]. The foundation of this method (Fig. 8, top), was the use of multiple mirrors, made of a particular mineral with a well-known resonance, to progressively filter out undesired frequencies. When combined with sources and windows with selective optical properties, it was possible to obtain relatively narrow spectral distributions, which could then be analyzed using a grating or an interferometer. Although Rubens and Nichols were not the first ones to research the high reflectivity of crystals at infrared frequencies (citing Magnus's previous work on the transmission of radiant heat through crystals,[2]) they were the first ones to understand that this peculiarity could be used to fabricate far-infrared optical instrumentation. However, the exceedingly small signal produced by this quasi-monochromatic radiation could not have been measured without the construction of an effective magnetic shield for the galvanometer that could resist interferences by magnetic disturbances from the Berlin traffic, manufactured in collaboration with du Bois [6].

[2] Gustav Magnus, whose early works on radiant heat have been omitted for brevity, was the most crucial figure in the development of experimental physics as a modern discipline in Germany, particularly in Berlin. The Magnus School was a training place for many acclaimed experimental physicists in the latter half of the nineteenth century, including Kundt. Through him, Rubens became heir to this tradition and continued to host colloquia at the University of Berlin in the spirit of those originally held by Magnus [34].

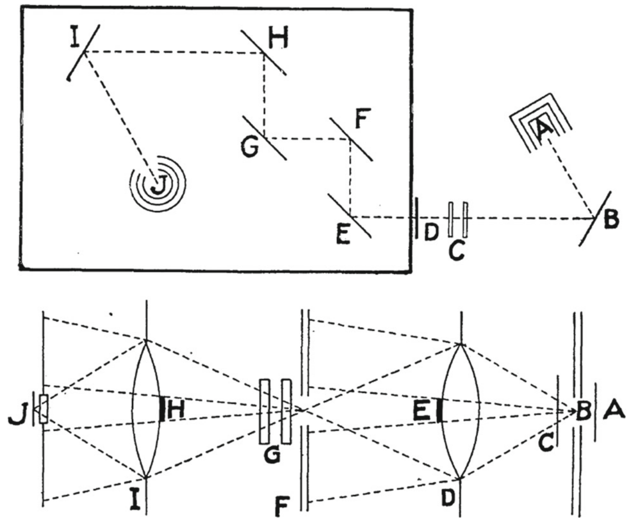

Fig. 8 Schematic representations of Rubens's techniques for far-infrared interferometry. Top: *reststrahlen* method; bottom: focal isolation method. Interferometric plates are represented as C and G, respectively, with other symbols having their usual meaning. Reproduced from Weniger [81]

Rubens's skill for experimentation and instrument development was already evident by this point, but he would not cease to develop new devices. Another one of his inventions was a refined thermopile [63], by which he tried to reverse the obsolescence of the bismuth-antimony version of Nobili and Melloni, which had fallen into disuse in favor of the bolometer and more modern radiometers. The reason for this was not a lack of sensitivity, but the low ductility of these metals, which meant they could only be drawn into thick wires with slow and unreliable thermal behavior (with a time constant of up to 10 seconds [80]). Rubens solved this issue by using iron-constantan thermal unions, with reduced sensitivity but simpler manufacture and more reliable operation [63]. He would later use his galvanometer and thermopile extensively in his quest for longer and ever more elusive wavelengths.

Rubens's last main invention over this period was developed in collaboration with Emil Aschkinass. Due to its obvious limitations, the *reststrahlen* method was impractical as a general procedure for far-infrared experimentation. The new method of focal isolation (Fig. 8, bottom) would become a fixture for the early exploration of very long wavelengths. This method made use of the great difference between the near-($\lambda < 5$ µm) and far-infrared ($\lambda > 50$ µm) values for the refractive index of quartz, which is also strongly absorbing between these limits [68]. By using quartz lenses with suitable apertures, it was possible to naturally filter out near-infrared pollution from the final measurement spot. Using this method, wavelengths an order of magnitude longer than those obtained up to that point would soon be available for research.

