Chapter 4

Creators and Creations in Earth and Space Science

Daher ist die Aufgabe nicht sowohl zu sehen was noch keiner gesehen hat, als bei Dem was Jeder sieht, zu denken was noch Keiner gedacht hat.	Therefore the problem is not so much, to see what no one has yet seen, but rather to think concerning that which everyone sees, what no one has yet thought.

Arthur Schopenhauer. 1851.
Parerga und Paralipomena: Kleine Philosophische Schriften.
Vol. 2, Section 76, p. 93. Berlin: A. W. Hayn.

This chapter gives an overview of some earth and space science innovations that have played major roles in the modern world and that were discovered or developed by scientists and engineers who were trained in the predominantly German-speaking central European research world in the nineteenth and early twentieth centuries.[1]

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[1] In addition to specific references that are cited in different areas throughout this chapter, this chapter makes use of general biographical and project information from: ACLS 2000; Albrecht et al. 1992; Ash and Söllner 1996; Bar-Zohar 1967; Bower 1987; Bunch and Hellemans 2004; Challoner 2009; Cornwell 2003; Crim 2018; EB 1911, 2010; Gillispie 1970–1990; Gimbel 1990a; Glatt 1994; Hall 2019a; István Hargittai 2006, 2011; Linda Hunt 1991; Impey et al. 2008; Jacobsen 2014; Koertge 2007; Kurowski 1982; Lasby 1971; Lusar 1956, 1971; Medawar and Pyke 2000; Mick 2000; Murray 2003; Nachmansohn 1979; NDB 1953–2020; Neufeld 2012; Nouzille and Huwart 1999; O'Reagan 2014, 2019; Porter 1994; Charles Walker 1946; Peter Watson 2010; Weitensfelder 2009.

For coverage of major portions of the history of earth and space science in the German-speaking world, see: von Boguslawski and Krümmel 1884–1887; Bowler 1993; Brückner and Penck 1909; Chambers 2002; Chladni 1794; Galle and Wattenberg 1963; Geiger 1950; Greene 2015; von Hann 1887; von Hann and Süring 1926; Haurwitz 1941; Hesse 1924, 1937; Hoskin 2011; Javanović-Kruspel 2015; Köppen 1955; Lemonick 2008; Lüdecke 2015; Mohs 1825; North 1995; Nothdurft and Smith 2002; Probst 2015; Schön 2004; Schwarzschild 1958; Spiess 1985; Wegener 1966; Wellnhofer 2008; Wulf 2015.

Creators from the German-speaking world made major contributions to geophysical and space science fields, including:

4.1. Geological science

4.2. Paleontology

4.3. Ocean and hydrological science

4.4. Atmospheric science

4.5. Planetary science

4.6. Astrophysics

4.1 Geological Science

German-speaking scientists made a long string of discoveries in geological science and related fields, including:

4.1.1. Stratigraphy and continental drift

4.1.2. Geophysics

4.1.3. The Universal Transverse Mercator (UTM) for map coordinates

Outside observers were impressed and even envious of how seriously the whole German-speaking world took the field of geology. For example, in BIOS 948, *German Academic Geology*, visiting British scientists wrote after World War II:

> Geology was a subject formerly taught in German schools but was removed from the curriculum under the Hitler regime. It is, we understand, to be replaced and it is clear that teachers should receive sound geological training up to the necessary level at their Universities. [...]
>
> Strong representations have been made for a number of years that Geology should be a part of the normal science curriculum in British schools. In this respect, the team regard the proposed German curriculum as on a considerably wider basis than the existing British practice. [...]
>
> In prewar times, German geologists found employment in considerable numbers outside Germany[...]
>
> We were impressed with the high status of German mining and miners. There is a deep-routed tradition derived from the thousand years of their honourable history that has given the German miners a sense of self-esteem and a realisation of their high place in the community.

I have deliberately left a blank space where images of some creators or creations should go. Those are people or projects that I felt were important enough that they should definitely be shown in this book, yet I have not yet been able to locate a suitable image that I have permission to use, despite my searches in Europe and in the United States. If readers have any relevant images and could send them to me, I would be very grateful and will include them in future editions of this book. Even where a suitable photo cannot be located, I believe that leaving a blank space pays tribute both to the scientific importance of that creator or creation and to how that historical fact has been very nearly forgotten.

4.1.1 Stratigraphy and Continental Drift

Abraham Gottlob Werner (German states, 1749–1817, Fig. 4.1) developed stratigraphy, the scientific analysis of rock layers of increasing age with increasing depth. He also taught a large number of students, many of whom became highly influential geologists. *Encyclopaedia Britannica* called him the "father of German geology" [EB 1911].

Eduard Suess (Austrian, 1831–1914) discovered and correctly interpreted evidence for the Paleozoic southern supercontinent Gondwana and the adjacent Tethys Ocean (1861); see Fig. 4.2. Suess also proposed methods of measuring changes in ancient sea levels vs. time and was one of the first scientists to discuss the ecology of biospheres. Oxford University's *Biographical Dictionary of Scientists* summarized some of Suess's research accomplishments [Porter 1994, p. 651]:

> The outcome of these interests was *The Face of the Earth* 1885–1909, a massive work devoted to analysing the physical agencies contributing to the Earth's geographical evolution. Suess offered an encyclopedic view of crustal movement, of the structure and grouping of mountain chains, of sunken continents, and of the history of the oceans. He also made significant contributions to rewriting the structural geology of each continent.
>
> In many respects, Suess cleared the path for the new views associated with the theory of continental drift in the twentieth century. In view of geological similarities between parts of the southern continents, Suess suggested that there had once been a great supercontinent, made up of the present southern continents; this he named Gondwanaland, after a region of India. Wegener's work was later to establish the soundness and penetration of such speculations.

Alfred Wegener (German, 1880–1930) marshalled detailed evidence for his theory of continental drift (1912–1930) and also made major contributions to the understanding of polar air circulation. Wegener, shown in Fig. 4.3, was the son-in-law of Wladimir Köppen (p. 782). Wegener died while on an expedition to Greenland to gather more evidence for his theories. His ideas regarding continental drift became widely accepted and celebrated after his death [Greene 2015; Wegener 1966]. The *Encyclopedia Britannica* described Wegener's research [EB 2010]:

> German meteorologist and geophysicist who formulated the first complete statement of the continental drift hypothesis. [...]
>
> In about 1910 he began toying with the idea that in the Late Paleozoic era (about 250 million years ago) all the present-day continents had formed a single large mass, or supercontinent, which had subsequently broken apart. Wegener called this ancient continent Pangaea. [...]
>
> Wegener first presented his theory in lectures in 1912 and published it in full in 1915 in his most important work, *Die Entstehung der Kontinente und Ozeane* (*The Origin of Continents and Oceans*). He searched the scientific literature for geological and paleontological evidence that would buttress his theory, and he was able to point to many closely related fossil organisms and similar rock strata that occurred on widely separated continents, particularly those found in both the Americas and in Africa.

Abraham Gottlob Werner (1749–1817) stratigraphy, “father of German geology”

Von den
äußerlichen
Kennzeichen der Foßilien,
abgefaßt
von
Abraham Gottlob Werner,
der Bergwerks = Wiſſenſchaften und Rechte Beflißenen, auch der Leipziger öconomiſchen Geſellſchaft Ehren-Mitglied.

Leipzig,
bey Siegfried Lebrecht Cruſius,
1774.

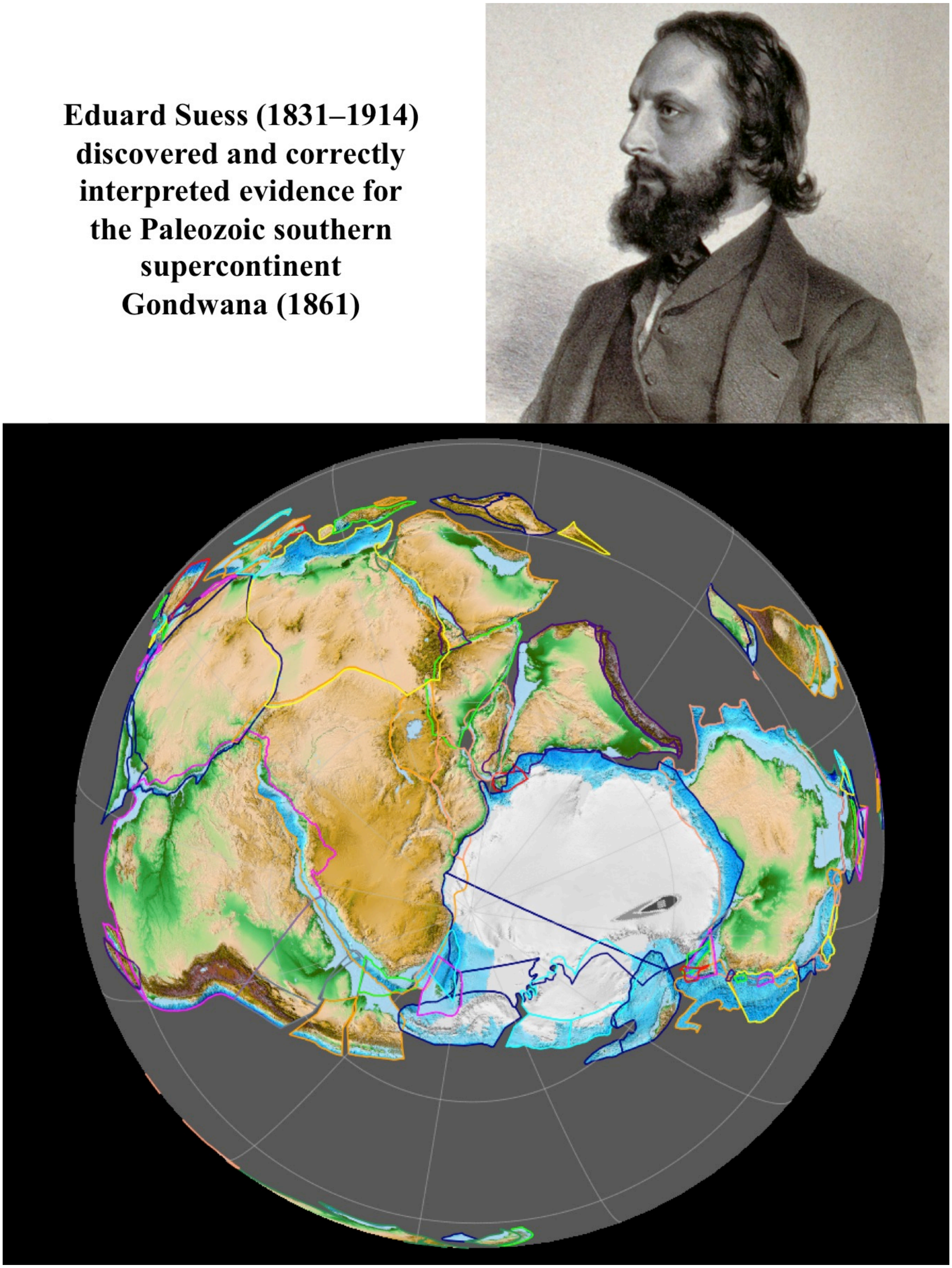
Kurze
Klaſſifikation und Beſchreibung
der
verſchiedenen Gebirgsarten,
von
A. G. Werner,
Bergakademie-Inſpektor und Lehrer der Bergbaukunſt und Mineralogie
zu Freyberg.

Dresden, 1787.
In der Waltheriſchen Hofbuchhandlung.

Neue Theorie
von der
Entſtehung der Gänge,
mit
Anwendung auf den Bergbau
beſonders
den freibergiſchen
von
Abraham Gottlob Werner.

Freiberg, 1791.
gedrukt und verlegt in der Gerlachiſchen Buchdrukkerei.

Figure 4.1: Abraham Gottlob Werner developed stratigraphy, the scientific analysis of rock layers of increasing age with increasing depth, and is regarded as the “father of German geology.”



Eduard Suess (1831–1914) discovered and correctly interpreted evidence for the Paleozoic southern supercontinent Gondwana (1861)

Figure 4.2: Eduard Suess discovered and correctly interpreted evidence for the Paleozoic southern supercontinent Gondwana (1861).

Figure 4.3: Alfred Wegener marshalled detailed evidence for his theory of continental drift (1910–1930) and also made major contributions to the understanding of polar air circulation.

4.1.2 Geophysics

Emil Wiechert (German, 1861–1928) established the detailed study of the structure of the Earth and the behavior of different types of seismic waves passing through parts of the Earth; see Fig. 4.4. Specifically, he invented an improved seismograph, calculated how seismic waves propagate through the Earth, demonstrated evidence for layers within the Earth, and proposed that the Earth's core was made of iron. Wiechert was also one of several German-speaking scientists who discovered and analyzed the electron before the more famous work of J. J. Thomson (p. 863).

Wiechert was the first professor of geophysics in Germany and founded the world's first Institute of Geophysics at Göttingen University in 1898. In 1922, he also initiated the foundation of the German Geophysical Society (initially called the Deutsche Seismologische Gesellschaft). Wiechert attracted, taught, and collaborated with many younger scientists who made fundamental discoveries in geophysics, such as:

- Gustav Angenheister (German, 1878–1945, Fig. 4.5) studied surface waves from earthquakes, was the director of an observatory in Samoa for several years, and in 1928 became the successor of Wiechert as head of the Institute of Geophysics at Göttingen University.

- Ludwig Carl Geiger (Swiss, 1882–1966, Fig. 4.5) made many contributions to seismology, most notably by developing a method to determine the epicenter of an earthquake.

- Beno Gutenberg (German, 1889–1960) was one of Wiechert's greatest students at the Göttingen Institute of Geophysics, and he continued to conduct geophysics research after he obtained his doctorate in 1911. Gutenberg built upon all of the Institute's work up to that time by developing a system of quantifying earthquake energy, and also by making major contributions to the knowledge of the Earth's interior structure and convective circulation in the Earth's mantle (Fig. 4.6). Due to rising antisemitism in Germany, in 1930 Gutenberg moved to the California Institute of Technology and founded the Seismological Laboratory there. In the United States, the name of one of Gutenberg's American students, Charles Richter, became associated with the earthquake energy scale that had been developed by Gutenberg and that was based on decades of German seismological work at Göttingen. As a result, Richter's name has been immortalized with the "Richter scale," and the work of Gutenberg and all of his predecessors back to Emil Wiechert has been largely forgotten by the general public.

- Gustav Herglotz (German, 1881–1953, Fig. 4.5) worked with Emil Wiechert to develop equations for the velocities and travel times of seismic waves in the Earth (the Wiechert-Herglotz method). He also made many important contributions to applied mathematics and relativistic physics.

- Ludger Mintrop (German, 1880–1956, Fig. 4.5) invented seismic methods of exploring for oil and minerals, using his own specially designed vibrometers and seismographs. His work revolutionized oil drilling and minerals mining industries worldwide. During World War I, he developed seismic methods to locate the position of enemy artillery guns.

- Wilhelm Schlüter (German?, 1875–1902, Fig. 4.5) invented the clinograph for measuring changes in the angle of inclination of a slope. He used his new instrument to demonstrate that long waves from earthquakes are not linear oscillations that vibrate in one direction, but rather elliptical oscillations that vibrate around an elliptical pattern in two dimensions.

- Karl Bernhard Zoeppritz (German, 1881–1908, Fig. 4.5) developed the Zoeppritz equations for calculating the propagation and reflection of S and P seismic waves. He probably would have gone on to make many more important discoveries in geophysics, but unfortunately he died from an infection when he was only 26 years old.

Loránd Eötvös (Hungarian, 1848–1919) and Felix Vening Meinesz (Dutch, 1887–1966) developed increasingly sensitive gravitational gradiometers for mapping the mass distribution of underlying geological structures; see Fig. 4.7.

Alexander von Humboldt (Prussian, 1769–1859, Fig. 4.8) pioneered geomagnetic mapping, making and recording measurements of the Earth's magnetic field in his travels around the world [Wulf 2015]. He discovered that the strength of the magnetic field increases as one travels from the equator toward the poles. He also coined the term "physical geography," which later became known as geophysics.

Carl Friedrich Gauss (German states, 1777–1855) and Wilhelm Weber (German, 1804–1891), shown in Fig. 4.8, greatly improved geomagnetic mapping. They invented more accurate instruments for measuring the strength and direction of the magnetic field, established a society to make magnetic measurements around the world, and developed mathematical methods (potential theory) for analyzing the results to locate magnetic sources and to distinguish magnetic sources inside the Earth from those outside the Earth [Dunnington 1955]. (See also pp. 793, 828, 858, and 972.)

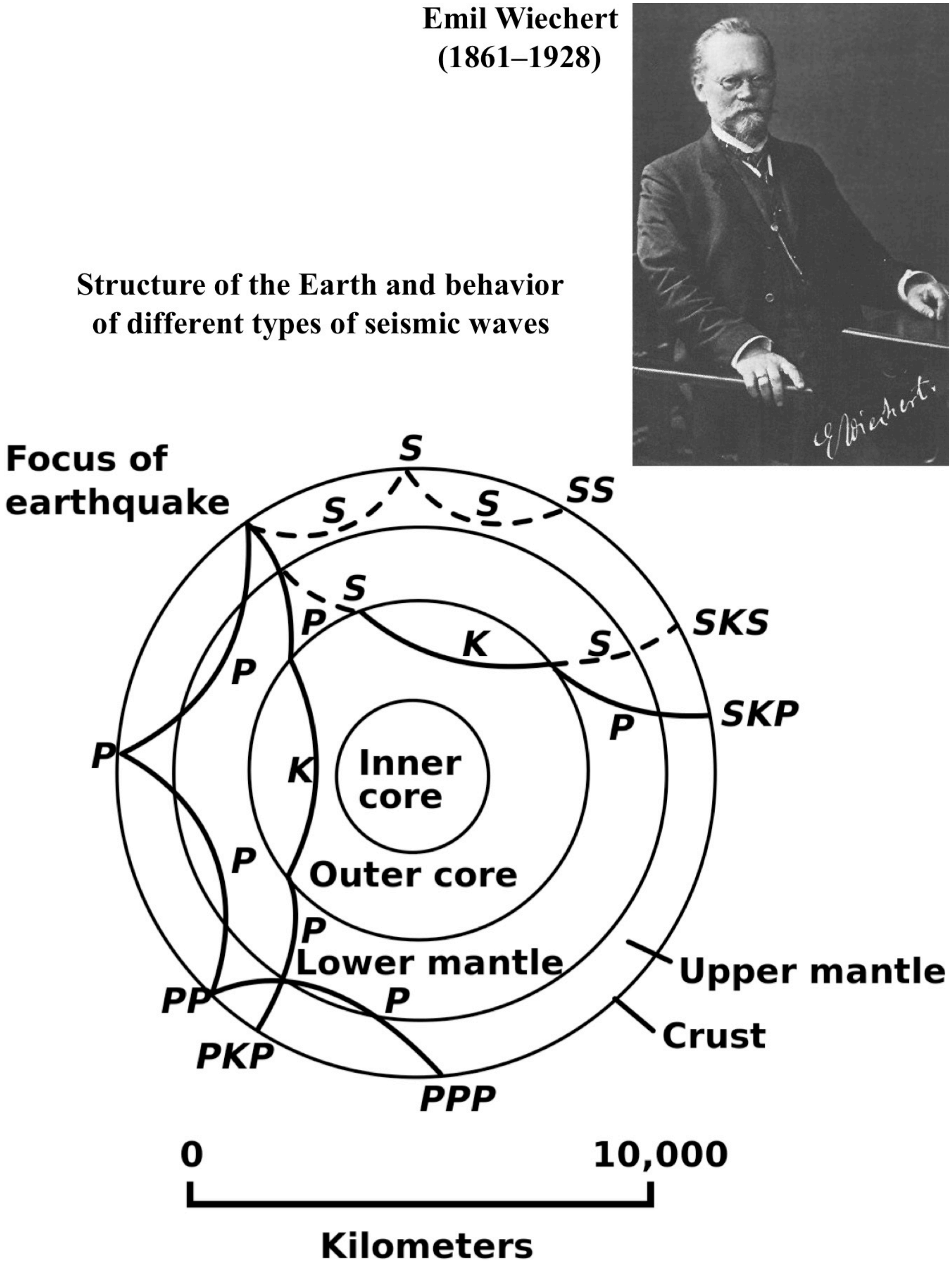
Julius Bartels (German, 1899–1964) and Gerhard Fanselau (German, 1904–1982) also made detailed studies of the Earth's magnetic field (Fig. 4.9).