The collaboration with Aschkinass proved to be fruitful in other aspects. Motivated by the observation that fluorite *reststrahlen* radiation (24.4 µm) was not strongly absorbed by the atmosphere, contrarily to Paschen's observations in the mid-infrared, Rubens and Aschkinass set out to map the absorption bands of water vapor and CO_2 using a sylvin prism that was transparent up to 20 µm [67]. This included, for the first time, resolved measurements of the 15 µm band of CO_2 most responsible for its associated greenhouse effect (Fig. 9). The complexity of the water spectra would also become very relevant, as it would later be used as a key experimental test for early quantum theories of molecular structure and rotation [39].

By the turn of the century, Rubens had secured a professorship and a reputation as the leading infrared spectroscopist, with access to cutting-edge facilities and ample international connections. It was at this point that he turned his attention to the problem that would be most associated with his name in modern historiography: the nature of Kirchhoff's universal radiation function.

4.3 Studies on blackbody radiation (1900)

Kirchhoff's proposal of a universal radiation function had intrigued scientists for 40 years, especially given the difficulty of manufacturing and measuring isothermal cavities in sufficiently wide ranges of temperature and wavelength. Wien's 1896 formulation of a rather simple distribution function lacked a sound theoretical grounding, but it featured all the necessary properties and accurately reproduced what limited observations were available [39]. Although Planck had already started working on the theoretical foundations of this empirical expression, the blackbody revolution would be started by unexpected experimental results.

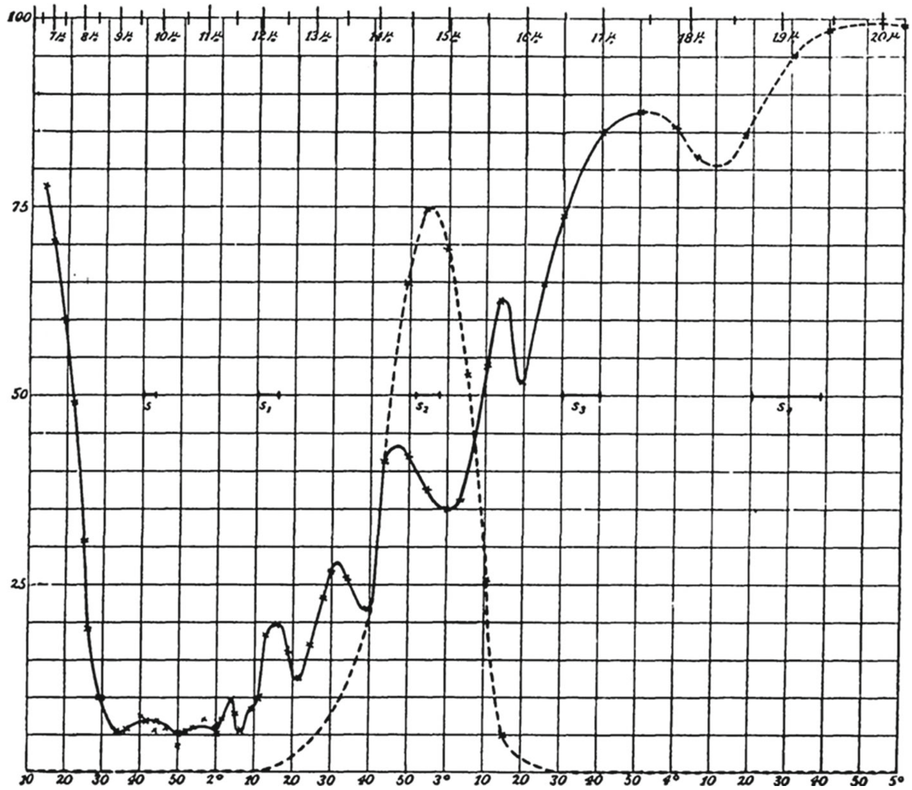

Fig. 9 First measurements of the resolved structure of carbon dioxide and water vapor beyond 10 μm [67]. Reproduced from Palik [55]

The most convincing evidence in favor of the original Wien-Planck distribution function was Paschen's 1897 work in the conventional infrared range (1–8 μm), where no deviation from the law could be observed [18,53]. This demonstration suggested that the problem was closed, and so Planck devoted his efforts to understanding the thermodynamics of the system described by such function. However, contradictory data soon emerged. Under the supervision of Rubens, Hermann Beckmann measured the temperature dependence of far-infrared blackbody radiation for the first time in 1898 using the *reststrahlen* bands of fluorite. A disagreement with the assumed distribution was noted, but the quality of the evidence was insufficient for Rubens, who considered the deviations to be consistent with instrumental error [2,39]. However, when Lummer and Peter Pringsheim reported similar anomalies in measurements with increasingly wider temperature and spectral ranges, Rubens and PTR's Ferdinand Kurlbaum set out to improve Beckmann's *reststrahlen* experiment to test the theory to its extreme, using four blackbody cavities spanning a temperature range from −180 to 1600 °C. Aside from the much larger temperature range, the authors improved on Beckmann's method by validating the fluorite results with additional measurements on rocksalt at even longer wavelengths (51.2 μm).

Figure 10 compares the pseudo-monochromatic radiances obtained by multiple reflections at CaF_2 crystals to several proposals for the temperature dependence of blackbody radiation [72]. These included the older Wien law, as well as purely empirical modifications by Thiesen, and also Lummer and Jahnke, which tried to account for the deviations observed by Lummer and Pringsheim. Another law, based on a conjecture by Lord Rayleigh (but distinct from the later and more famous Rayleigh-Jeans formula), was also tested [58]. All of them were consistent with the expected properties of blackbody radiation, but, crucially, each of them predicted different behaviors at large values of the product λT, thus the need for far-infrared data to settle the issue.

$$E_{\mathrm{Wien}} = C\lambda^{-5}e^{-c/\lambda T} \tag{1}$$

$$E_{\mathrm{Thiesen}} = C\lambda^{-5}\sqrt{\lambda T}e^{-c/\lambda T} \tag{2}$$

$$E_{\mathrm{Rayleigh}} = C\lambda^{-5}(\lambda T)e^{-c/\lambda T} \tag{3}$$

$$E_{\mathrm{Lummer-Jahnke}} = C\lambda^{-\mu}T^{5-\mu}e^{-c/(\lambda T)^{\nu}} \tag{4}$$

However, as Fig. 10 clearly shows, none of these expressions reproduced precisely the observed data for all temperatures. That honor would correspond to a law that Planck had obtained shortly before. On October 7, 1900, Rubens and his wife invited the Plancks over, an occasion which Rubens used to communicate the discovery that the limit of the radiation law for large λT was a linear function of temperature [29,53]. Planck went back home to rework the thermodynamic properties of his empirically based blackbody system and quickly responded