Educated at Göttingen University and building upon all of that earlier German work on geomagnetism and geophysics, Walter Elsasser (German, 1904–1991) developed the dynamo model that explains how the Earth's magnetic field is generated by the Earth's core (Fig. 4.9). Though sadly little remembered now, Elsasser made strikingly innovative contributions to multiple scientific fields, including methods of calculating the "magic numbers" of protons and neutrons required to fill different energy levels of the atomic nucleus (p. 1535) [Rubin 1995]. The *Encyclopedia Britannica* praised his many revolutionary insights [EB 2010]:

> Elsasser received the Ph.D. from the University of Göttingen in 1927[...]
>
> While Elsasser was a graduate student he correctly predicted that a beam of electrons would be diffracted by a crystalline material; after the neutron was discovered, he predicted the same behaviour for neutrons. Independently of Nobel Prize winner Hans Bethe, Elsasser carried out important work on the likelihood of certain interactions between neutrons and atomic nuclei.
>
> Elsasser formulated what is called the dynamo model of the Earth's structure to account for the origin and properties of its magnetic field. He suggested that convection within the core, driven by the energy of radioactive decay, generates electric currents that

> intereract with concentric spherical shells of the Earth's mantle, which are rotating at different speeds, and that the Coriolis effect produces eddies at the boundaries of these shells.
>
> He also investigated the applicability of contemporary theoretical concepts of physics, especially quantum mechanics, to the biological sciences, presenting his views in *The Physical Foundation of Biology* (1958), *Atom and Organism* (1966), and *The Chief Abstractions of Biology* (1975).

As illustrated in Fig. 4.10, Victor Goldschmidt (Swiss, 1888–1947) founded the field of geochemistry, and Walter Hermann Bucher (German, 1888–1965) made major contributions to structural geology and paleontology.



Emil Wiechert (1861–1928)

Structure of the Earth and behavior of different types of seismic waves

Figure 4.4: Emil Wiechert established the detailed study of the structure of the Earth and the behavior of different types of seismic waves passing through parts of the Earth.

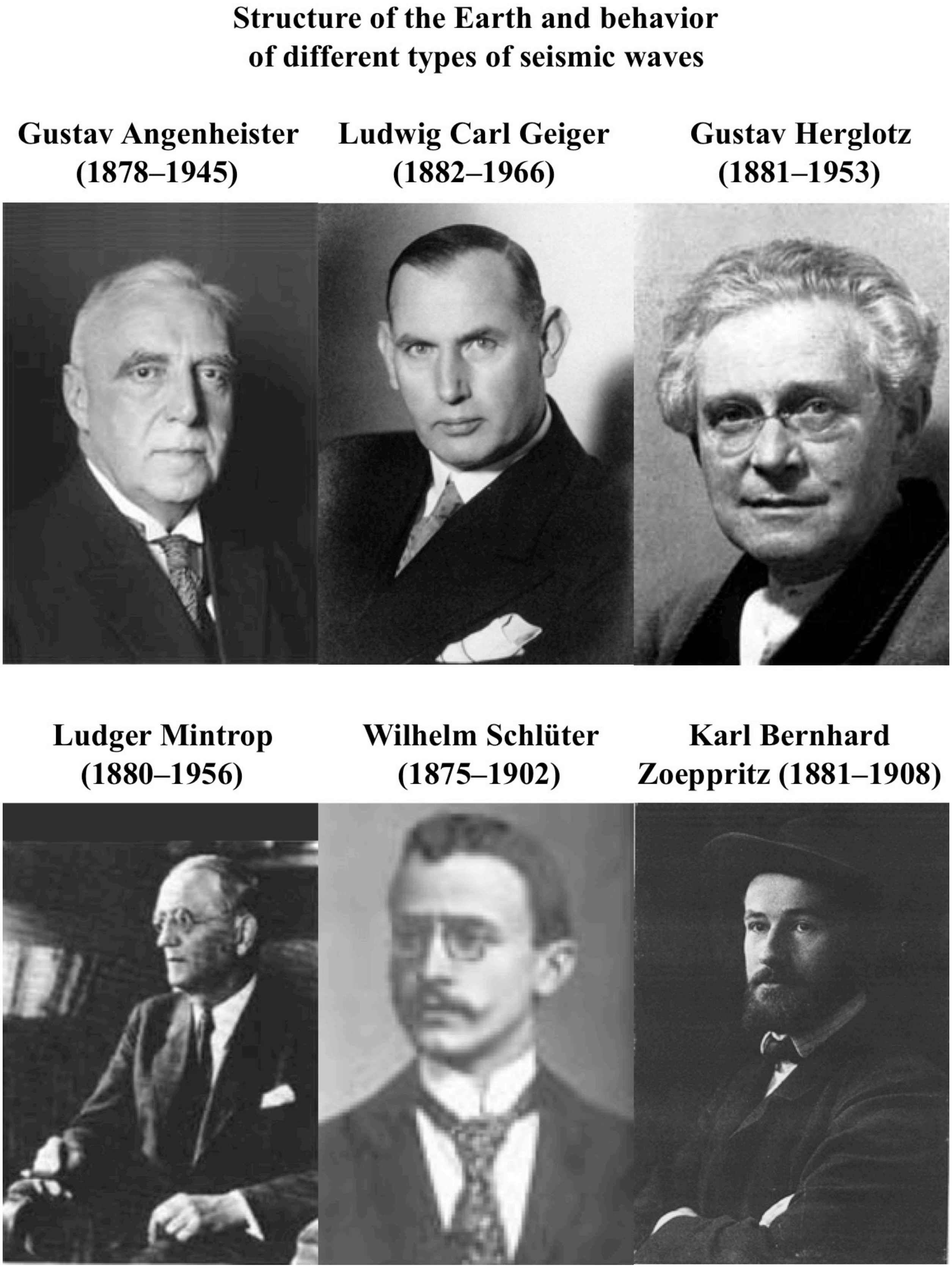
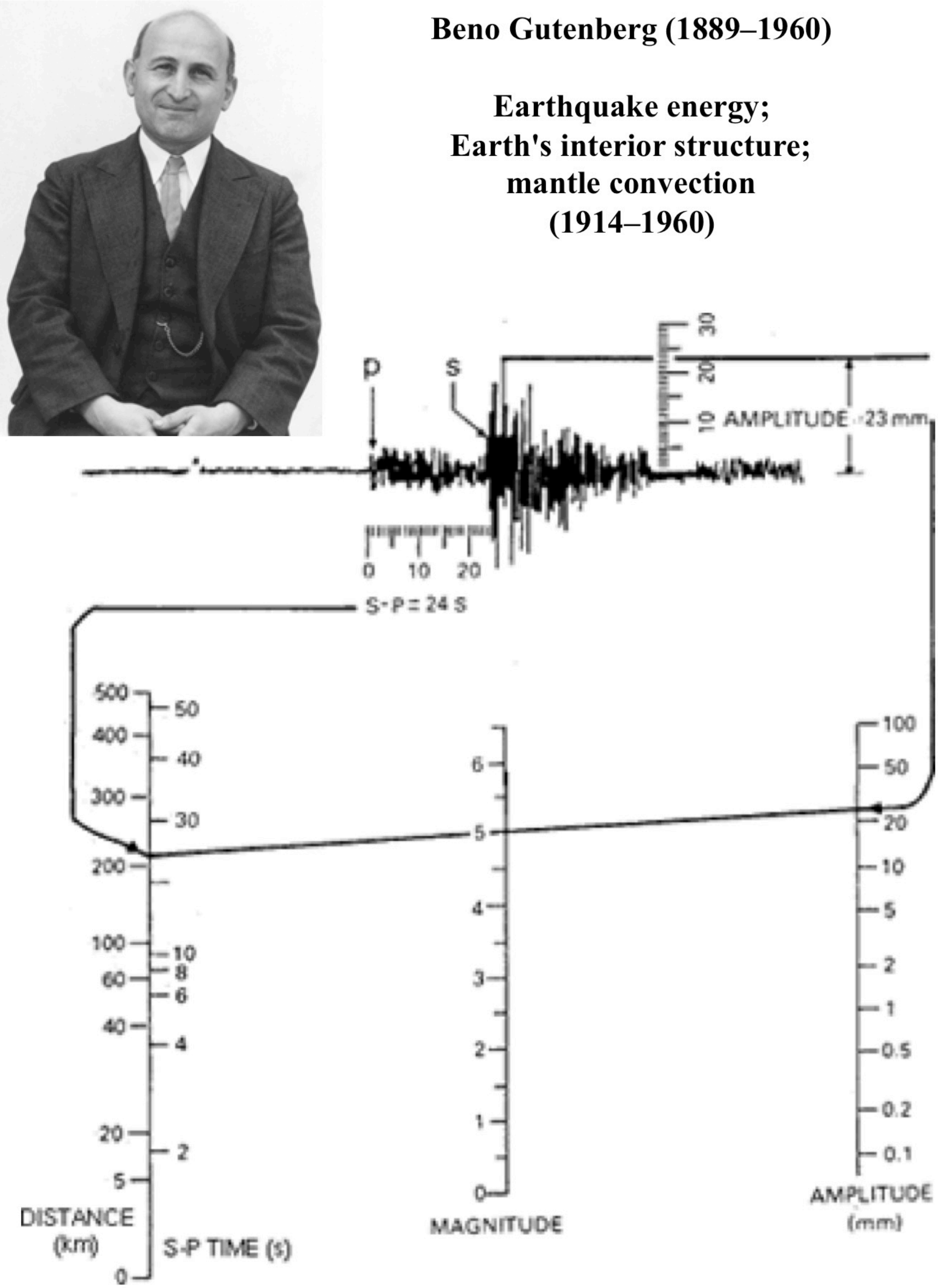


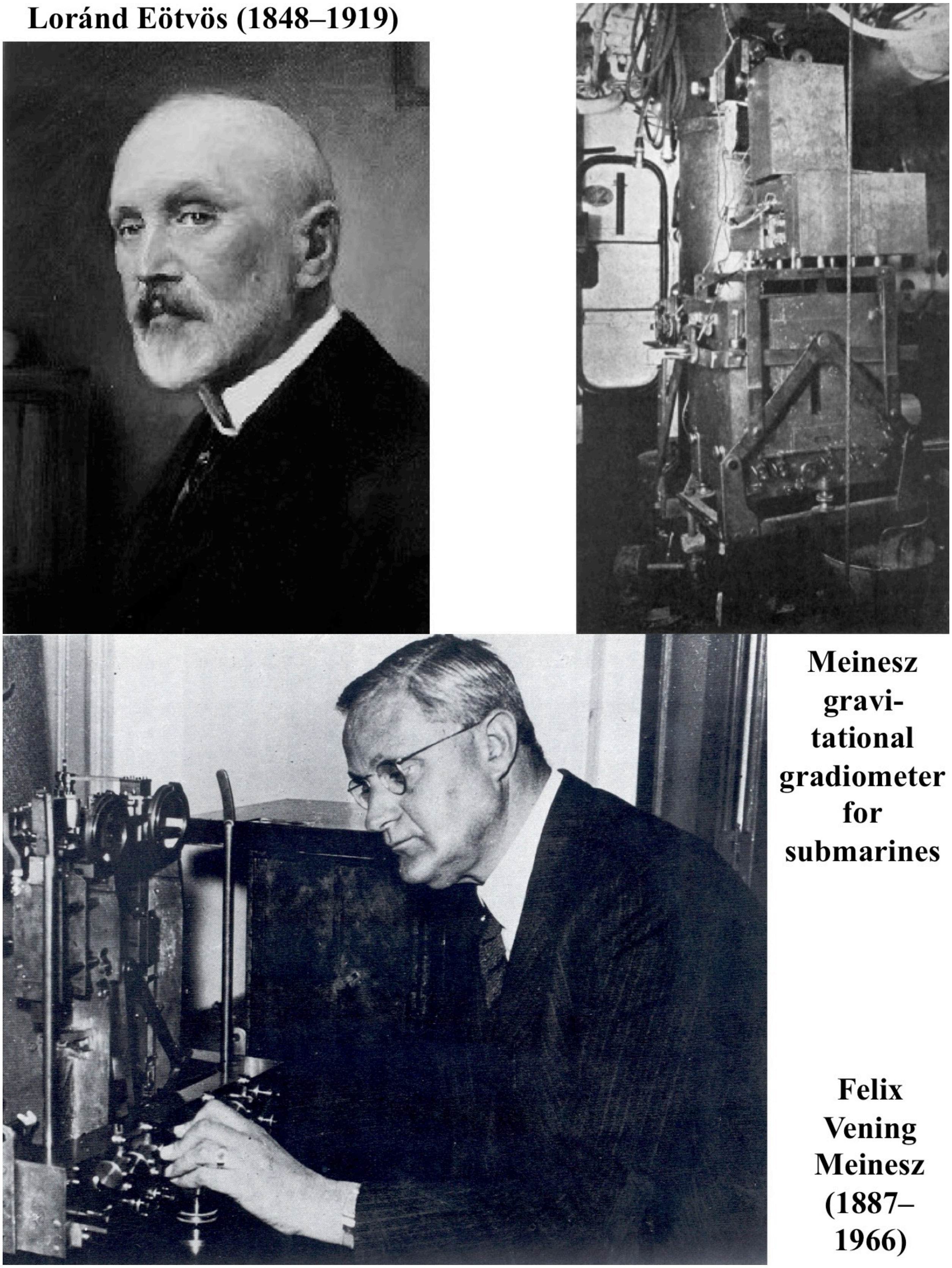
Figure 4.5: Some other creators who made major contributions to knowledge of the structure of the Earth and the behavior of different types of seismic waves included Gustav Angenheister, Ludwig Carl Geiger, Gustav Herglotz, Ludger Mintrop, Wilhelm Schlüter, and Karl Bernhard Zoeppritz.



Beno Gutenberg (1889–1960)

**Earthquake energy;
Earth's interior structure;
mantle convection
(1914–1960)**

Figure 4.6: Beno Gutenberg developed a system of quantifying earthquake energy. He also made major contributions to knowledge regarding the Earth's interior structure and convective circulation in the Earth's mantle (1914–1960).



Loránd Eötvös (1848–1919)

Meinesz gravitational gradiometer for submarines

Felix Vening Meinesz (1887–1966)

Figure 4.7: Loránd Eötvös and Felix Vening Meinesz developed increasingly sensitive gravitational gradiometers for measuring the mass of underlying geological structures.

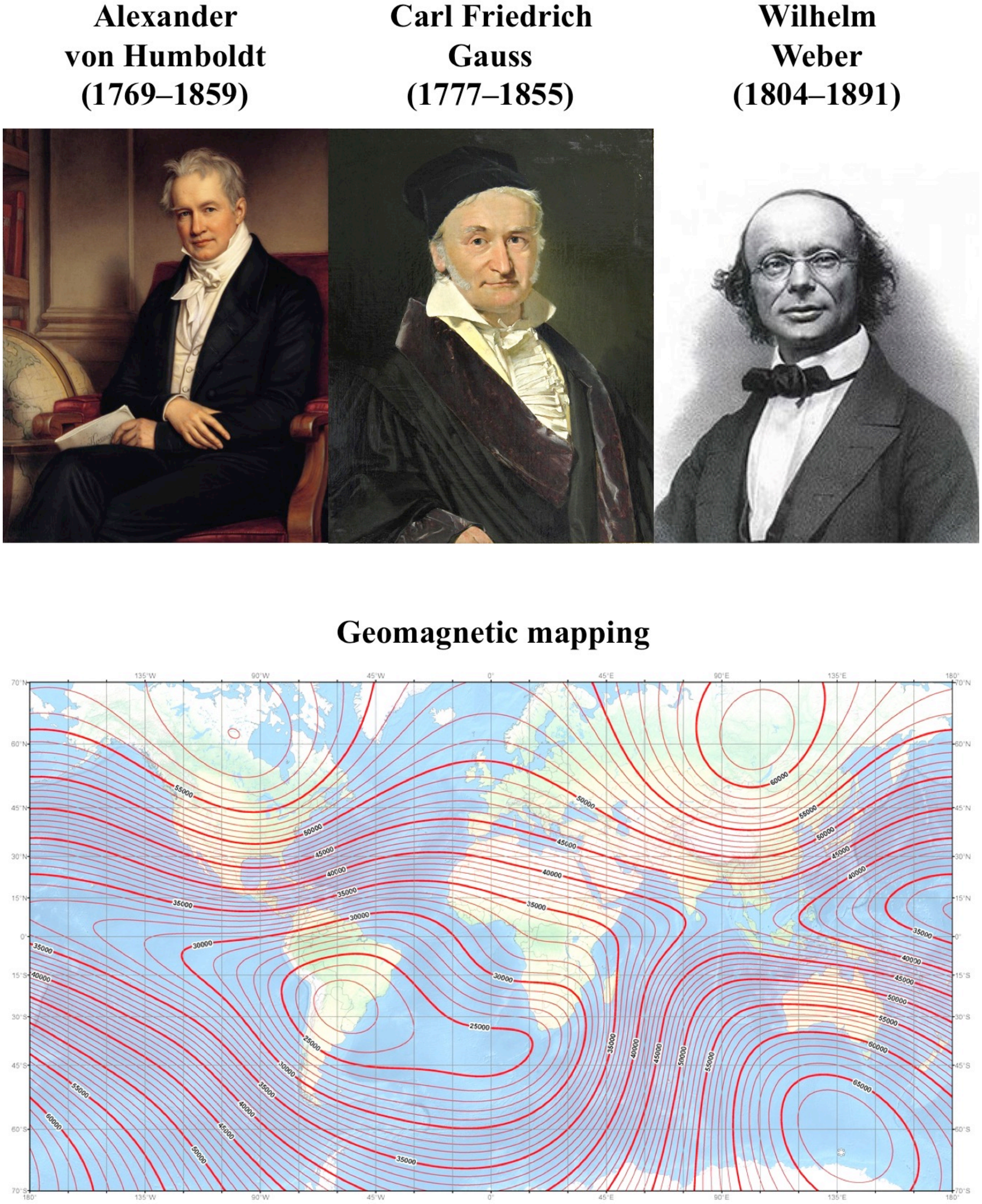


Figure 4.8: Alexander von Humboldt, Carl Friedrich Gauss, and Wilhelm Weber developed geomagnetic mapping.