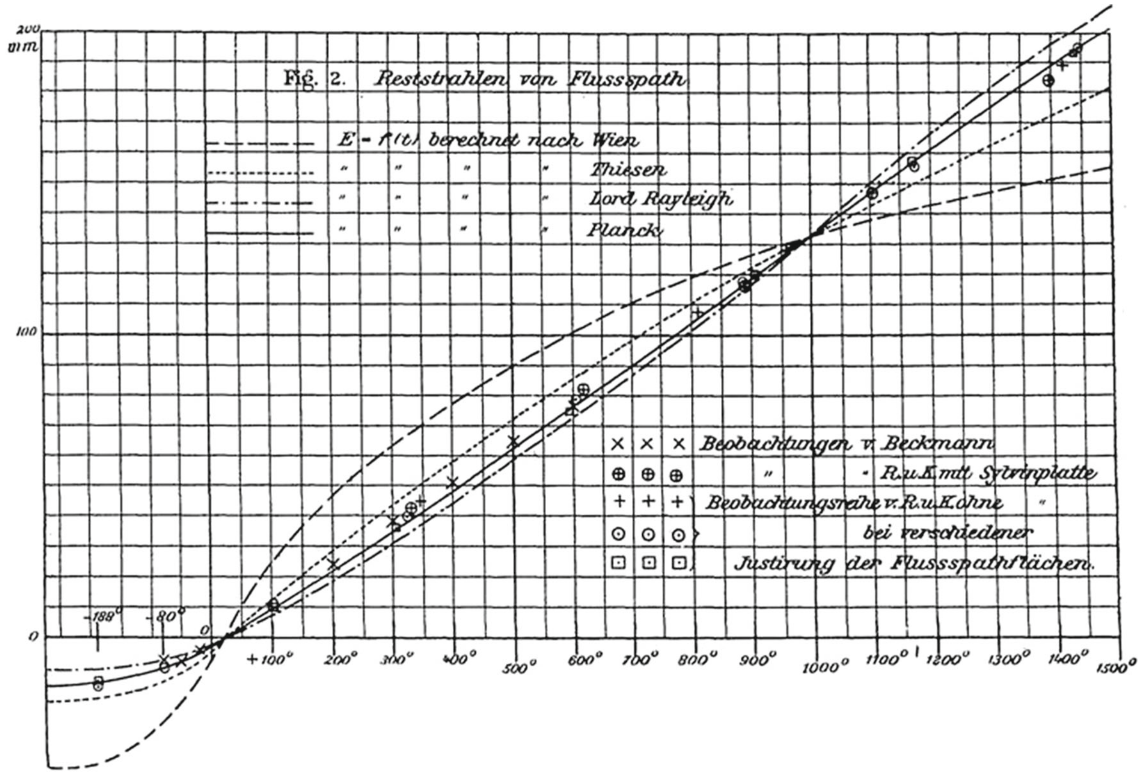

Fig. 10 Comparison of several radiation laws to the observed signals emitted by a blackbody at 24.3 μm, as measured after repeated reflections on fluorspar (fluorite) surfaces. Reproduced from Rubens and Kurlbaum [72]

with an equation that could predict all the observed phenomena. Rubens replied that the proposed equation fitted the results perfectly, and both Planck and Rubens and Kurlbaum presented their results at the same meeting of the Physical Society on October 19. The result was one of the most famous and consequential formulas in physics [57]:

$$E_{\text{Planck}} = C\lambda^{-5}(e^{c/\lambda T} - 1)^{-1} \tag{5}$$

Not only would Planck's law prove to be the superior fit to the experiment, but it also had less parameters than the runner-up, the Lummer–Jahnke formula. This unexpected result led Planck, who had already accumulated great experience in this field, to try to find an explanation for the entropy of radiation that his *ad hoc* law implied. This conduced him to the use of statistical mechanics and the quantum hypothesis, as has been widely documented [2, 42–44, 53]. He presented his derivation on December 14, 1900, a date that is conventionally celebrated as the birthday of modern physics.

5 Late career (1901–1922)

After demonstrating the enormous potential of his *reststrahlen* method for the study of cutting-edge problems, Rubens would dedicate most of his remaining two decades to revisiting his old research themes, namely extending the infrared range and testing Maxwell's electromagnetic theory. In this regard, this latter part of his career was built on pushing his previous innovations towards progressively further limits of precision and spectral range. This goal was studied in the second part of Kangro's work on Rubens [38].

As part as his new role as full professor and director of the Physical Institute, he took on at least eight PhD students during this time (Table 1). Interestingly, three of the aforementioned theses were co-supervised by Planck, evidence of the good understanding between the two men. Although they never published together, they frequently cited each other's work and kept in close contact. Among the students that they shared, three special mentions must be given. The first is to Gustav Hertz, nephew of the more famous Heinrich Hertz, who would go on to win the Nobel Prize for the Franck–Hertz experiment, in which they showed that accelerated electrons moving through mercury vapor could only lose energy in multiples of 4.9 eV [20]. The second special mention is Walter Schottky, the famous inventor and researcher in semiconductor technology. Rubens was the main advisor to Hertz's experimental work on infrared absorption by CO_2, while Planck was the main advisor of Schottky's studies on relativity [48].

Table 1 Doctoral students of Rubens

Name	Dissertation year	Notes
Ernest Nichols	1897	Measurements supervised by Rubens, defended at Cornell University
Hermann Beckmann	1898	Measurements supervised by Rubens, defended in Tübingen
Georg Gehlhoff	1907	
Carl Müller	1908	
Gustav Hertz	1911	Co-supervised by Planck
Theodor Hartmann	1912	Co-supervised by Otto Staude, defended in Rostock
Walter Schottky	1912	Co-supervised by Planck
Erich Kretschmann	1914	Co-supervised by Planck
Gerhard Hettner	1918	
Marianus Czerny	1923	Interrupted by Rubens's death, defended under Gerhard Hettner

Information compiled from the Mathematics Genealogy Project [48] and supplemented by additional information. Dissertations were defended at the University of Berlin, unless otherwise noted. Missing records may be lacking

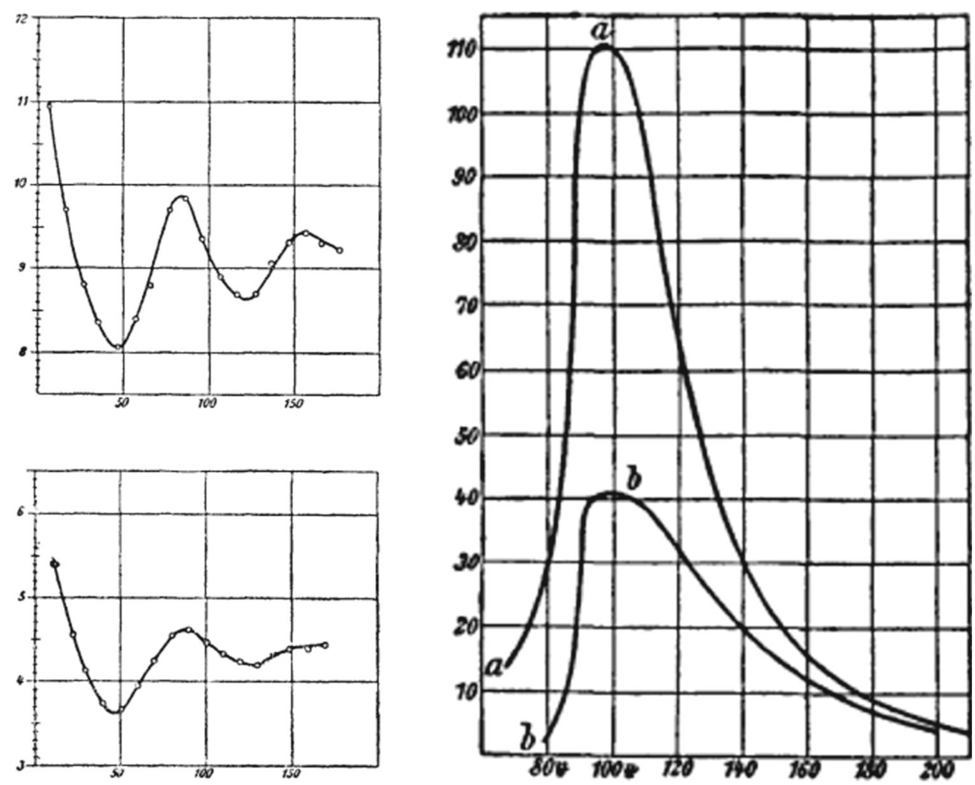

Fig. 11 Interferograms obtained by Rubens and Wood (left) and the approximate reconstruction of the original signal emitted by a Welsbach mantle, obtained manually by trial and error (right). Reproduced from Rubens and Wood [79]

Finally, Rubens died before the completion of the dissertation of his latest student, Marianus Czerny, the man who would become his successor as the leading far-infrared spectroscopist in Germany [23,49].

Rubens's research during the first decade of the new century was largely defined by his prolific collaboration with Ernst Hagen, in which they revisited in depth Rubens's dissertation topic on the optical properties of metals. They reported an extensive number of reflectivity, emissivity, and thin-film absorption measurements of pure metals and alloys from the ultraviolet to the mid-infrared. Emissivity measurements, in particular, were an innovative alternative that solved some of the issues in conventional reflectometry, especially at high temperatures or for long wavelengths. One of the crucial realizations of Hagen and Rubens was that the expected straightforward relationship between the DC conductivity and optical transmittance was indeed obeyed at low frequencies, before the onset of electron transitions that complicated the optical response and broke the proportionality between metals. In this way, they could explain away the apparent paradox that the visible/UV transparencies of metals were not ordered in the same way as their resistivities [25]. Although this relation between low-frequency optical properties and the electrical resistivity would later be known as the Hagen–Rubens relation, it had actually been derived by Drude a decade earlier in his trailblazing book *Physik des Äthers auf elektromagnetischer Grundlage* (1894), one of the most important early implementations of Maxwell's work [33]. The authors acknowledged this fact, content with being able to experimentally prove the validity of Maxwell's electromagnetic theory once again.