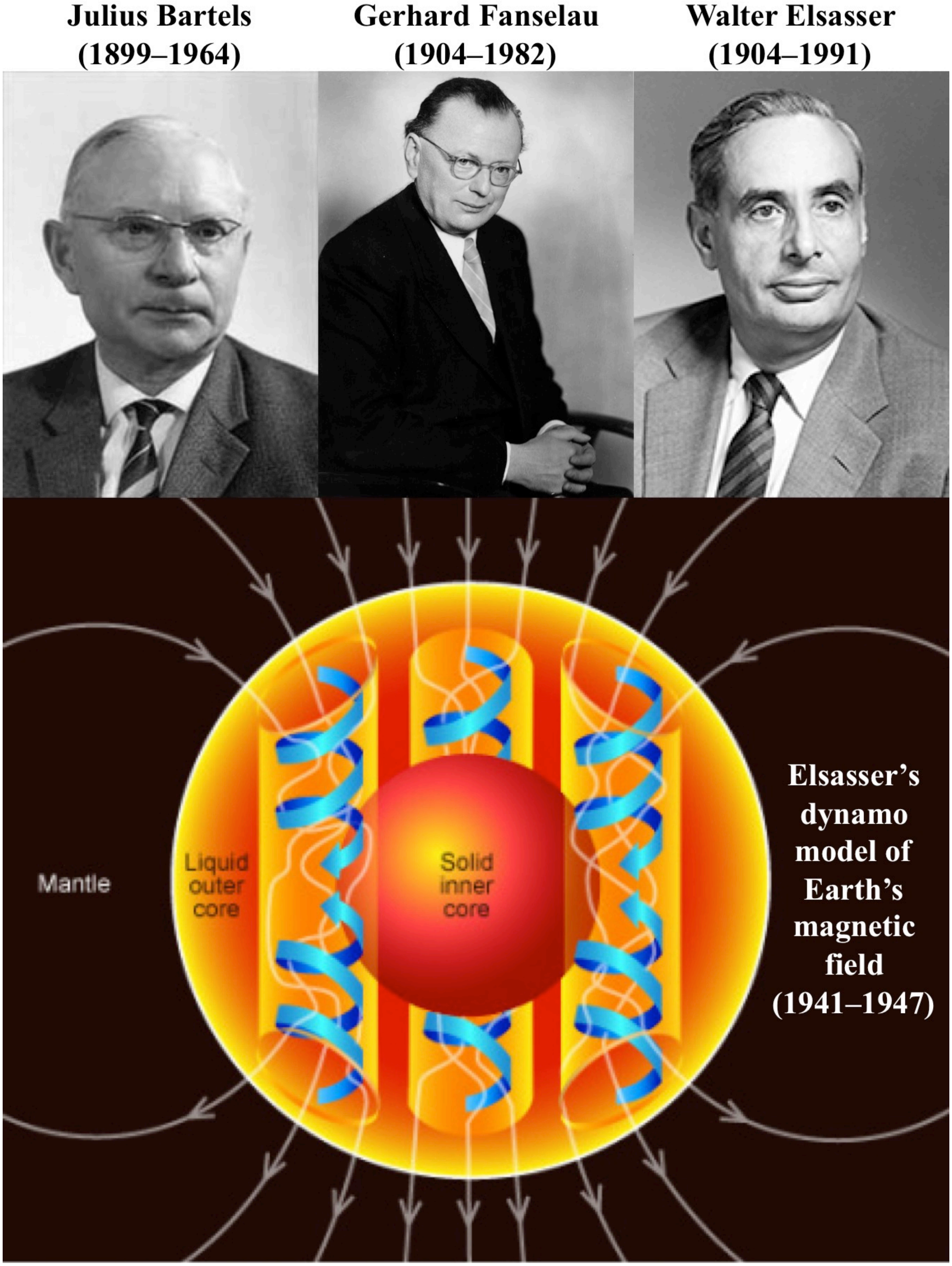


Figure 4.9: Julius Bartels and Gerhard Fanselau made detailed studies of the Earth's magnetic field, and Walter Elsasser developed the dynamo model that explains how the Earth's magnetic field is generated (1941–1947).

Victor Goldschmidt
(1888–1947, right)
founder of geochemistry

Walter Hermann Bucher
(1888–1965)
structural geology,
paleontology

Figure 4.10: Victor Goldschmidt founded the field of geochemistry, and Walter Hermann Bucher made major contributions to structural geology and paleontology.

4.1.3 Universal Transverse Mercator (UTM) for Map Coordinates

German-speaking creators also developed the Universal Transverse Mercator (UTM) projection system for map coordinates, which is now used worldwide for the Global Positioning System (GPS) [Buchroithner and Pfahlbusch 2016]. Official histories have claimed that the UTM system was developed by the United States after World War II, but cartographers Manfred Buchroithner and René Pfahlbusch discovered evidence that the UTM system was developed in Germany before and during World War II, and seized by the United States at the end of the war:

> Recent discoveries of Wehrmacht Maps in the Military Archive of the Federal Archive of Germany in Freiburg im Breisgau raised the motivation for further investigations into the history of the internationally employed Universal Transverse Mercator (UTM) projection which actually represents a prerequisite for the global use of Global Positioning System (GPS)—and thus of any type of navigation—instruments. In contrast to the frequently stated opinion that this map projection was first operationally used by U.S. Americans it turned out that presumably the first operational maps with indication of the orthogonal UTM grid were produced by German Wehrmacht officers prior to the post World War (WW) II triumph of this projection. Based on the authors' recent discoveries this article reveals some hitherto hardly known facts concerning the history of cartography of the 1940s. [...]
>
> With the complete military occupation of Germany through the Allied Forces in spring 1945 the largest part of the German geodetic documents and records stored in the Thuringian temporary evasion quarters of the "Reichsamt für Landesaufnahme" (RfL, Reich Office for Surveying) and the "Kriegskartenhauptamt" (Main Office for Military Maps) fell into the hands of the American troops. The U.S. Army Map Service (AMS) immediately examined these "German Materials, as they came to be called" (Cloud 2002, 264, cum lit.) and recognized its value. Since Thuringia was by negotiation provided as part of the Soviet Occupation Zone, all the material and the expert staff was evacuated to Bamberg in the American Occupation Zone. Directly after the war (Bamberg Conference in June 1945), with cooperation of staff members of the former RfL, a new geodetic "armaments program" for Europe began. Leading members of the mapping activities of the Deutsches Reich, last not least of the Reconnaissance Unit "Dora" and the "Forschungsstaffel zur besonderen Verwendung" (Research Squadron for Special Deployment) were, during the first months and years after the war, interrogated by the Americans.
>
> In his memoirs, Wolfgang Pillewizer (1911–1999), first member of the Reconnaissance Unit "Dora" and then of the "Forschungsstaffel zur besonderen Verwendung" (cf. Stams 2012) and as chair holder of cartography predecessor of the first author of this article, describes in considerable detail the interrogations of himself and also other members of the Reconnaissance Unit "Dora" and the "Research Squadron for Special Deployment" by OSS, the Office of Strategic Services, the then military secret service (Pillewizer 1986). In his book and later during oral communications with the prime author in the 1990s, he also mentioned that one task of the "Forschungsstaffel" was the mapping of possible "extension areas" of the Deutsches Reich, and that immediately after the war OSS chased him and subsequently kept him detained in Kransberg Castle, Germany,

over 16 months for interrogations about his cartographic activities in Eastern Europe and outside Europe (cf. also Häusler 2007b; Buchroithner, Koch, and Stams 2012). There, not only thematic but also geometric questions of the cartographic work were subject of the questioning. [...]

Early German research and development results were adopted by the Soviet Union in the 1930s and later by the USA and gained worldwide recognition—last not least through the introduction of the UTM system by the NATO member states in 1951. The end of the Cold War and the release of the military satellite navigation system of NATO for civilian purposes led to its final breakthrough. This implies that today almost all industrialized countries use for their authoritative map series a geodetic coordinate system which has its origin, for the most essential part, in Germany. In the twenty-first century, in a world of ubiquitous application of GPS at a global scale, UTM Projection became simply a *conditio sine qua non* for everyday life.

4.2 Paleontology

Scientists from the German-speaking world made many valuable contributions to areas of paleontology including:[2]

4.2.1. Animal and plant fossils

4.2.2. Hominid fossils

4.2.3. Biogeography

4.2.1 Animal and Plant Fossils

Friedrich von Alberti (German, 1795–1878), shown in Fig. 4.11, identified and characterized Triassic rock strata and their fossils, as well as the preceding large Permian-Triassic extinction event, and the following Triassic-Jurassic extinction event. He published the results of those studies in 1834. He also greatly improved salt mining and salt processing by introducing a process of steam heating.

Christian Leopold von Buch (German states, 1774–1853, Fig. 4.12) similarly characterized Jurassic rock strata and their fossils, and also explained igneous rock formation. He created the first geological map of Germany in 1826.

As shown in Fig. 4.13, Karl Häberlein (German?, 18??–19??), Hermann von Meyer (German states, 1801–1869), and Wilhelm Dames (German, 1843–1898) discovered and analyzed *Archaeopteryx* specimens, which are important transitional fossils for bird evolution (1861–1884) [Chambers 2002; Wellnhofer 2008]. Hermann von Meyer also discovered *Plateosaurus*, an important step in the evolution of sauropod dinosaurs, and Wilhelm Dames also studied whale evolution.

The American Council of Learned Societies described von Meyer's importance in the field of paleontology [ACLS 2000, p. 602]:

> His main scientific area of interest was the fossil vertebrates, and his chief work was *Fauna der Vorwelt* (4 vols., 1845). He considered all types of vertebrates and was one of the most distinguished scientists in the field; his descriptions were characterized by great accuracy and clarity of expression.

Ernst Stromer (German, 1871–1952, Fig. 4.14) led an important expedition to Egypt to excavate Cretaceous deposits, and he spent much of the rest of his career analyzing his finds in Germany. Through this material, Stromer discovered *Spinosaurus* and several other Cretaceous dinosaurs along with many non-dinosaur species. Unfortunately almost all of his fossil collection was destroyed when the Munich museum housing it was bombed by the Allies in 1944 [Nothdurft and Smith 2002; Probst 2015].

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[2] Bowler 1993; Chambers 2002; Colbert 1984; Hesse 1924, 1937; Javanović-Kruspel 2015; Nothdurft and Smith 2002; Probst 2015; Wellnhofer 2008; Wulf 2015.

Louis Agassiz (Swiss, 1807–1873, Fig. 4.15) studied in Germany and worked in Switzerland before eventually moving to the United States, where he helped to build up the field of paleontology from his post at Harvard. He found and analyzed a wide variety of fossils over the course of his career.

Heinrich Ernst Beyrich (German, 1815–1896, Fig. 4.15) discovered many Cenozoic fossils and named the Oligocene epoch of the Cenozoic era.

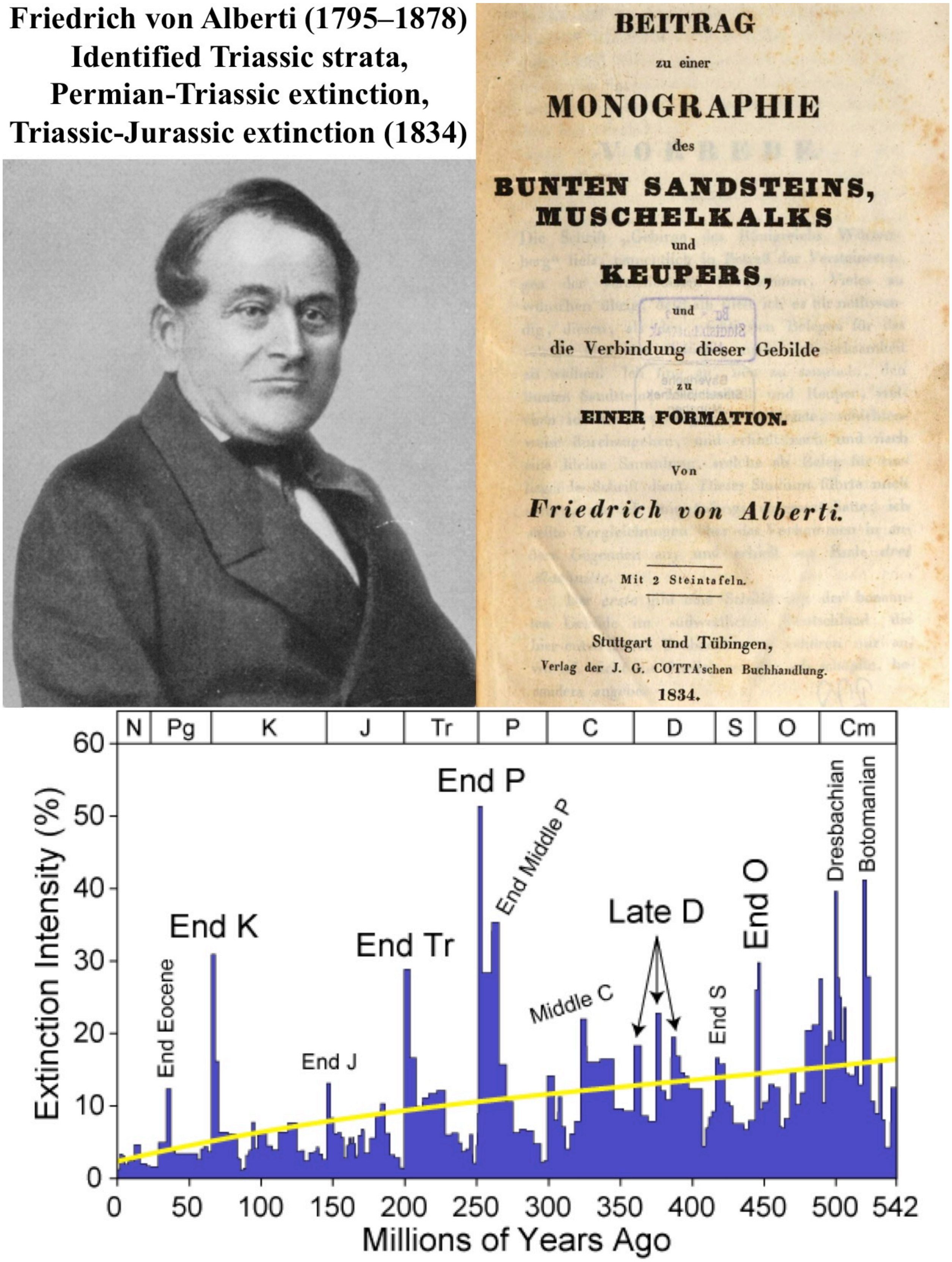
Johanna "Tilly" Edinger (German, 1897–1967, Fig. 4.15) founded the field of paleoneurology, the study of brain structure and brain evolution from endocasts preserved inside some fossil skulls. Oxford University's *Biographical Dictionary of Scientists* emphasized the importance of Edinger's research [Porter 1994, p. 201]:

> Edinger was a leading figure in the field of twentieth-century vertebrate palaeontology and laid the foundations for the study of palaeoneurology. In her two great works *Die fossilen Gehirne* (Fossil Brains) (1929) and *The Evolution of the Horse Brain* (1948) she demonstrated that the evolution of the brain could be studied directly from fossil cranial casts.

Hanns Bruno Geinitz (German, 1814–1900, Fig. 4.15) collected and analyzed fossils from Europe, Asia, and North America, and discovered a wide variety of Paleozoic and Mesozoic species.

Friedrich von Hüne (German, 1875–1969, Fig. 4.15) discovered fossils of many new species of dinosaurs, other reptiles, and amphibians, and worked to reclassify previously discovered fossil species in a much more systematic fashion. Edwin Colbert, a curator of paleontology at the American Museum of Natural History, praised von Hüne's accomplishments [Colbert 1984, pp. 108–109]:

> Von Huene was wholeheartedly interested in the dinosaurs; during his lifetime he became one of the great authorities on these reptiles. [...]
>
> He has spent many decades in the study of fossil reptiles, with a singleness of purpose and a degree of industry that are truly amazing. The volume of his publications through the years is prodigious, and his contributions to our knowledge of fossil reptiles are numerous and significant. They include papers on reptilian relationships and classification, descriptions of dinosaurs from all over the world, investigations of various Mesozoic marine reptiles, especially ichthyosaurs, and other technical studies too numerous to mention. [...]
>
> He has been noted for his activity in the field, traveling all over the world to study and collect fossil reptiles—not only in his native Germany but also in other parts of Europe, in North America, in Brazil, in Argentina, in Africa, and in Asia.



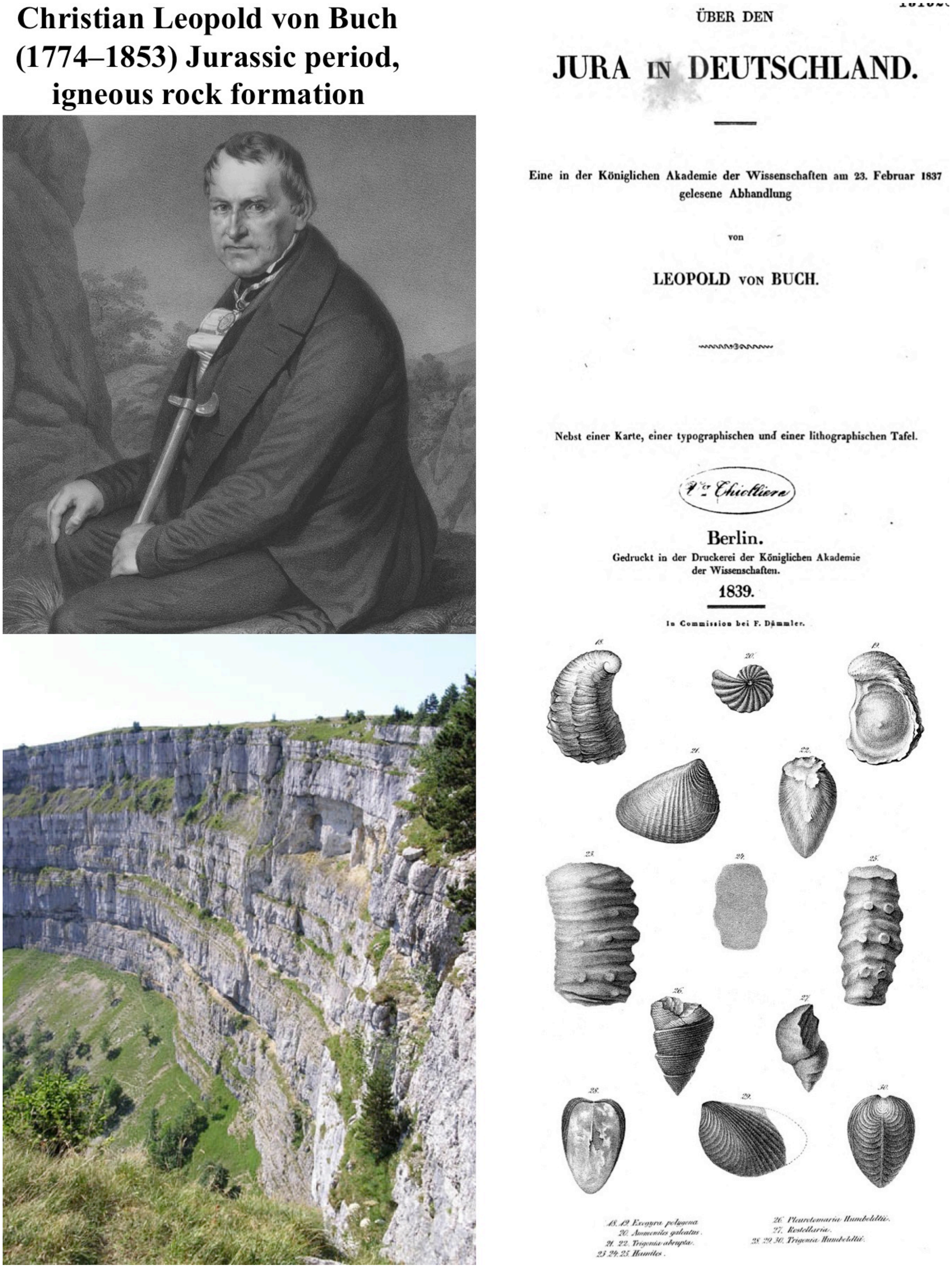
BEITRAG
zu einer
MONOGRAPHIE
des
BUNTEN SANDSTEINS,
MUSCHELKALKS
und
KEUPERS,
und
die Verbindung dieser Gebilde
zu
EINER FORMATION.

Von
Friedrich von Alberti.

Mit 2 Steintafeln.

Stuttgart und Tübingen,
Verlag der J. G. COTTA'schen Buchhandlung.
1834.

Figure 4.11: Friedrich von Alberti identified and characterized Triassic rock strata and their fossils, the preceding Permian-Triassic extinction, and the following Triassic-Jurassic extinction (1834).



ÜBER DEN

JURA IN DEUTSCHLAND.

Eine in der Königlichen Akademie der Wissenschaften am 23. Februar 1837
gelesene Abhandlung

von

LEOPOLD VON BUCH.

Nebst einer Karte, einer typographischen und einer lithographischen Tafel.

Vve Chiclliere

Berlin.
Gedruckt in der Druckerei der Königlichen Akademie
der Wissenschaften.
1839.

In Commission bei F. Dümmler.

Figure 4.12: Christian Leopold von Buch characterized Jurassic rock strata and their fossils, and also explained igneous rock formation.

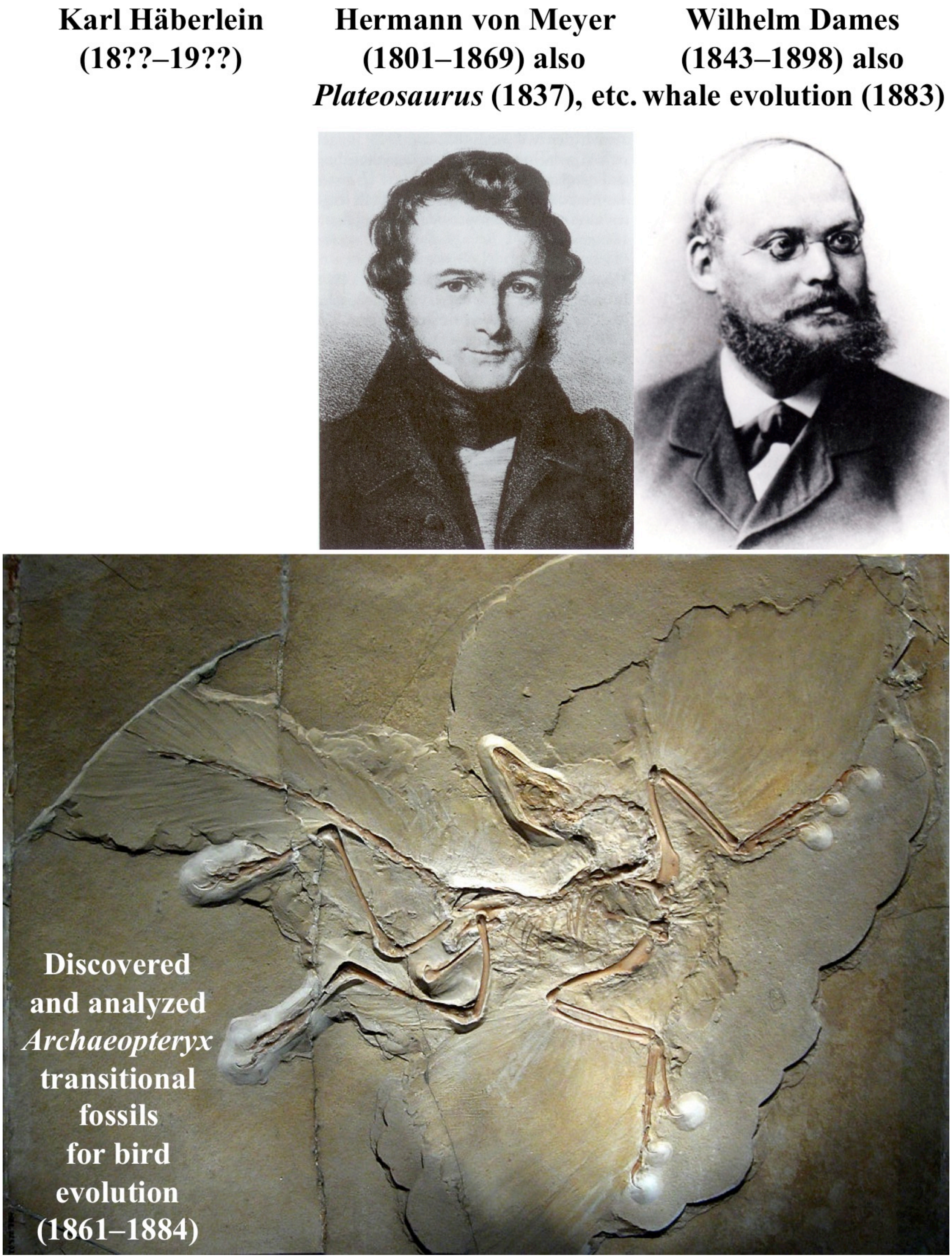


Figure 4.13: Karl Häberlein, Hermann von Meyer, and Wilhelm Dames discovered and analyzed *Archaeopteryx* specimens, which are important transitional fossils for bird evolution, during the period 1861–1884.

Ernst Stromer (1871–1952)

Paläozoologisches Praktikum

von

Ernst Stromer

Mit 6 Textabbildungen

Berlin
Verlag von Gebrüder Borntraeger
W 35 Schöneberger Ufer 12a
1920

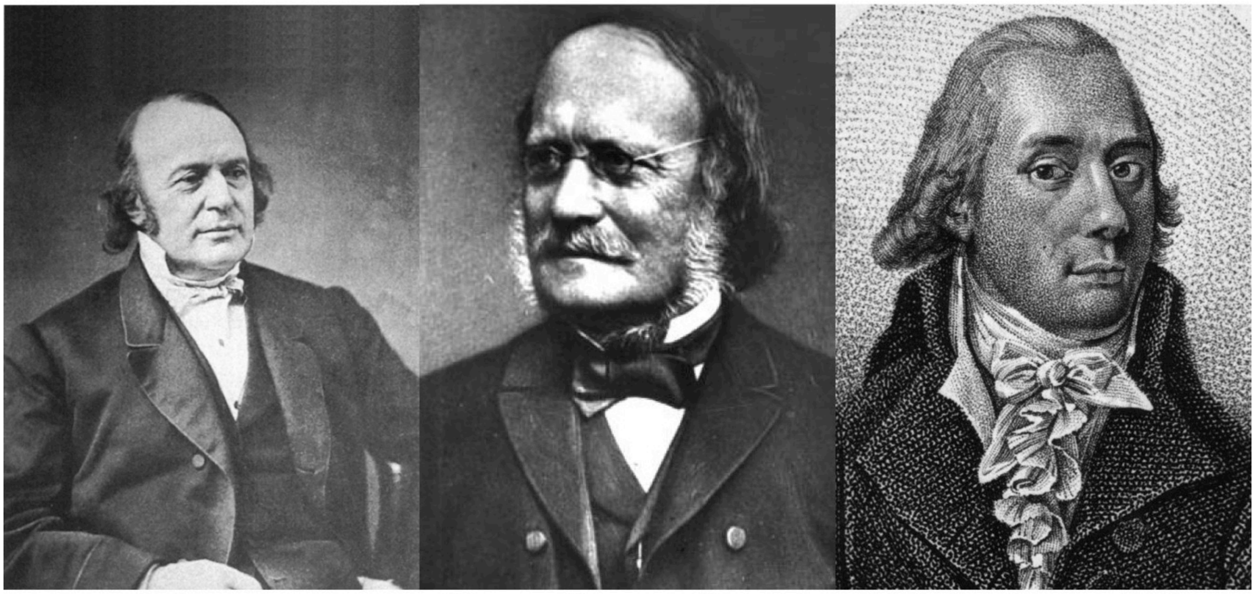
Spinosaurus and other Cretaceous dinosaurs

Figure 4.14: Ernst Stromer discovered Spinosaurus and other Cretaceous dinosaurs.

Louis Agassiz (1807–1873) found and analyzed a wide variety of fossils

Heinrich Ernst Beyrich (1815–1896) discovered many Cenozoic fossils

Johann Blumenbach (1752–1840) developed the foundations of anthropology



Johanna "Tilly" Edinger (1897–1967) founded paleoneurology

Hanns Bruno Geinitz (1814–1900) discovered a wide variety of Paleozoic and Mesozoic fossils

Friedrich von Hüne (1875–1969) discovered many dinosaurs, other reptiles, and amphibians

Figure 4.15: Other creators who made important discoveries in paleontology included Louis Agassiz, Heinrich Ernst Beyrich, Johann Blumenbach, Johanna "Tilly" Edinger, Hanns Bruno Geinitz, and Friedrich von Hüne.

4.2.2 Hominid Fossils

Many important discoveries in human evolution were made by scientists from the greater German-speaking world.

Johann Blumenbach (German states, 1752–1840, Fig. 4.15) developed the foundations of the field of anthropology, studying the skeletal remains and evidence of the lifestyles of prehistoric humans worldwide.

Marie Eugène Dubois (Dutch, 1858–1940) discovered the first fossils of *Homo erectus* (dubbed "Java Man") in 1891; see Fig. 4.16. *Homo erectus* was a widespread and tremendously important ancestor of modern *Homo sapiens*. Franz Weidenreich (German, 1873–1948) and Ralph von Königswald (German, 1902–1982) discovered and analyzed additional *Homo erectus* fossils.

As shown in Fig. 4.17, in 1907 Otto Schoetensack (German, 1850–1912) and Daniel Hartmann (German?, 18??–19??) discovered the first fossils of *Homo heidelbergensis*, which was either a direct ancestor or a close cousin of modern humans.

Johann Fuhlrott (German, 1803–1877) and Hermann Schaaffhausen (German, 1816–1893) discovered the first fossils of *Homo neanderthalensis* in 1856 (Fig. 4.18). *Homo neanderthalensis* or Neanderthals were a sophisticated species of humans that existed in parallel with *Homo sapiens* for thousands of years, then disappeared for reasons that are still unclear.

Hugo Obermaier (German, 1877–1946) made important discoveries regarding the migrations, tools, and cave paintings of humans during the Ice Ages, as illustrated in Fig. 4.19.

4.2.3 Biogeography

As shown in Fig. 4.20, several creators made major contributions to the field of biogeography, or the worldwide distributions of modern species.

Alexander von Humboldt (Prussian, 1769–1859) collected and compared plant samples from around the world, as illustrated in Fig. 4.20. He published many books on his discoveries and thereby helped to establish the field of biogeography. He also made important measurements of geomagnetism in his travels around the world [Wulf 2015].

Christian Ehrenberg (German, 1795–1876) collected zoological, botanical, and microbiological specimens, and studied the comparative anatomy of samples from Europe, the Middle East, and around the world.

Richard Hesse (German, 1868–1944) published *Tiergeographie auf Ökologischer Grundlage* in 1924. Together with its 1937 revised English edition, *Ecological Animal Geography*, that book had an enormous impact in advancing the field of biogeography [Hesse 1924, 1937].

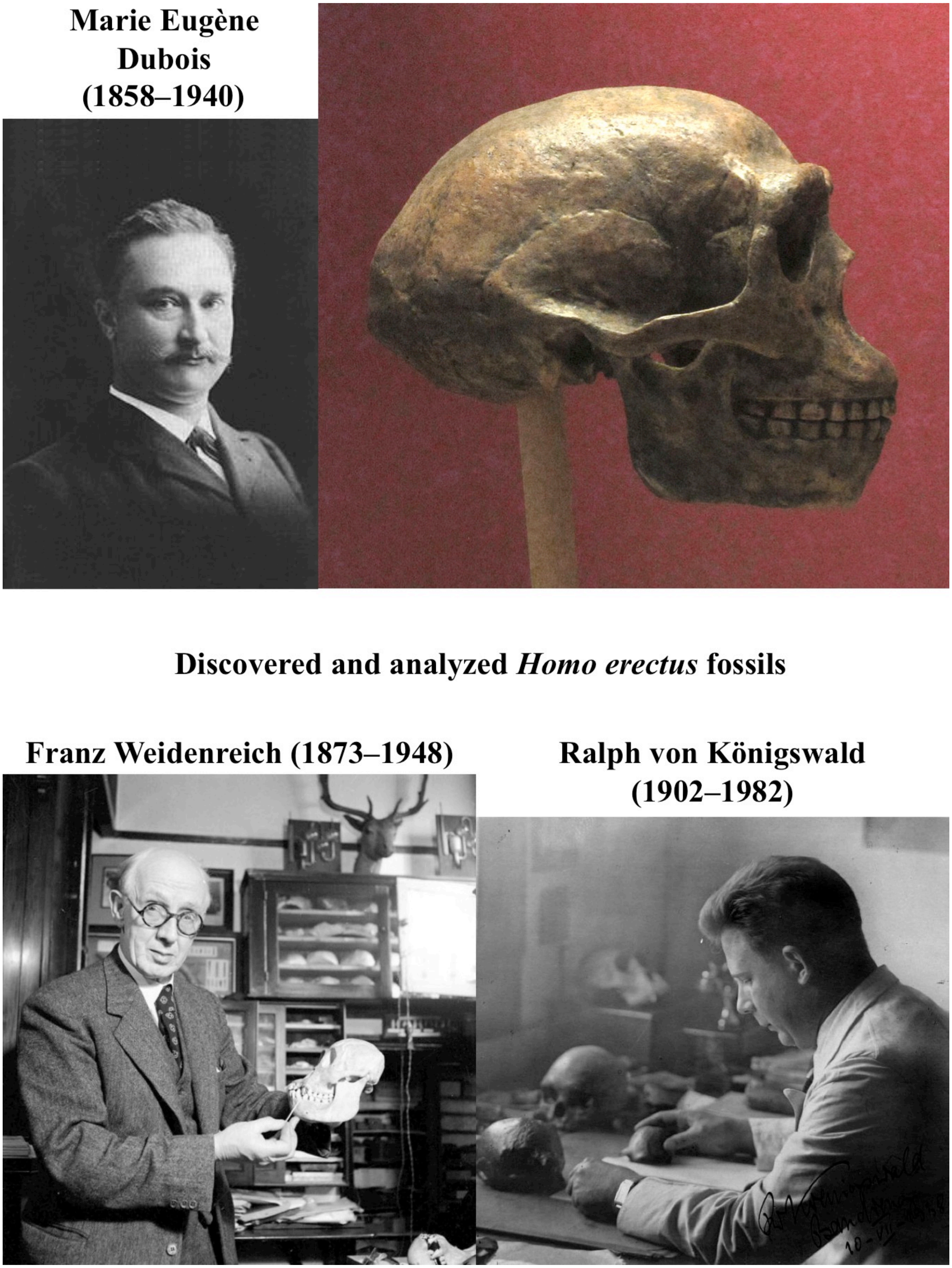


Figure 4.16: Marie Eugène Dubois, Franz Weidenreich, and Ralph von Königswald discovered and analyzed *Homo erectus* fossils.

Otto Schoetensack (1850–1912) **Daniel Hartmann (18??–19??)**

Discovered *Homo heidelbergensis* (1907)

Figure 4.17: Otto Schoetensack and Daniel Hartmann discovered *Homo heidelbergensis* in 1907.