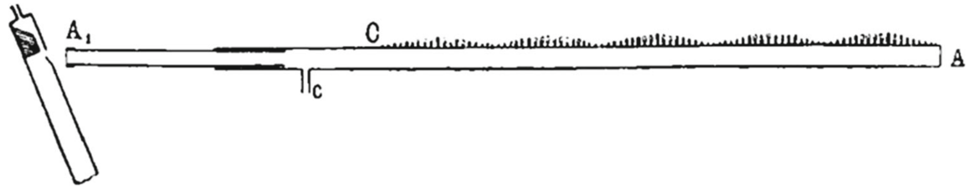

Fig. 12 Original depiction of the Rubens flame tube. A standing acoustic wave produced along the tube is visualized by supplying a flammable gas and allowing it to escape through small holes, where it is ignited. Reproduced from Rubens and Krigar-Menzel [71]

From 1910 onwards, Rubens's research would include many revisions of older topics in more depth, mostly concerned with driving back the frontier of optically generated waves [38, 40]. Some important results are summarized below:

- 1910: Rubens and Herbert Hollnagel resolved the spectral structure of *reststrahlen* radiation in several crystals using an interferometer, finding a doublet structure [70].
- 1911: Rubens and Robert W. Wood used the focal isolation method to record what is often[3] considered the first real application of interferometric spectroscopy (Fig. 11) [79]. Reconstruction of the asymmetric profiles of the Welsbach mantle was performed manually through trial and error, with no reference to Fourier transforms.
- 1911: Rubens and Otto von Baeyer used the same method to discover the potential of the quartz mercury lamp as a far-infrared source beyond 100 µm, with an emission band centered around 314 µm [69]. This source remains in use in modern spectrometers.
- 1911: Rubens and Hans von Wartenberg measured the long-wavelength absorption spectra of several common gases [77]. These data would be revised by Eva von Bahr, who used them to test Bjerrum's early quantum theory of rotation [4].
- 1914: Rubens and von Wartenberg measured the furthest *reststrahlen* band in thallium iodide (150 µm) [78].
- 1914: Rubens and Karl Schwarzschild attempted to study the far-infrared region of the solar spectrum, but found complete attenuation beyond 60 µm, attributing it to the opacity of the atmosphere in this range [75].
- 1920: Rubens used polarized far-infrared radiation to prove that the optical symmetry axes of monoclinic crystals converge towards their dielectric counterparts at sufficiently long wavelengths [65].
- 1921: Rubens used a wire-grid method to record a spectrally resolved profile of the mercury lamp emission down to 400 µm, while noting the influence of water vapor rotational modes in the spectra [66].

As could be expected, Rubens would also remain linked to the blackbody question, which he kept testing to greater precision. Two dates are important in this regard. First, the inaugural Solvay conference in 1911, where he reported on new blackbody radiation measurements and confirmed that only Planck's law could fit them satisfactorily [64]. Second, in 1921, when Gerhardt Michel and him produced a newer comparison in which they verified the constancy of the product $E(e^x - 1)$ with temperature, E being the measured signal and $x = c/\lambda T$ [73]. Only Planck's equation predicted a constant product of these quantities, and indeed this they found to a precision better than 1%. This new agreement was necessary to appeal to some reticent scientists, like Nernst and Wulf, who had raised objections about the experimental foundation behind Planck's law.

Finally, a scientific biography of Rubens could not be complete without mentioning his popular contribution to physics teaching, the Rubens tube [71]. This demonstration device allows visualizing acoustic resonances in an aesthetically pleasing manner by means of a burning gas (Fig. 12). Rubens first had the idea in 1904 and later developed this sketch into a full demonstration with his collaborator Otto Krigar-Menzel. However, inspiration from a similar device invented by Kundt is evident [21]. Kundt's prototype, which is not cited in the 1905 *Annalen der Physik* publication, was built on the same concept, but with powder being used to visualize the standing waves, instead of flames. It is worth noting, however, an important difference between both devices. Whereas Kundt went to great lengths to precisely determine the speed of sound in different gases, and thus their heat capacity ratios [11], Rubens and Krigar-Menzel did not seem interested in pursuing research applications of their device. Nevertheless, the Rubens variation was more attractive for teaching purposes and its design quickly spread among fellow academics, some of whom also introduced their own variations on the basic idea [21]. Even if rather inconsequential from the point of view of his scientific production, it would prove to be Rubens's most popular legacy, probably exerting a greater direct influence on physicists in the century since than any of his remaining work. Moreover, this lone instance of departure from his characteristic hyper-specialization serves to illustrate once again Rubens's approach to science as an instrument-building enterprise.