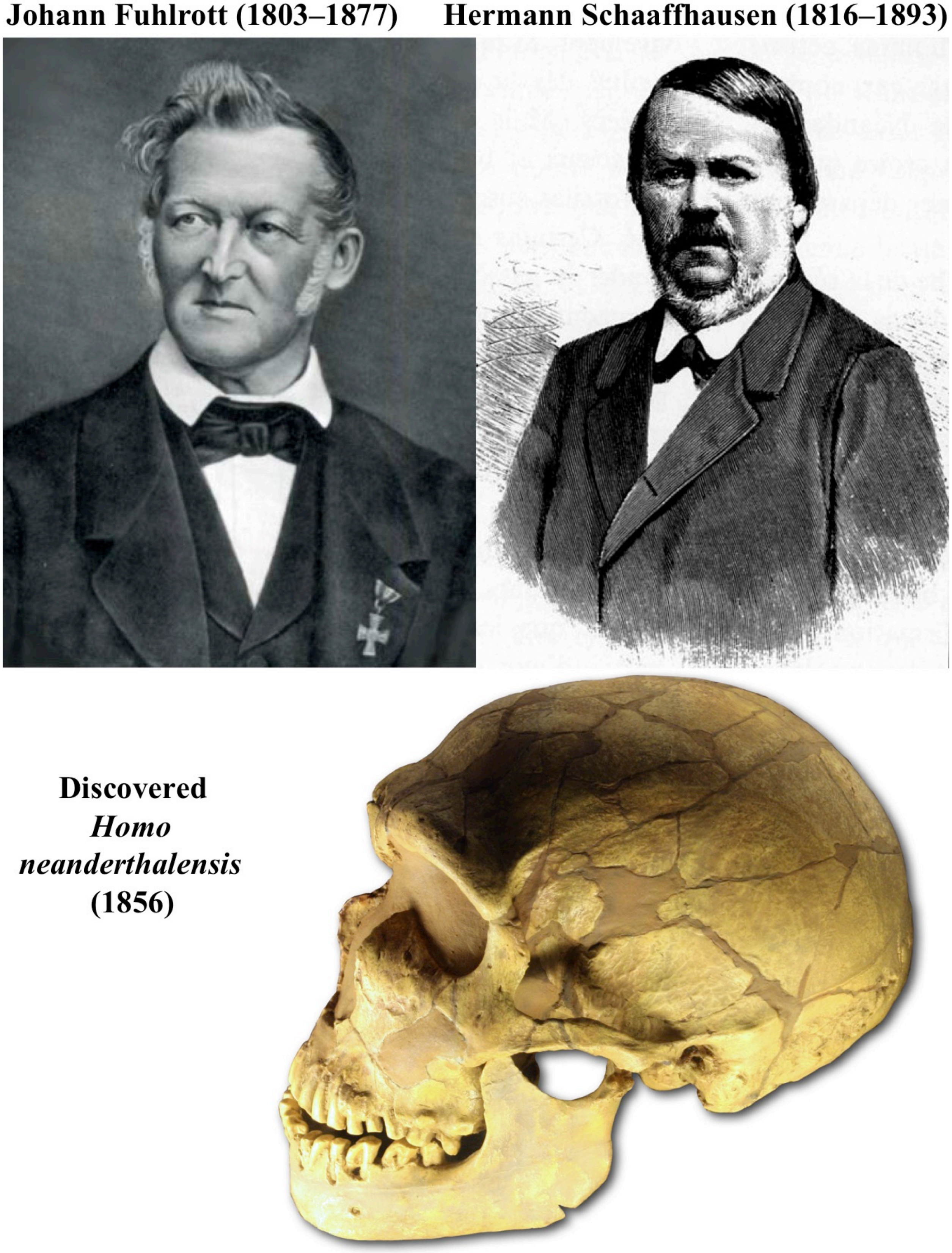


Figure 4.18: Johann Fuhlrott and Hermann Schaaffhausen discovered *Homo neanderthalensis* in 1856.

Figure 4.19: Hugo Obermaier made important discoveries regarding the migrations and the tools of humans during the Ice Ages.

Alexander von Humboldt (1769–1859, also geomagnetism)

Christian Ehrenberg (1795–1876)

Richard Hesse (1868–1944)

Biogeography

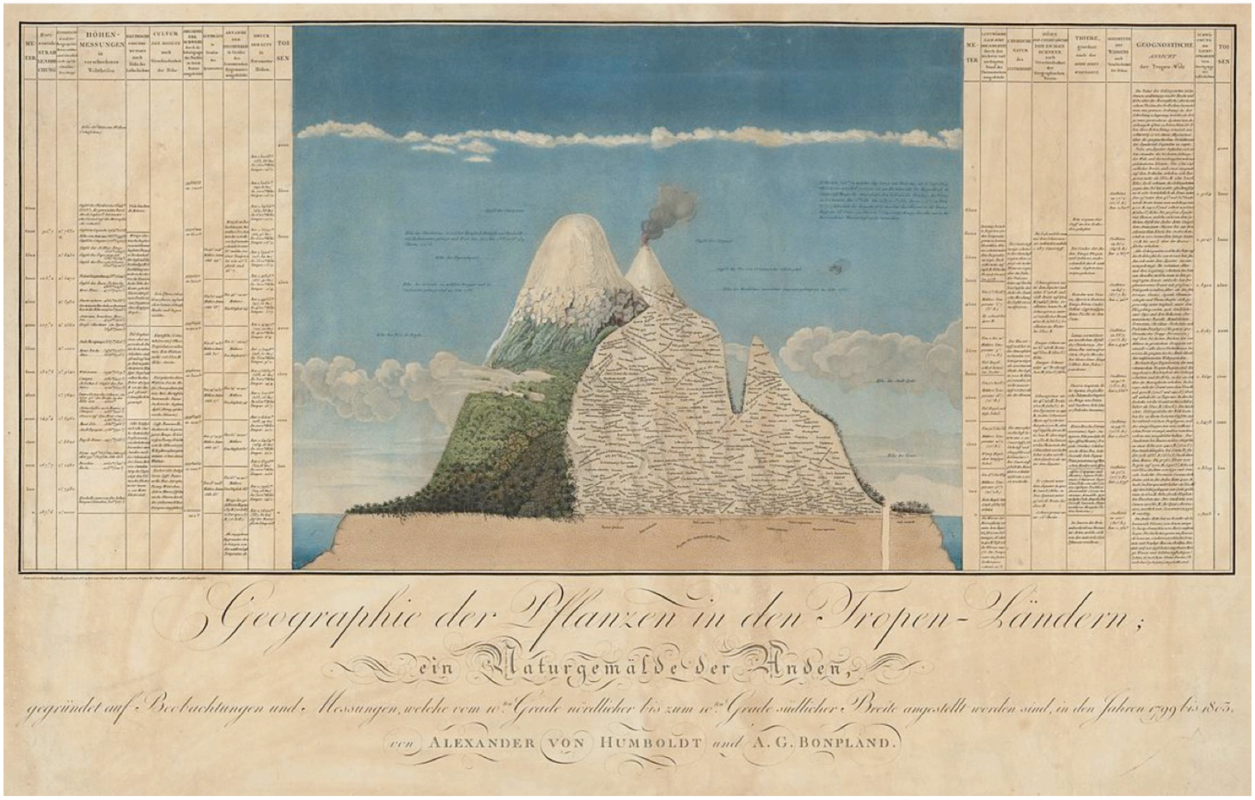


Figure 4.20: Creators who made major contributions to the field of biogeography, or the worldwide distributions of modern species, included Alexander von Humboldt, Christian Ehrenberg, and Richard Hesse.

4.3 Ocean and Hydrological Science

German-speaking scientists made major contributions to ocean and hydrological sciences and related areas, including:[3]

4.3.1. Oceanography

4.3.2. The discovery and exploration of Antarctica

4.3.3. Evidence for the Ice Ages

4.3.1 Oceanography

Heinrich Georg von Boguslawski (German, 1827–1884, Fig. 4.21) coauthored the *Handbuch der Ozeanographie* [*Handbook of Oceanography*] with Otto Krümmel. It appeared in 1884–1887 in two large volumes covering all major aspects of ocean spatial distribution, physical properties, chemistry, circulation, etc., and became the standard reference work on the subject for many decades, including later updates.

Carl Chun (German, 1852–1914, Fig. 4.21) led expeditions in the *Valdivia* research ship (Fig. 4.23) and made important discoveries regarding deep sea life, marine invertebrates, and subarctic seas.

Carl Wilhelm Correns (German, 1893–1980, Fig. 4.21) was the world's leading expert in marine sediments [BIOS 1368]. He collected sediments on marine expeditions in the 1920s, and used new methods such as X-ray diffraction to analyze them in his laboratory in the 1930s. He was the son of the biologist Karl Correns (p. 107). The American Council of Learned Societies described some of his accomplishments [ACLS 2000, pp. 209–210]:

> A pioneer in modern sedimentary petrology, he found that clays are not amorphous substances but mixtures of well-defined crystalline minerals such as kaolinite, halloysite, montmorillonite, and mica materials. With samples from the bottom of the South Atlantic, he developed methods for dividing sediments into grain size classes that could be investigated by optical microscopy, X-ray diffraction, and chemical analysis.

Albert Defant (Austrian, 1884–1974, Fig. 4.21) founded the field of physical oceanography and was an expert on the physics of the ocean, the atmosphere, and the interactions between the two. He was one of the main scientists on the *Meteor* oceanographic research ship.

Günter Dietrich (German, 1911–1972, Fig. 4.21) helped to refine the comprehensive understanding of ocean tides, currents, and circulation.

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[3] von Boguslawski and Krümmel 1884–1887; Bowler 1993; Spiess 1985.

Felix Anton Dohrn (German, 1840–1909, Fig. 4.21) established the model of marine biological research stations, especially with a station on the Gulf of Naples (Stazione Zoologica, initiated in 1871). The American Council of Learned Societies described the importance of his work [ACLS 2000, p. 256–257]:

> Primary contribution was the establishment of the Zoological Station in Naples: not only the first laboratory set up specifically for marine studies, but also the first institute formally organized for the sole pursuit of research. The station was conceived by Dohrn in 1870, and the doors opened in February 1874. [...M]any important pioneering experimental investigations were carried out. Especially significant were studies in comparative physiology and experimental embryology, which became the foundations of whole new sciences.

Ernst Ehrenbaum (German, 1861–1942, Fig. 4.22) made major contributions to systematic ichthyology as well as the study of marine invertebrates.

Vagn Walfrid Ekman (1874–1954, Fig. 4.22) was Swedish but worked very closely with German expeditions, providing oceanographic measuring instruments and conducting theoretical calculations to compare with the measured data. Many oceanographic properties are named after him: the Ekman layer, Ekman number, Ekman pumping, Ekman spiral, Ekman transport, etc.

Otto Krümmel (German, 1854–1912, Fig. 4.22) coauthored the *Handbuch der Ozeanographie* [*Handbook of Oceanography*] with Heinrich Georg von Boguslawski, completing the first edition after von Boguslawski's death and then updating it later. Some of Krümmel's greatest contributions involved the study of ocean currents and circulation patterns (Fig. 4.24).

Alfred Merz (Austrian, 1880–1925, Fig. 4.22) was a pioneer of oceanography and was the first chief scientist for the *Meteor* research ship (Fig. 4.23).

Friedrich (Fritz) Spiess (German, 1881–1959, Fig. 4.22) championed the funding and execution of oceanographic research, and he planned and commanded the expeditions of the *Meteor* research ship.

Georg Wüst (German, 1890–1977, Fig. 4.22) studied ocean circulation and was one of the main scientists on the *Meteor* research ship.

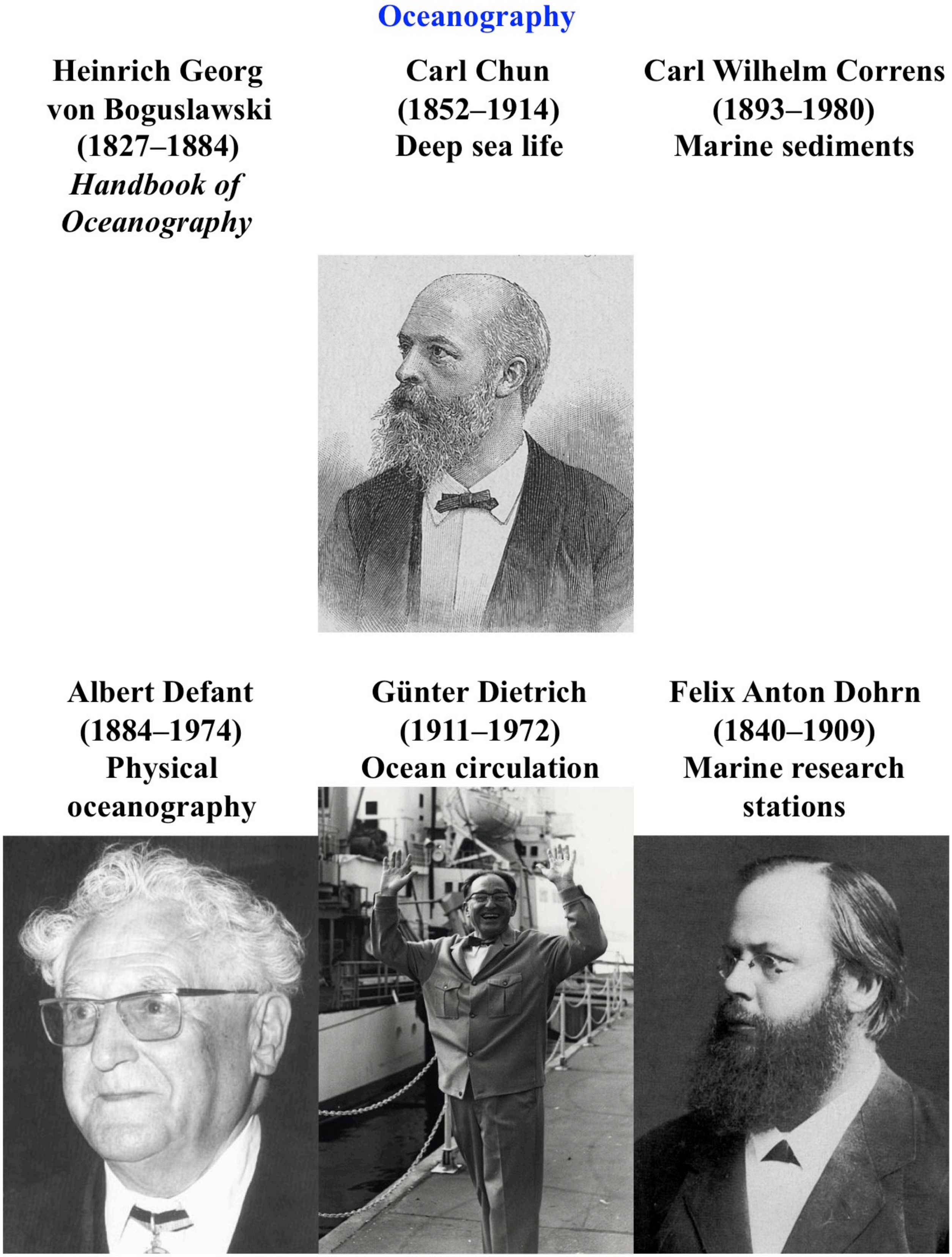


Figure 4.21: Some important creators in oceanography included Heinrich Georg von Boguslawski, Carl Chun, Carl Wilhelm Correns, Albert Defant, Günter Dietrich, and Felix Anton Dohrn.

Oceanography

Ernst Ehrenbaum
(1861–1942)
Ichthyology

Vagn Ekman
(1874–1954)
Measuring instruments and calculations

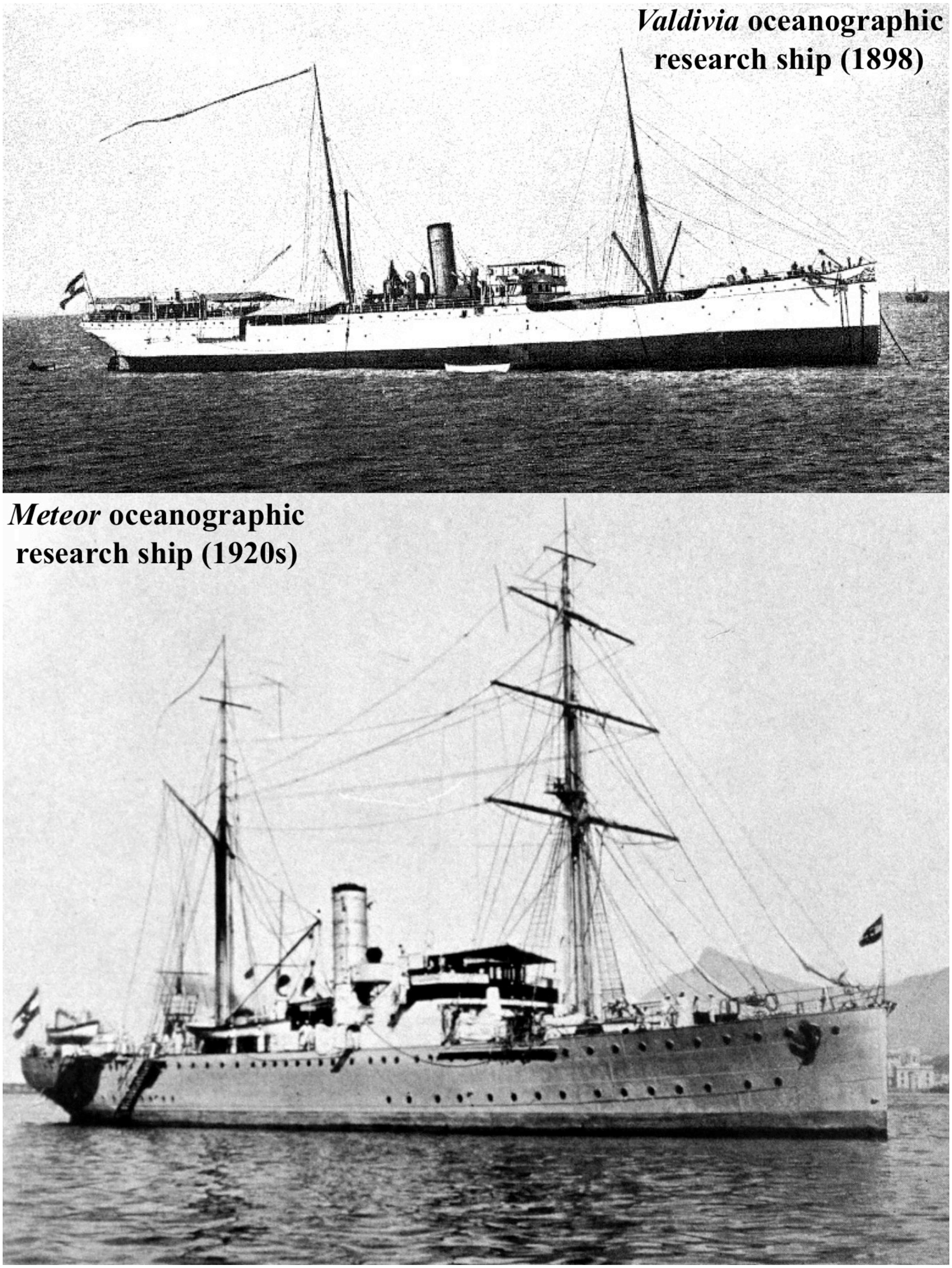
Otto Krümmel
(1854–1912)
Handbook of Oceanography

Alfred Merz
(1880–1925)
Oceanography

Friedrich (Fritz) Spiess
(1881–1959)
Oceanographic expeditions

Georg Wüst
(1890–1977)
Ocean circulation

Figure 4.22: Other important creators in oceanography included Ernst Ehrenbaum, Vagn Ekman, Otto Krümmel, Alfred Merz, Friedrich (Fritz) Spiess, and Georg Wüst.



Valdivia oceanographic research ship (1898)

Meteor oceanographic research ship (1920s)

Figure 4.23: Examples of important German oceanographic research ships included the *Valdivia* and the *Meteor*.

Map of Atlantic ocean currents by Otto Krümmel (1883)

Figure 4.24: Map of Atlantic ocean currents by Otto Krümmel from 1883.

4.3.2 Antarctica

German-speaking scientists discovered Antarctica and played a major role in its exploration [Lüdecke 2015; Schön 2004].

Fabian Gottlieb von Bellingshausen (Baltic German, 1778–1852) led an expedition that discovered Antarctica in 1820. He proceeded to circumnavigate Antarctica and to make contact with its coastline at several points along the way; Fig. 4.25 illustrates the route of his expedition. Bellingshausen Island and Bellingshausen Sea near Antarctica are named after him.

Erich von Drygalski (German, 1865–1949, Fig. 4.26) led groups that explored Greenland during 1891–1893 and Antarctica during 1901–1903. In Antarctica, his expedition discovered and named Kaiser Wilhelm II Land and the Gaussberg volcano, and was the first to use a balloon for Antarctic exploration and photography. Drygalski Island in Antarctica is named after him.

Wilhelm Filchner (German, 1877–1957, Fig. 4.26) headed an Antarctic expedition during 1911–1912 that discovered the Luitpold Coast and mapped part of Antarctica. The Filchner-Ronne Ice Shelf in the Antarctic is named for him (and the much later U.S. Ronne expedition from 1947–1948).

Alfred Ritscher (German, 1879–1963, Fig. 4.26) led a major Antarctic expedition during 1938–1939 that mapped a large part of Queen Maud Land. Ritscher Peak and Ritscher Upland in Antarctica are named after him.

4.3.3 Ice Ages

As illustrated in Fig. 4.27, Eduard Brückner (German, 1862–1927) and Albrecht Penck (German, 1858–1945) amassed and correctly interpreted a huge amount of evidence for the Ice Ages, especially from the Alps, from 1901 onward. In 1909, they published their results as the landmark three-volume work, *Die Alpen im Eiszeitalter* [*The Alps in the Ice Age*].

Fabian Gottlieb von Bellingshausen (1778–1852) discovered Antarctica (1820)

Figure 4.25: Fabian Gottlieb von Bellingshausen discovered Antarctica in 1820.

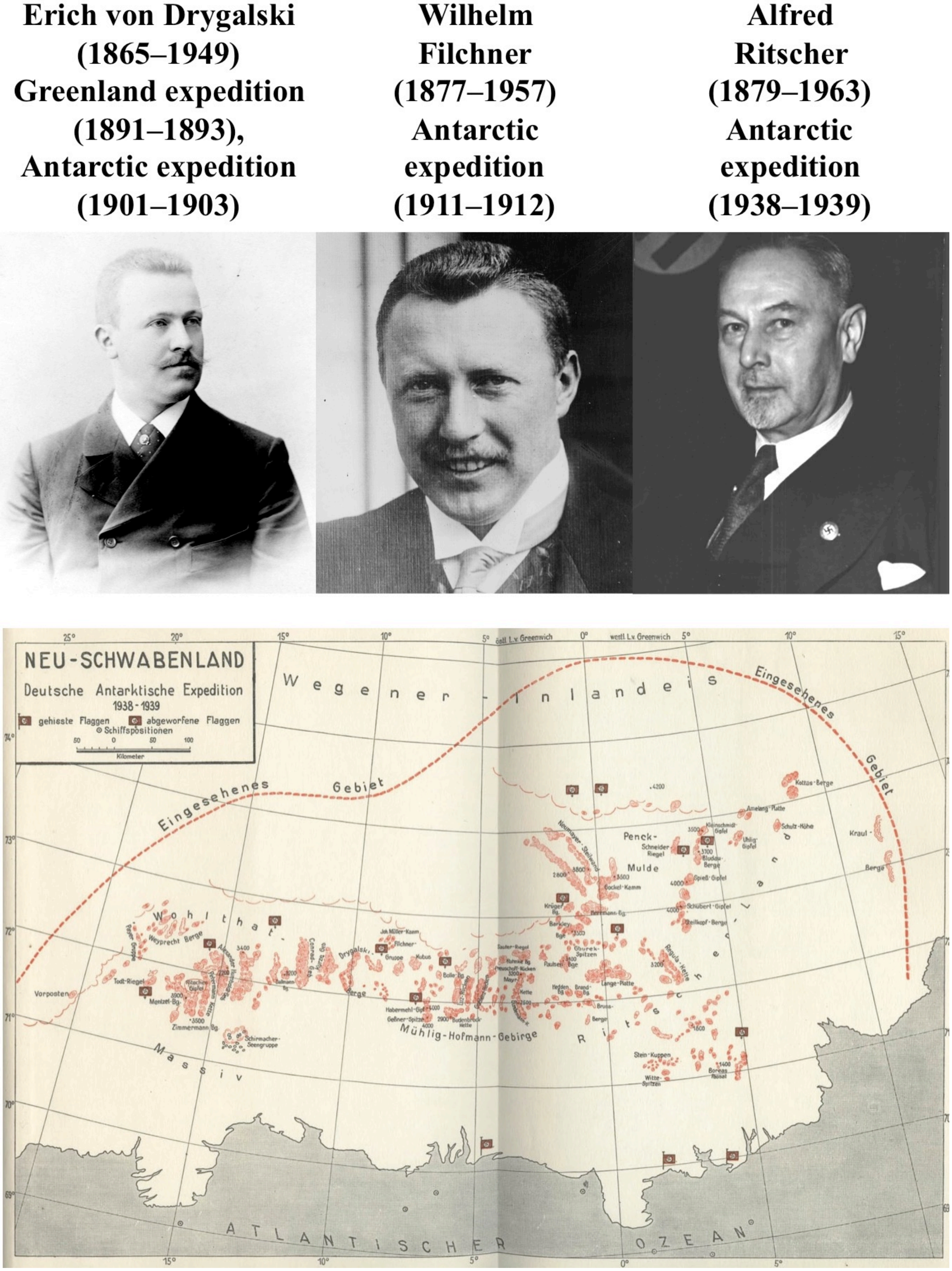
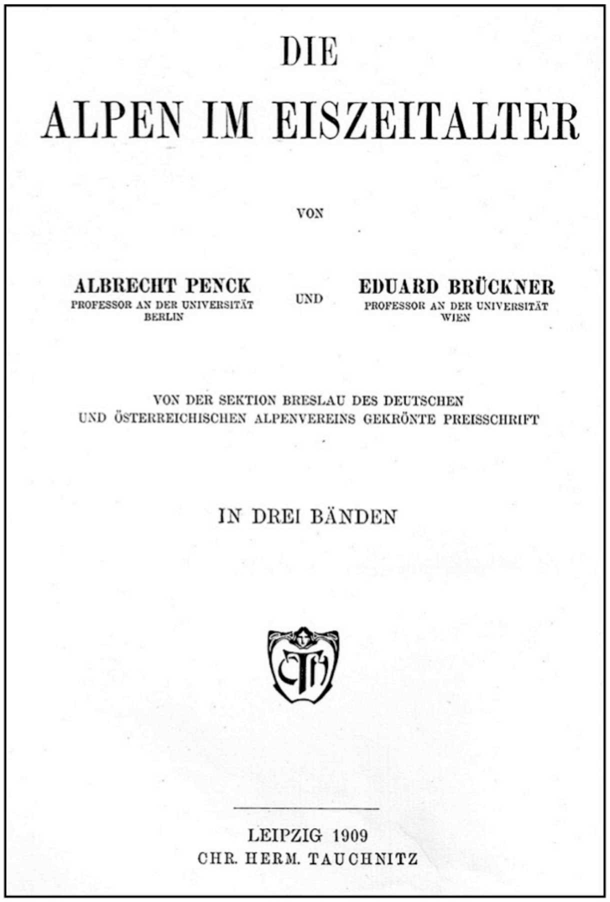


Figure 4.26: Erich von Drygalski led important scientific expeditions to both Greenland and Antarctica. Wilhelm Filchner and Alfred Ritscher led major expeditions to Antarctica.

Eduard Brückner (1862–1927)

Albrecht Penck (1858–1945)

Identified Ice Ages (1901–1909)



DIE
ALPEN IM EISZEITALTER

VON

ALBRECHT PENCK
PROFESSOR AN DER UNIVERSITÄT
BERLIN

UND

EDUARD BRÜCKNER
PROFESSOR AN DER UNIVERSITÄT
WIEN

VON DER SEKTION BRESLAU DES DEUTSCHEN
UND ÖSTERREICHISCHEN ALPENVEREINS GEKRÖNTE PREISSCHRIFT

IN DREI BÄNDEN

LEIPZIG 1909
CHR. HERM. TAUCHNITZ

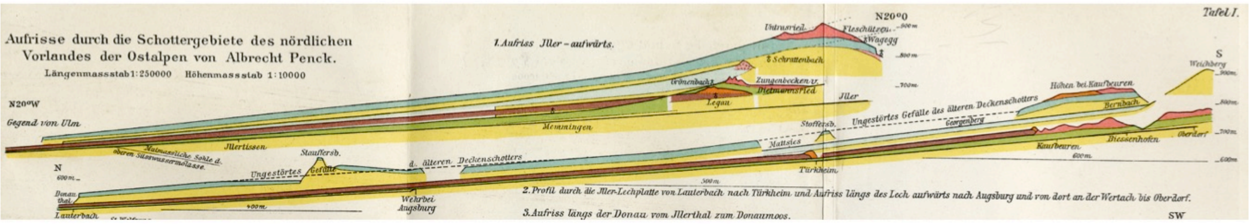


Figure 4.27: Eduard Brückner and Albrecht Penck collected and correctly interpreted evidence for the Ice Ages (1901–1909).

4.4 Atmospheric Science

As shown by the examples in Figs. 4.28–4.34, many creators from the German-speaking world made major discoveries in atmospheric science.[4]

Richard Assmann (German, 1845–1918, Fig. 4.28) published the first weather map for Germany in 1880, invented the Assmann aspiration psychrometer around 1890, and discovered the stratosphere in 1902. He was a strong and effective advocate for meteorology research and education.

Arthur Berson (German, 1859–1942, Fig. 4.28) made measurements of atmospheric conditions and human physiology at high altitudes, and led expeditions to study weather conditions in the Arctic, South America, Africa, and other regions.

Wilhelm von Bezold (German, 1837–1907, Fig. 4.28) made important discoveries regarding atmospheric thermodynamics and thunderstorms, as well as optical illusions (the Bezold effect and the Bezold–Brücke shift).

C. H. D. Buys Ballot (Dutch, 1817–1890, Fig. 4.28) studied the direction of air flow in weather systems (now known as the Buys Ballot law) and the effect of the annual cycle on Earth's atmospheric temperatures (now known as the Buys Ballot table). Even the American Council of Learned Societies deemed his work especially noteworthy, over a century after his death [ACLS 2000, p. 158]:

> [H]is chief accomplishment was to help shape the new field of meteorology by emphasizing and himself collecting data from the widest possible network of simultaneous observations.

Paul Crutzen (Dutch, worked in Germany, 1933–, Fig. 4.28) was instrumental in analyzing and predicting damage to the ozone layer by pollution, climate change effects caused by burning fossil fuels, and the possibility of a nuclear winter created by dust from numerous explosions. He won the Nobel Prize in Chemistry in 1995 for his work on the ozone layer. Professor Ingmar Grenthe of the Royal Swedish Academy of Sciences noted [https://www.nobelprize.org/prizes/chemistry/1995/ceremony-speech/]:

> In 1970 Paul Crutzen demonstrated that nitrogen oxides, formed during combustion processes, could affect the rate of ozone depletion in the stratosphere. He suggested that dinitrogen monoxide, popularly known as "laughing gas" and formed through microbiological processes in the ground, could have the same effect. He has also studied the formation of ozone in the lower atmosphere. Ozone is one ingredient of "smog," which is formed by the influence of solar radiation on air pollutants, especially exhaust gases from motor vehicles and other combustion systems. Whereas stratospheric ozone is a prerequisite for life, tropospheric ozone is strongly toxic and harmful to most organisms, even in small quantities.

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[4] Bowler 1993; von Hann 1887; von Hann and Süring 1926; Haurwitz 1941.

Julius von Hann (Austrian, 1839–1921, Fig. 4.28) was arguably the founder of systemic global meteorology. Figures 4.32–4.32 show a few pages from his *Atlas der Meteorologie* (1887) giving average isotherms, isobars, winds, and rainfall worldwide. Julius von Hann and Reinhard Süring wrote the *Lehrbuch der Meteorologie*, which became the standard textbook for generations of meteorology students. The American Council of Learned Societies noted [ACLS 2000, p. 394]:

> Hann was one of the most prominent meteorologists of his day. His importance rested less on the creation of new theoretical concepts than on his efforts to coordinate empirical and theoretical results into a coherent structure. [...] He was a driving force in the establishment of mountain observatories, where he studied upper-air data from many different aspects. He produced the first comprehensive climatologies of both the tropics and the polar regions.

Bernhard Haurwitz (German, 1905–1986, Fig. 4.29) received his Ph.D. in meteorology and geophysics from the University of Leipzig in 1927, worked there after graduating, and then moved to the United States in late 1932 due to rising antisemitism in Germany. He helped to bring German methods of meteorology to the United States. Haurwitz taught at MIT and New York University and wrote *Dynamic Meteorology*, which became the standard reference on the subject.

Hugo Hergesell (German, 1859–1938, Fig. 4.29) organized the regular collection of temperature, humidity, and pressure data by balloons at different altitudes in order to improve weather forecasts.

Karl Jelinek (Austrian, 1822–1876, Fig. 4.29) studied both meteorology and geomagnetism, combining measurements with new types of instruments and sophisticated mathematical analysis to obtain important new results.

Joseph Kölzer (German, 1883–1970, Fig. 4.29) established the field of military meteorology before World War I and continued to develop that area until after World War II. He also studied the propagation of sound waves in different layers of the atmosphere.

As shown in Fig. 4.33, Wladimir Köppen (German, 1846–1940) developed a detailed system of climate classification (how wet/dry and how hot/cold a region tends to be) that is still in use, with subsequent improvements by Rudolf Geiger (German, 1894–1981) [Geiger 1950; Köppen 1955]. Wladimir Köppen was the father-in-law of Alfred Wegener (p. 738), and Rudolf Geiger was the brother of Hans Geiger (p. 1520). The *Encyclopedia Britannica* described the importance of Köppen and his work [EB 2010]:

> German meteorologist and climatologist best known for his delineation and mapping of the climatic regions of the world. He played a major role in the advancement of climatology and meteorology for more than 70 years. His achievements, practical and theoretical, profoundly influenced the development of atmospheric science. [...]
>
> A climax in geographical climatology was reached in 1900 when Köppen introduced his mathematical system of climatic classification. Each of five major climate types was assigned a mathematical value according to temperature and rainfall. Since then, many of the systems introduced by other scholars have been based on Köppen's work. [...]

> In 1927 he undertook, with Rudolph Geiger, the editorship of a five-volume *Handbuch der Klimatologie* ("Handbook of Climatology"), which was nearly completed when he died. [...]
>
> Köppen was one of the last scholars of an era when an erudite man could attain competence in, and make significant contributions to, many branches of natural science.

As illustrated in Fig. 4.34, Auguste Piccard (Swiss, 1884–1962) and Paul Kipfer (Swiss, 1905–1980) studied the upper atmosphere and cosmic rays using their own specially designed high-altitude balloon with a pressurized crew compartment.

Reinhard Süring (German, 1866–1950, Fig. 4.29) made important discoveries regarding clouds, atmospheric radiation, the upper atmosphere, and high-altitude physiology. He and Julius von Hann wrote the *Lehrbuch der Meteorologie*, which became the standard textbook for generations of meteorology students.

See also related work in the German-speaking world on:

- Aerospace medicine (p. 390)
- Cosmic rays (p. 804)
- Lighter-than-air craft (p. 1640)

Atmospheric science

Richard Assmann (1845–1918) **Arthur Berson (1859–1942)** **Wilhelm von Bezold (1837–1907)**

C. H. D. Buys-Ballot (1817–1890) **Paul Crutzen (1933–)** **Julius von Hann (1839–1921)**

Figure 4.28: Some creators who made major discoveries in atmospheric science included Richard Assmann, Arthur Berson, Wilhelm von Bezold, C. H. D. Buys-Ballot, Paul Crutzen, and Julius von Hann.