[3] The reason why this milestone is given this title by some authors [12] is the fact that it used a general technique, the focal isolation method, to study an arbitrary distribution given by a source, rather than just the *reststrahlen* structure of a particular crystal. Others have considered the Rubens–Hollnagel work to be the groundbreaking moment [14, 38].

At the time of Rubens's untimely death in 1922, his lifelong goal of merging the electrical and optical regimes of wave production was almost complete, with only a small window left in the process [28]. It would only take a couple of years for this feat to be independently accomplished by Alexandra Glagolewa–Arkadiewa in the USSR [24] and the Nichols-Tear team in the USA [51]. It would be the final contribution of Rubens's collaborator Nichols, who died while presenting the results at a conference in 1924 [52].

6 Critical revision of Rubens's legacy

Heinrich Rubens was a pioneering experimentalist whose main body of work took place during the revolutionary decade from 1895 to 1905. His connections to Hertzian radiation, the blackbody problem, or the earliest developments in infrared spectroscopy could suggest a prominent place in historical narratives around this time. The aim of this section is to analyze possible reasons behind the observed lack of enduring recognition.

Many accounts of Rubens's life stressed his contribution to electromagnetism over the remainder of his work [28,45,46]. In this regard, contemporary opinion generally aligned with his own assessment of his career, in which he considered bridging the electromagnetic spectrum as his most important goal. In his speech when taking Drude's place at the Royal Prussian Academy of the Sciences, he mentioned Hertz and Maxwell as his main inspirations [37]. However, in contrast to his hero Hertz, he could not claim a single momentous experimental discovery as his defining legacy. Indeed, neither was he the one to report definitive evidence of a bridging of the spectrum, although it can be argued that Rubens and von Baeyer's optical detection of feeble electrical waves counts as a successful enterprise, even though they could not record stable measurements nor perform any kind of study on them [8]. Nevertheless, the commendable extension of the available range of wavelengths from approximately 10 μm, where his rival Paschen stopped, to 400 μm can be attributed almost exclusively to Rubens, who devised, constructed, and operated the instruments required for this task. This equipment allowed him to record a large volume of high-quality optical data, especially for the less extreme wavelengths, that would be of great use in the advancement of spectroscopy [55,81]. The larger significance of this research, however, was exaggerated by some of his contemporaries. As a particularly relevant example, there is a claim by Gustav Hertz that Maxwell's theory of light would have remained a hypothesis were it not for Rubens's work [28]. This is an obvious exaggeration, given the wealth of evidence available from other sources already in Rubens's lifetime, from Hertz's electrical waves to Drude's electromagnetic explanation of the Kerr effect [33].

Despite Rubens's undoubtedly important contributions to electromagnetism and optics in general, a modern revision of his figure must necessarily include the blackbody measurements of 1900 as a central point. In the decades since, experimental evidence for the electromagnetic theory of light has become taken for granted and that collected after Hertz is seldom discussed. In contrast, the story of the blackbody radiation is still a central topic of the history of physics for its role as the genesis of quantum theory. Naturally, Rubens's contribution to this problem was the highlight chosen by Planck to commemorate his late colleague, when he stated that, without Rubens's work, the quantum theory would have taken longer to develop and it may not even have been found by German scientists at all [9]. This serves as a reminder of how unexpected the blackbody revolution was and how satisfied many researchers would have remained with the Wien-Planck formulation were it not for incontrovertible evidence of its failure. Indeed, Rubens himself was also initially skeptical of the first experimental discrepancies with the theory. Regarding this situation, it must also be noted how the influence of the ultraviolet catastrophe narrative, which was only formulated *a posteriori* [42–44], contributes to the misunderstanding, by implying an evident clash between theory and experiments. There was no such contrast at the time, and it was only Rubens and Kurlbaum's experiment (in the infrared, not the ultraviolet) that forced Planck to try to find an explanation for the anomaly. Some authors have tried to fight the conventional narrative by emphasizing the crucial role of infrared experimentation in the history of the blackbody problem [32,39]. However, even in this case it is difficult to determine the merit attributable to Rubens and Kurlbaum, as it can be argued that the real breakthrough in showing convincing evidence of a breakdown of Wien's law was the Lummer–Pringsheim work [32]. It is worth noting that Rubens's work would also be useful for other aspects of the quantum theory, such as the study of rotational spectra [4,19,38], but it would exert little lasting influence, especially as the inconsistent early quantum theories gave way to the more rigorous quantum mechanics.