Atmospheric science

Bernhard Haurwitz (1905–1986)

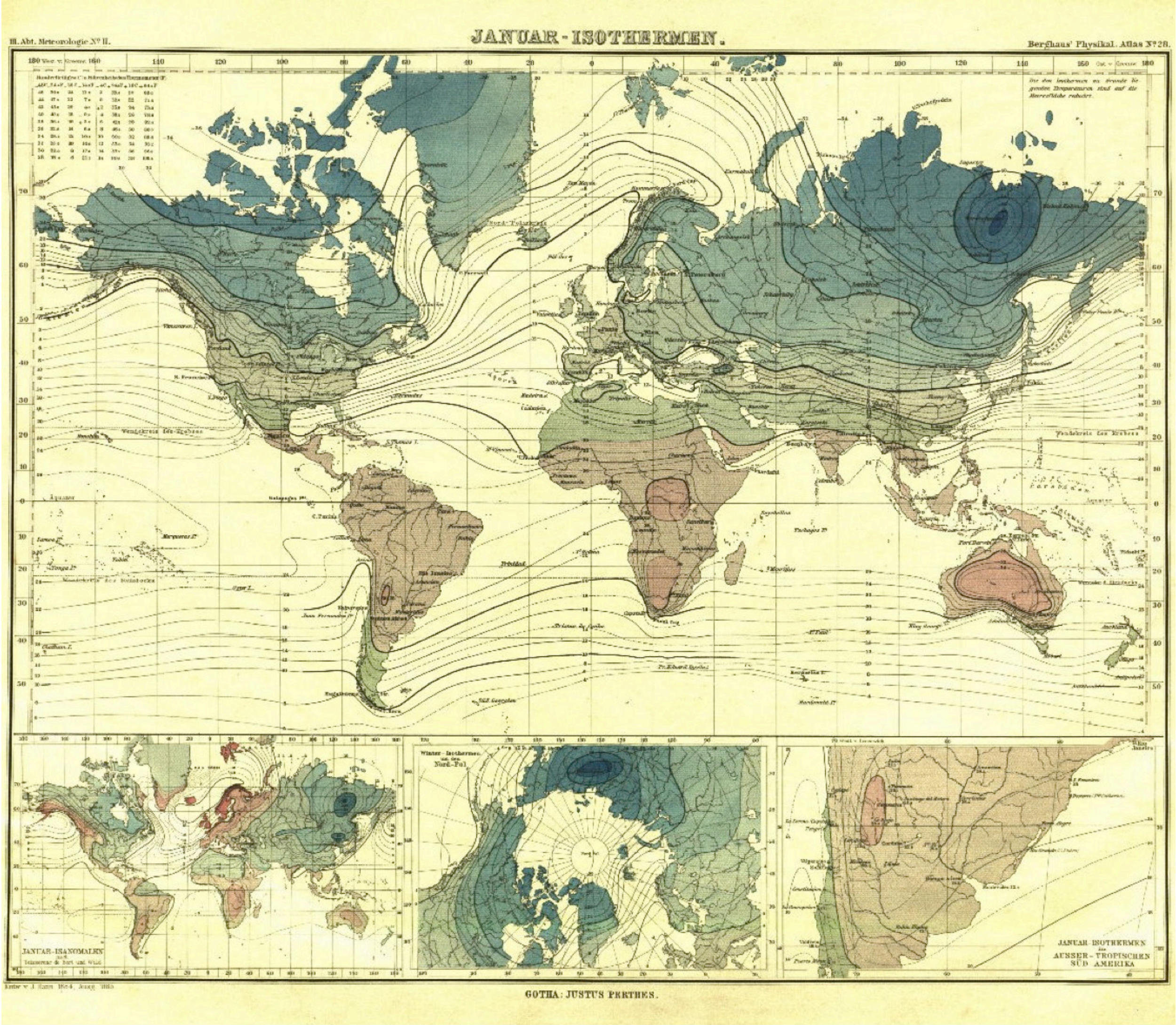
Hugo Hergesell (1859–1938)

Karl Jelinek (1822–1876)

Joseph Kölzer (1883–1970)

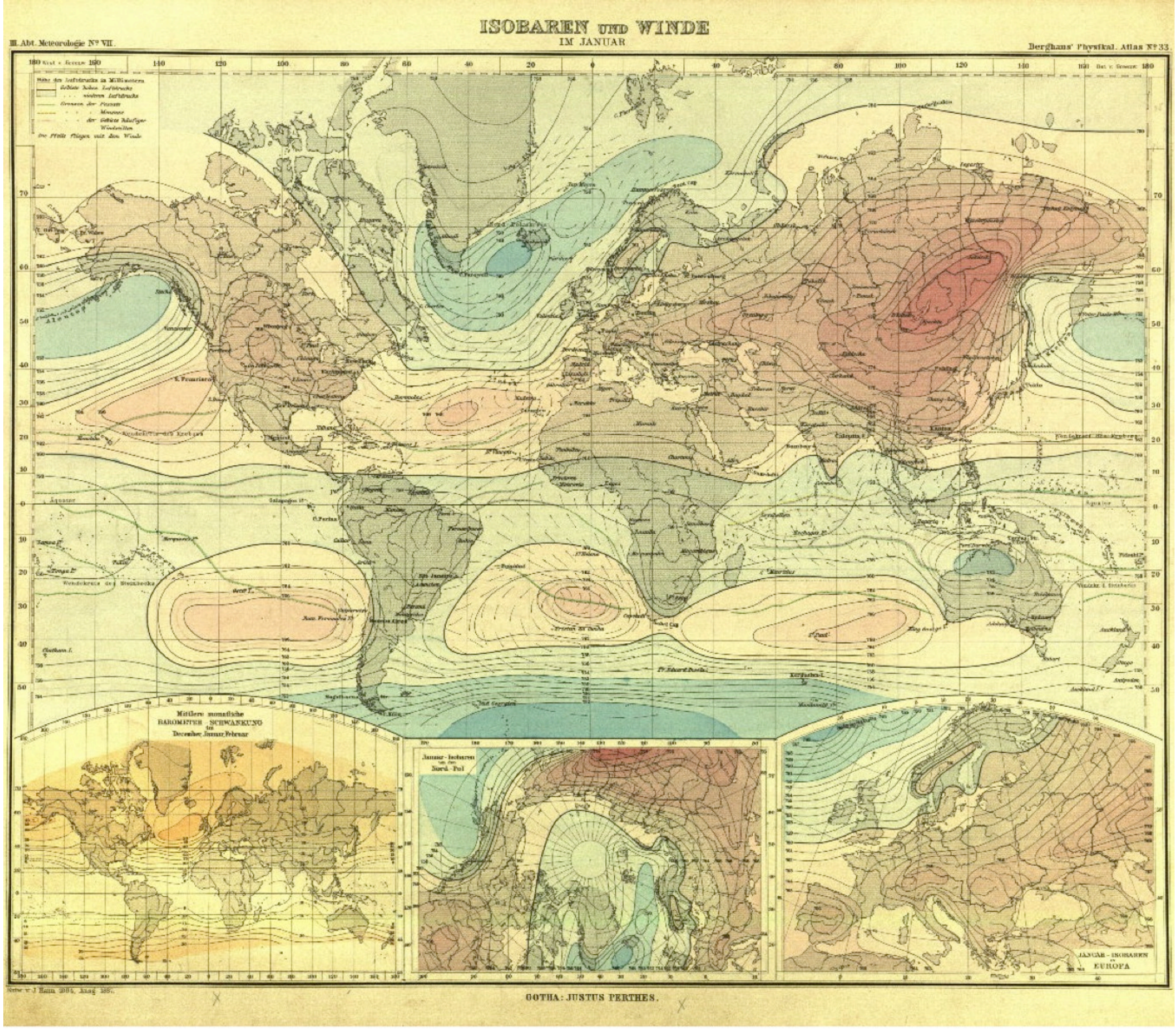
Reinhard Süring (1866–1950)

Figure 4.29: Other creators who made major discoveries in atmospheric science included Bernhard Haurwitz, Hugo Hergesell, Karl Jelinek, Joseph Kölzer, and Reinhard Süring.



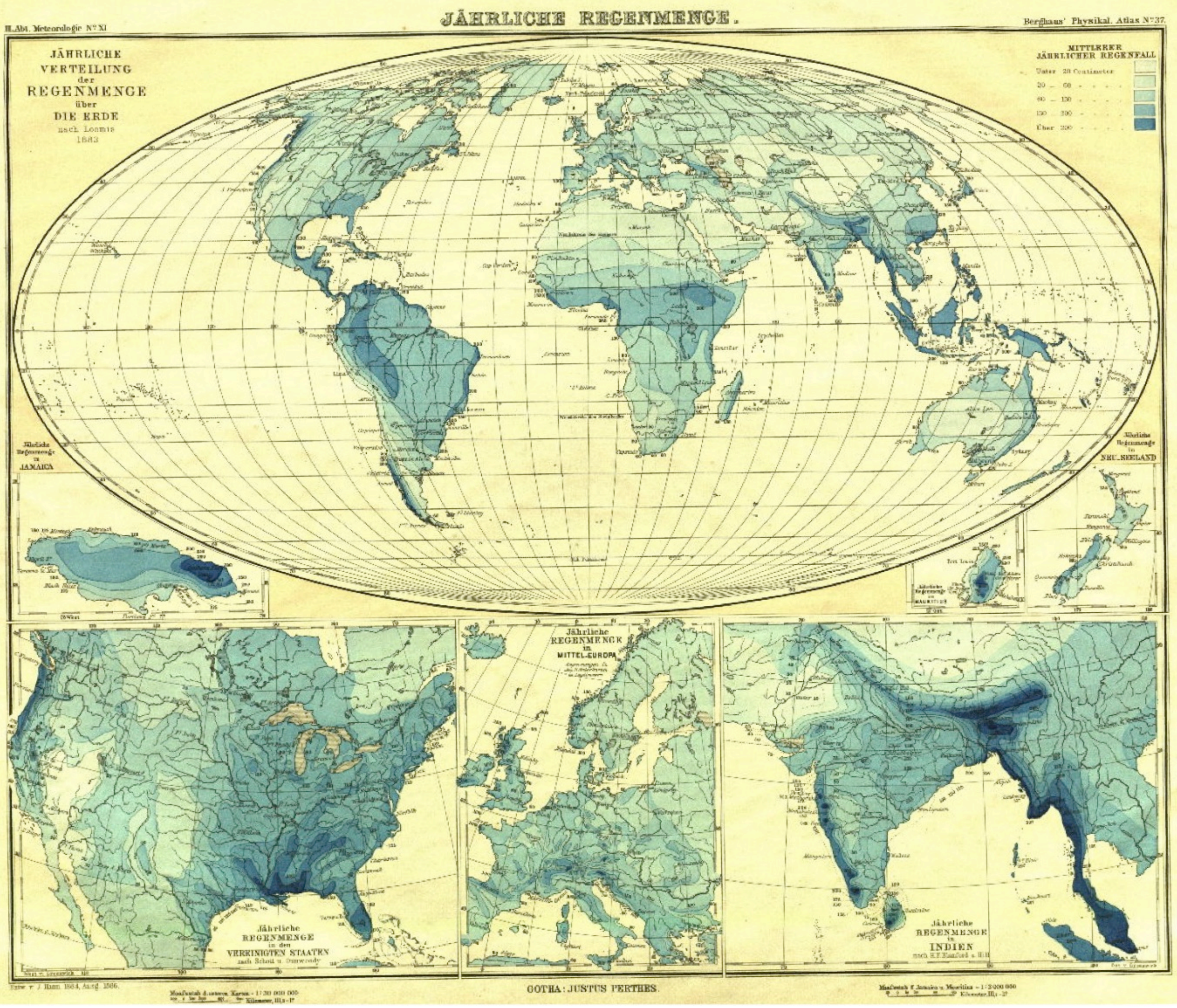
Page from Julius von Hann's *Atlas der Meteorologie* (1887)

Figure 4.30: A page from Julius von Hann's *Atlas der Meteorologie* (1887) showing average isotherms worldwide in January.



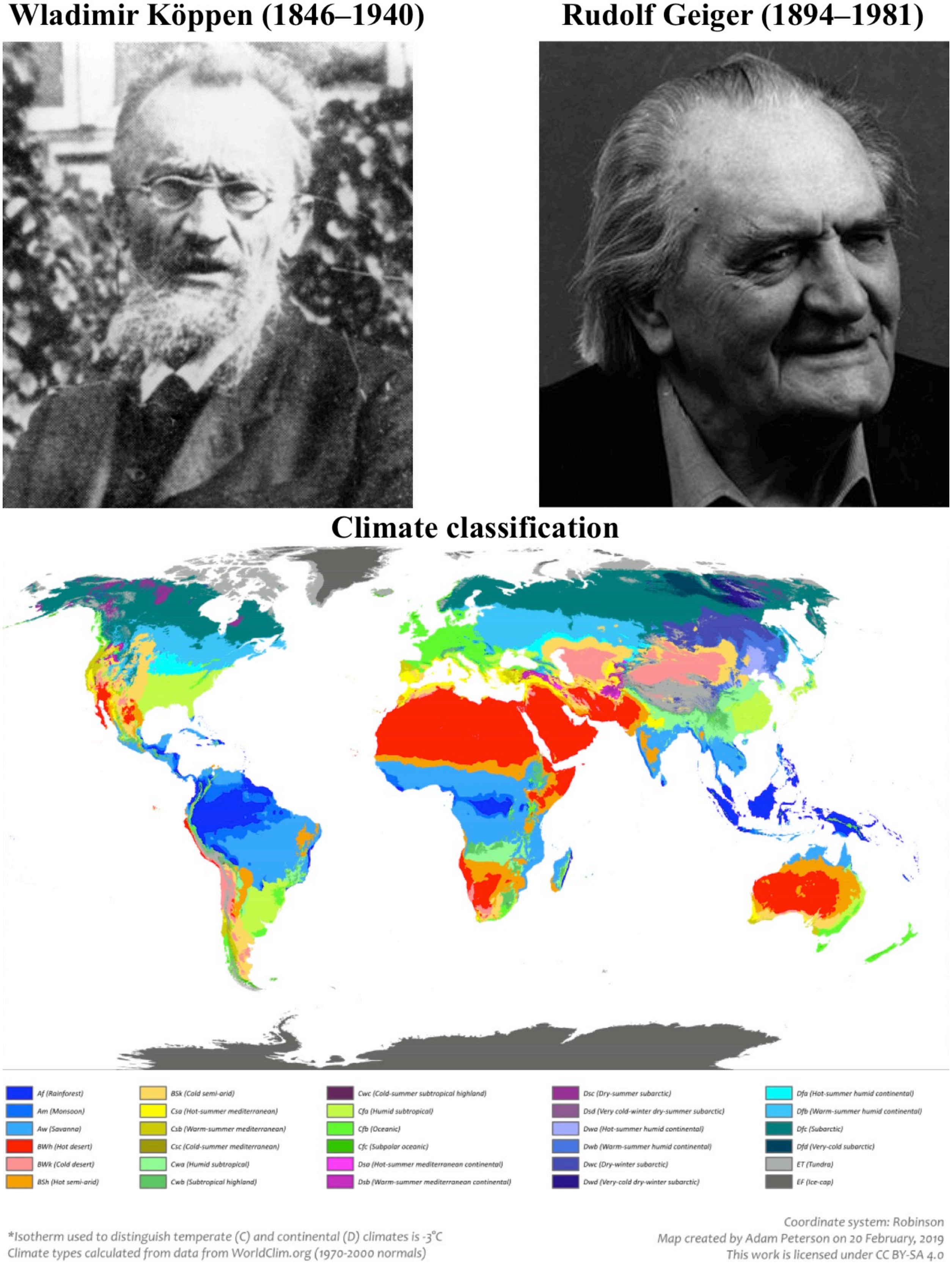
Page from Julius von Hann's *Atlas der Meteorologie* (1887)

Figure 4.31: A page from Julius von Hann's *Atlas der Meteorologie* (1887) showing average isobars and winds worldwide in January.



Page from Julius von Hann's *Atlas der Meteorologie* (1887)

Figure 4.32: A page from Julius von Hann's *Atlas der Meteorologie* (1887) showing average annual rainfall worldwide.



*Isotherm used to distinguish temperate (C) and continental (D) climates is -3°C
Climate types calculated from data from WorldClim.org (1970-2000 normals)

Coordinate system: Robinson
Map created by Adam Peterson on 20 February, 2019
This work is licensed under CC BY-SA 4.0

Figure 4.33: Wladimir Köppen and Rudolf Geiger developed a detailed system of climate classification that is still in use.

Figure 4.34: Auguste Piccard and Paul Kipfer also used balloons to study the upper atmosphere and cosmic rays.

4.5 Planetary Science

German-speaking scientists made a large number of important discoveries in planetary science [North 1995], including:

4.5.1. The heliocentric nature and orbits of the solar system

4.5.2. Moon and Mars maps

4.5.3. Asteroids

4.5.4. The outer solar system

For related contributions by German-speaking scientists to space travel and exploration, see Sections 9.7–9.10.

4.5.1 Heliocentric Solar System and Planetary Orbits

Although the German-speaking research world became more established after 1800 or so, one cannot cover planetary science without mentioning three very important creators from before that time:

Nicolaus Copernicus (Prussian, 1473–1543, Fig. 4.35) proposed that the planets orbit around the sun and conducted other work on astronomy and the design of scientific instruments. The scientific historian John North explained [North 1995, pp. 280–281]:

> Copernicus' greatest work, *De revolutionibus orbium caelestium* (On the Revolutions of the Celestial Spheres), was his definitive statement. It was completed at the very end of his life (1543) and differed in several technical respects from the brief sketch, which was probably written around 1510 (and certainly not later than 1514). The sketch contains a statement that the calculations in it are reduced to the meridian of Cracow, which he took to be the same as that of Frombork. In arguing that the Earth revolves around the Sun like any other planet, he introduced the names of authorities that he knew would carry weight in his own time, namely the Pythagoreans.

Tycho Brahe (Danish but educated and worked in the German-speaking world, 1546–1601, Fig. 4.36) made detailed astronomical observations that were used by Johannes Kepler to calculate planetary orbits.

Johannes Kepler (Weil der Stadt, 1571–1630, Fig. 4.37) worked out the physics of planetary orbits, which are slightly elliptical and not perfectly circular as Copernicus had previously assumed. Kepler also conducted other scientific research, including publishing a star catalog/astronomy handbook (*Rudolphine Tables*), describing the hexagonal close-packed symmetry of some crystals, and studying optics. Oxford University's *Biographical Dictionary of Scientists* praised Kepler's approach and accomplishments [Porter 1994, pp. 385, 387]:

> Kepler [...] was a German astronomer who combined great mathematical skills with patience and an almost mystical sense of universal harmony. He is particularly remembered for what are now known as Kepler's laws of motion. These had a profound influence on Newton and hence on all modern science. Kepler was also absorbed with the forces that govern the whole universe and he was one of the first and most powerful advocates of Copernican heliocentric (Sun-centred) cosmology.
>
> [...H]e finally completed the Rudolphine Tables. They appeared in 1627 and brought Kepler much popular acclaim. These were the first modern astronomical tables, a vast improvement on previous attempts of this kind, and they enabled astronomers to calculate the positions of the planets at any time in the past, present or future. The publication also included other vital information, such as a map of the world, a catalogue of stars, and the latest aid to computation, logarithms.
>
> Kepler wrote the first science-fiction story, *Solemnium*, which described a man who travelled to the Moon. It was published in 1631, a year after his death, although it had been written 20 years earlier. Kepler was a remarkable man and a brilliant scientist. He kept a steady eye on what he saw as his true vocation as a 'speculative physicist and cosmologist' and, despite living in times of political unrest and religious turmoil, was never swayed by religious bigotry or political pressures. His new astronomy provided the basis on which Newton and others were to build, and to this day his three laws of motion are considered to be the basis of our understanding of the Solar System.

As shown in Fig. 4.38, Milutin Milanković (or Milankovitch, Serbian but educated and worked in Austria, 1879–1958) worked out how periodic changes in the Earth's orbit and axis affect its climate (Milanković or Milankovitch cycles). He also studied similar effects for Mercury, Venus, the Moon, and Mars.