There is yet another aspect of Rubens's legacy that is more often ignored than those mentioned above, but which could have completely altered his later reception: his pioneering work on what would later be known as Fourier-transform spectroscopy [13]. Starting in 1910 with his collaboration with Hollnagel, Rubens developed a rough but functional approach to interferometric spectroscopy that would not be resumed after his death. Decades before the Fellgett–Jacquinot formulations of the advantages of interferometric methods, he demonstrated a clear intuitive understanding of the advantages of this method with regard to the lossy gratings and slits common in mainstream spectroscopy. The clarity of these advantages was also realized at the time by other authors aware of Rubens's work [81]. An interesting alternative history of the field was raised by Connes and others, one in which Rubens was aware of Albert Michelson's mechanical computer for spectral analysis [14]. Had this been the case, he could have automated the spectral analysis of his interferograms, a feature that Michelson himself never implemented, advancing the development of Fourier-transform spectroscopy by decades. Instead, Michelson died without a real application of his analyzer, and Rubens went back to grating-based methods [66]. This can be considered an instance of the *Faraday spirit* Joseph Larmor saw in Rubens, in the sense of being an exceptional experimentalist with great creativity but little interest in formal mathematical arguments [46]. An additional consideration to the points raised by the Connes hypothesis must be discussed: Rubens left his work unfinished. A tireless worker, he downplayed the severity of his illness and expected to get back to work only days before his death [47]. Therefore, his last project, a monograph of infrared metrology detailing the entire breadth of knowledge acquired over three decades dedicated to the foundations of the infrared, would never see light [82]. This loss prevented him from carrying out an in-depth review of his own career and achievements and, although it would be unrealistic to expect a rigorous treatment of the Fourier-transform method, probably hurt the chances of his work being continued by a new generation.

From all the points explored above, it is clear that there was no single definite scientific discovery among Rubens's numerous contributions that could secure him a spot among the most well-known scientists of the time. Still, his legacy and influences are far-reaching. The story of blackbody radiation or infrared spectroscopy should not be written without his contributions. His name is recounted often in the context of the optical properties of metals in the infrared, where the low-frequency Hagen–Rubens relation is still featured in modern textbooks as an approximation to the Drude model [16]. His influence has also started to be recognized by the modern terahertz community, especially given its renewed relevance and numerous novel applications that could not be predicted during Rubens's lifetime [9]. The terahertz gap, a region where optical and electrical technologies seem equally ill-suited, is a modern term for a problem which Rubens first faced almost a century before the proliferation of terahertz sources. From a personal point of view, Rubens was also widely respected as a mentor by his large number of students and collaborators, with a style of supervision that was supportive but encouraged independence [59]. Ironically, his famous tube would provide him a degree of recognition among students, in a manner similar to the case of another great spectroscopist, Robert Bunsen, and his eponymous burner. Overall, Rubens's greatest honor is probably the fact that, one hundred years after his death, any historical account on far-infrared or terahertz research has to start with an exposition of his work [9,12,13,49,55].

7 Conclusions

The lack of modern historiographical studies on Heinrich Rubens is an unfortunate consequence of fading interest in a figure, well known to historians but obscure to the vast majority of physicists, that was one of the most famous experimentalists of his time. His story provides room for exploring questions on scientific legacy and historical narratives, as well as valuable insights into the state of German physics around the crucial year 1900. During his lifetime, Rubens was mostly linked to the development of infrared technology and the verification of Maxwell's electromagnetic theory of light for long wavelengths, both of which are scarcely discussed topics at present. His contribution to the blackbody radiation problem, while valuable, suffers from the general lack of awareness about the role experimental evidence played in this issue, which is further exacerbated by the ultraviolet catastrophe narrative. Finally, it is notable that his key contributions to interferometric spectroscopy were almost completely lost and were not recognized as such by the pioneers in the field, who considered Michelson their only significant forerunner. A renewed exploration of this figure reveals a prolific and inventive character, held in high esteem by students and collaborators, who almost single-handedly gave birth to the fields of far-infrared spectroscopy and terahertz science and technology.

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