4.5.2 Moon and Mars Maps

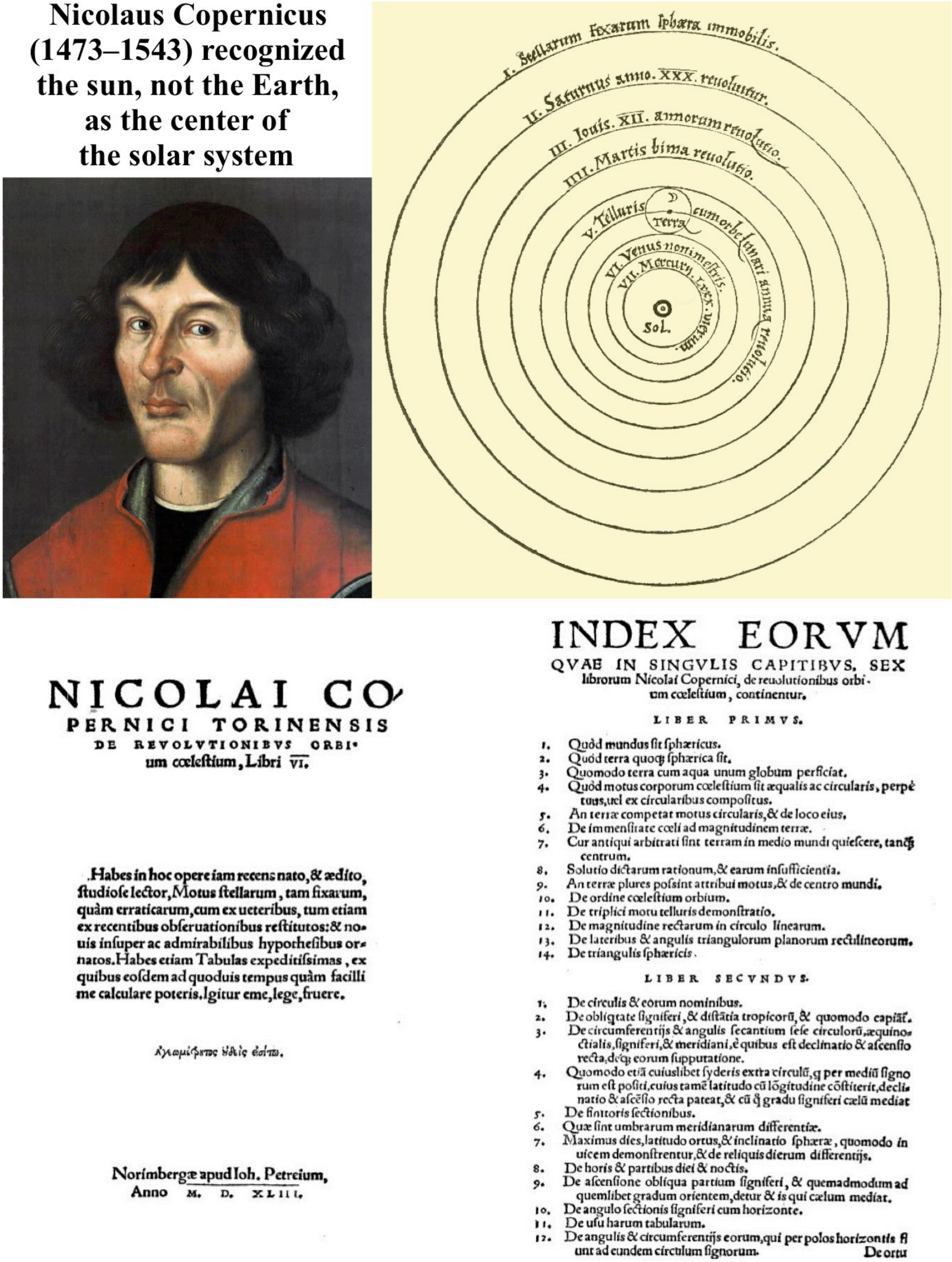
Creators who made important early detailed maps of the Moon and Mars included (Fig. 4.39):

Johann Hieronymus Schröter (German states, 1745–1816) created a Moon map in 1791 and a Mars map in 1800. The American Council of Learned Societies noted [ACLS 2000, p. 789]:

> The observatory he built and equipped at Lilienthal was a center of astronomical research for thirty years, becoming world-famous for the excellence of its instruments. First to observe the surface of the moon and the planets systematically over a long period; discovered and named the lunar rills. He had important influence on Harding, Bessel, and J. F. J. Schmidt.

Wilhelm Beer (Prussian, 1797–1850) and Johann Heinrich von Mädler (German, 1794–1874) produced a highly detailed Moon map during the period 1834–1837 (Fig. 4.40) and the best Mars map then available during the period 1830–1840 (Fig. 4.41).

Johann Friedrich Julius Schmidt (German, 1825–1884) created a Moon map even more detailed than that of Beer and Mädler during the period 1858–1874.



NICOLAI CO-
PERNICI TORINENSIS
DE REVOLVTIONIBVS ORBI-
um cœleſtium, Libri VI.

Habes in hoc opere iam recens nato, & ædito, ſtudioſe lector, Motus ſtellarum, tam fixarum, quàm erraticarum, cum ex ueteribus, tum etiam ex recentibus obſeruationibus reſtitutos: & nouis inſuper ac admirabilibus hypotheſibus ornatos. Habes etiam Tabulas expeditiſsimas, ex quibus eoſdem ad quoduis tempus quàm facillime calculare poteris. Igitur eme, lege, fruere.

Ἀγεωμέτρητος οὐδεὶς εἰσίτω.

Norimbergæ apud Ioh. Petreium,
Anno M. D. XLIII.

INDEX EORVM
QVAE IN SINGVLIS CAPITIBVS, SEX
librorum Nicolai Copernici, de reuolutionibus orbium cœleſtium, continentur.

LIBER PRIMVS.

1. Quòd mundus ſit ſphæricus.
2. Quòd terra quoq; ſphærica ſit.
3. Quomodo terra cum aqua unum globum perficiat.
4. Quòd motus corporum cœleſtium ſit æqualis ac circularis, perpètuus, uel ex circularibus compoſitus.
5. An terræ competat motus circularis, & de loco eius.
6. De immenſitate cœli ad magnitudinem terræ.
7. Cur antiqui arbitrati ſint terram in medio mundi quieſcere, tanq̃ centrum.
8. Solutio dictarum rationum, & earum inſufficientia.
9. An terræ plures poſsint attribui motus, & de centro mundi.
10. De ordine cœleſtium orbium.
11. De triplici motu telluris demonſtratio.
12. De magnitudine rectarum in circulo linearum.
13. De lateribus & angulis triangulorum planorum rectilineorum.
14. De triangulis ſphæricis.

LIBER SECVNDVS.

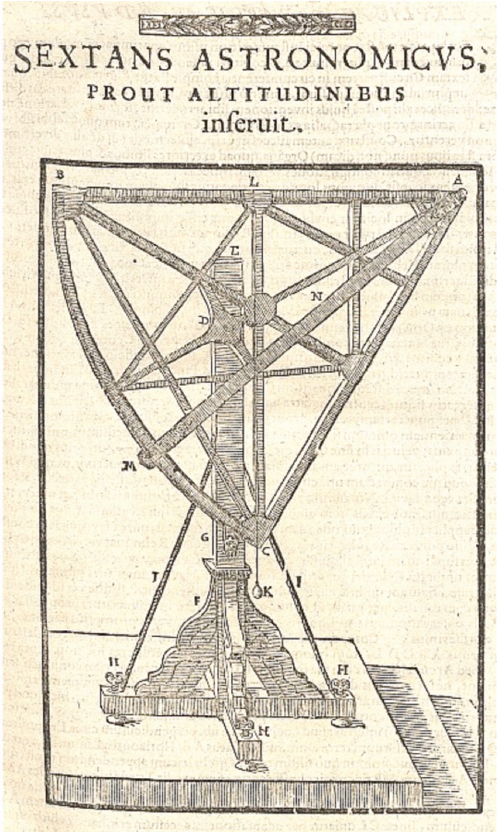
1. De circulis & eorum nominibus.
2. De obliqtate ſigniferi, & diſtãtia tropicorũ, & quomodo capiãt.
3. De circumferentijs & angulis ſecantium ſeſe circulorũ, æquinoctialis, ſigniferi, & meridiani, è quibus eſt declinatio & aſcenſio recta, deq; eorum ſupputatione.
4. Quomodo etiã cuiuslibet ſyderis extra circulũ, q per mediũ ſignorum eſt poſiti, cuius tamẽ latitudo cũ lõgitudine cõſtiterit, declinatio & aſcẽſio recta pateat, & cũ q̃ gradu ſigniferi cælũ mediat
5. De finitoris ſectionibus.
6. Quæ ſint umbrarum meridianarum differentiæ.
7. Maximus dies, latitudo ortus, & inclinatio ſphæræ, quomodo inuicem demonſtrentur, & de reliquis dierum differentijs.
8. De horis & partibus diei & noctis.
9. De aſcenſione obliqua partium ſigniferi, & quemadmodum ad quemlibet gradum orientem, detur & is qui cælum mediat.
10. De angulo ſectionis ſigniferi cum horizonte.
11. De uſu harum tabularum.
12. De angulis & circumferentijs eorum, qui per polos horizontis fiunt ad eundem circulum ſignorum.

De ortu

Figure 4.35: Nicolaus Copernicus recognized the sun, not the Earth, as the center of the solar system.

Tycho Brahe (1546–1601) made detailed astronomical observations that were used by Johannes Kepler to calculate planetary orbits

TYCHONIS
BRAHE DANI,
ASTRONOMIÆ INSTAURATÆ PROGYMNASMATA.
Quorum hæc
PRIMA PARS
DE RESTITVTIONE MOTVVM
Solis & Lunæ, Stellarumque inerrantium
tractat.
ET PRÆTEREA DE ADMIRANDA
noua Stella Anno 1572. exorta luculenter agit.
ANNO M. DCX.
Excudi primum cœpta Vraniburgi Daniæ,
aſt Pragæ Bohemiæ abſoluta.
PROSTANT
Francofurti apud Godefridum Tampachium.
Cum Cæſaris & Regum quorundam priuilegiis.



SEXTANS ASTRONOMICVS,
PROUT ALTITUDINIBUS
inſeruit.

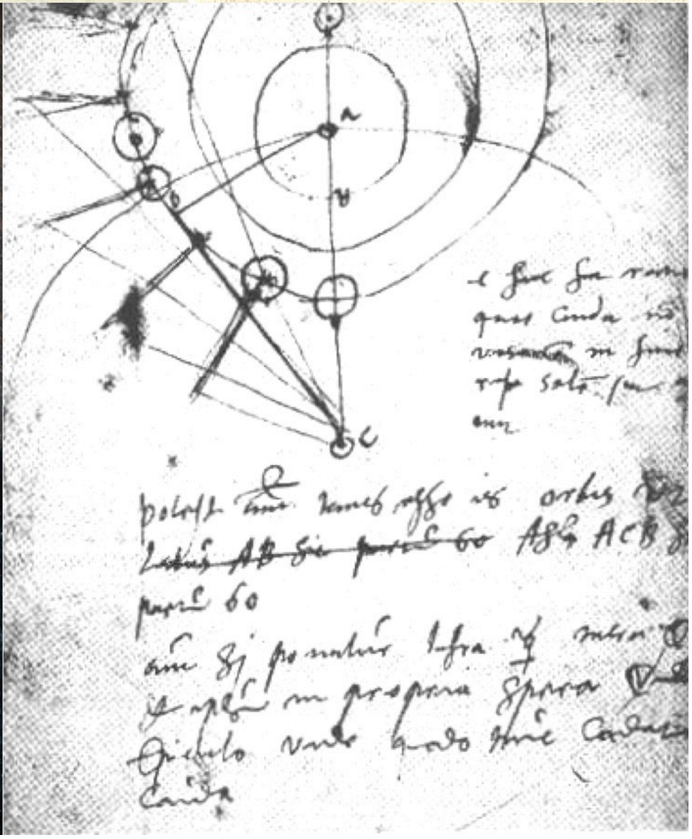
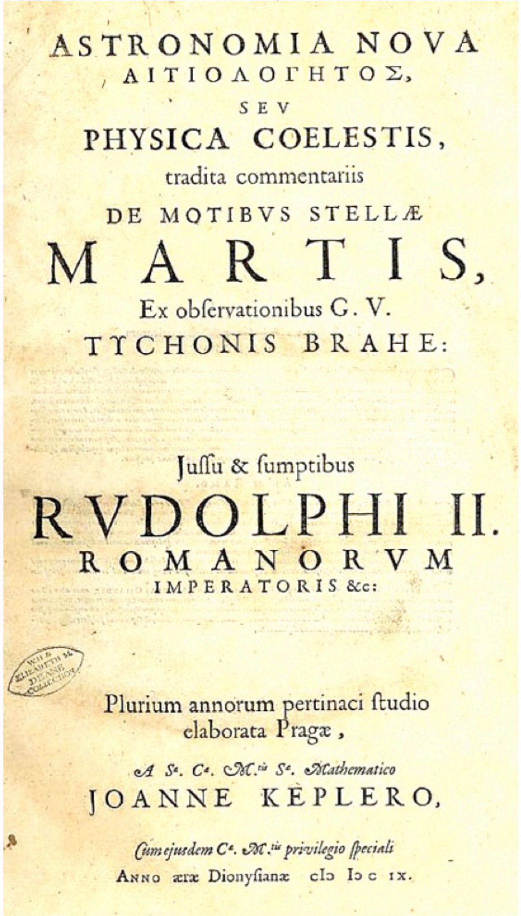


Figure 4.36: Tycho Brahe made detailed astronomical observations that were used by Johannes Kepler to calculate planetary orbits.

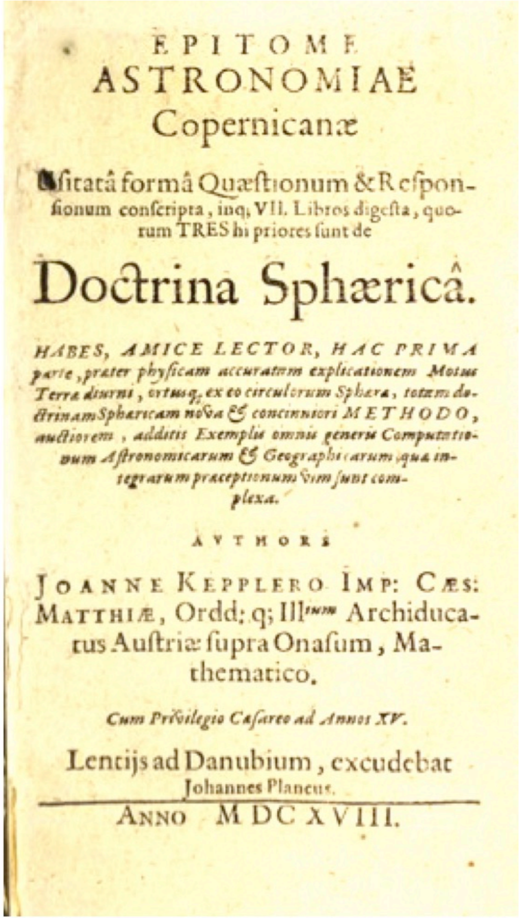
Johannes Kepler (1571–1630) calculated the elliptical orbits of planets in the solar system



ASTRONOMIA NOVA
ΑΙΤΙΟΛΟΓΗΤΟΣ,
SEV
PHYSICA COELESTIS,
tradita commentariis
DE MOTIBVS STELLÆ
MARTIS,
Ex obſervationibus G. V.
TYCHONIS BRAHE:

Juſſu & ſumptibus
RVDOLPHI II.
ROMANORVM
IMPERATORIS &c:

Plurium annorum pertinaci ſtudio
elaborata Pragæ,
A S^{ae}. C^{ae}. M.^{tis} S^{ae}. Mathematico
JOANNE KEPLERO,
Cum ejusdem C^{ae}. M.^{tis} privilegio ſpeciali
Anno æræ Dionyſianæ cIↃ IↃ c ix.



EPITOME
ASTRONOMIÆ
Copernicanæ
Uſitatâ formâ Quæſtionum & Reſponſionum conſcripta, inq; VII. Libros digeſta, quorum TRES hi priores ſunt de
Doctrina Sphæricâ.

HABES, AMICE LECTOR, HAC PRIMA parte, præter phyſicam accuratam explicationem Motus Terræ diurni, ortusq; ex eo circulorum Sphæræ, totam doctrinam Sphæricam nova & concinniori METHODO, auctiorem, additis Exemplis omnis generis Computationum Aſtronomicarum & Geographicarum, quæ integrarum præceptionum vim ſunt complexa.

AVTHORE
JOANNE KEPPLERO IMP: CÆS: MATTHIÆ, Ordd: q; Ill^{mm} Archiducatus Auſtriæ ſupra Onaſum, Mathematico.

Cum Privilegio Cæſareo ad Annos XV.

Lentijs ad Danubium, excudebat Johannes Plancus.
ANNO MDCXVIII.

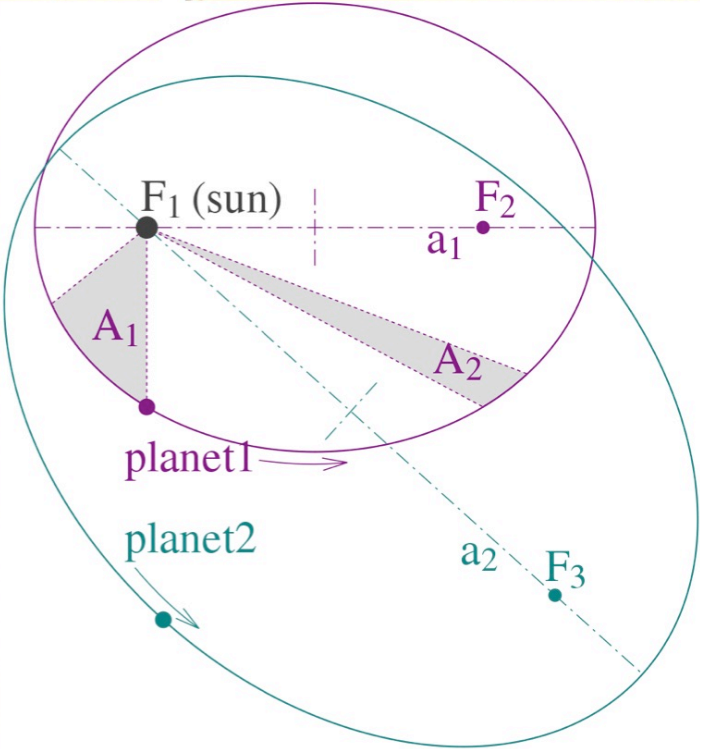
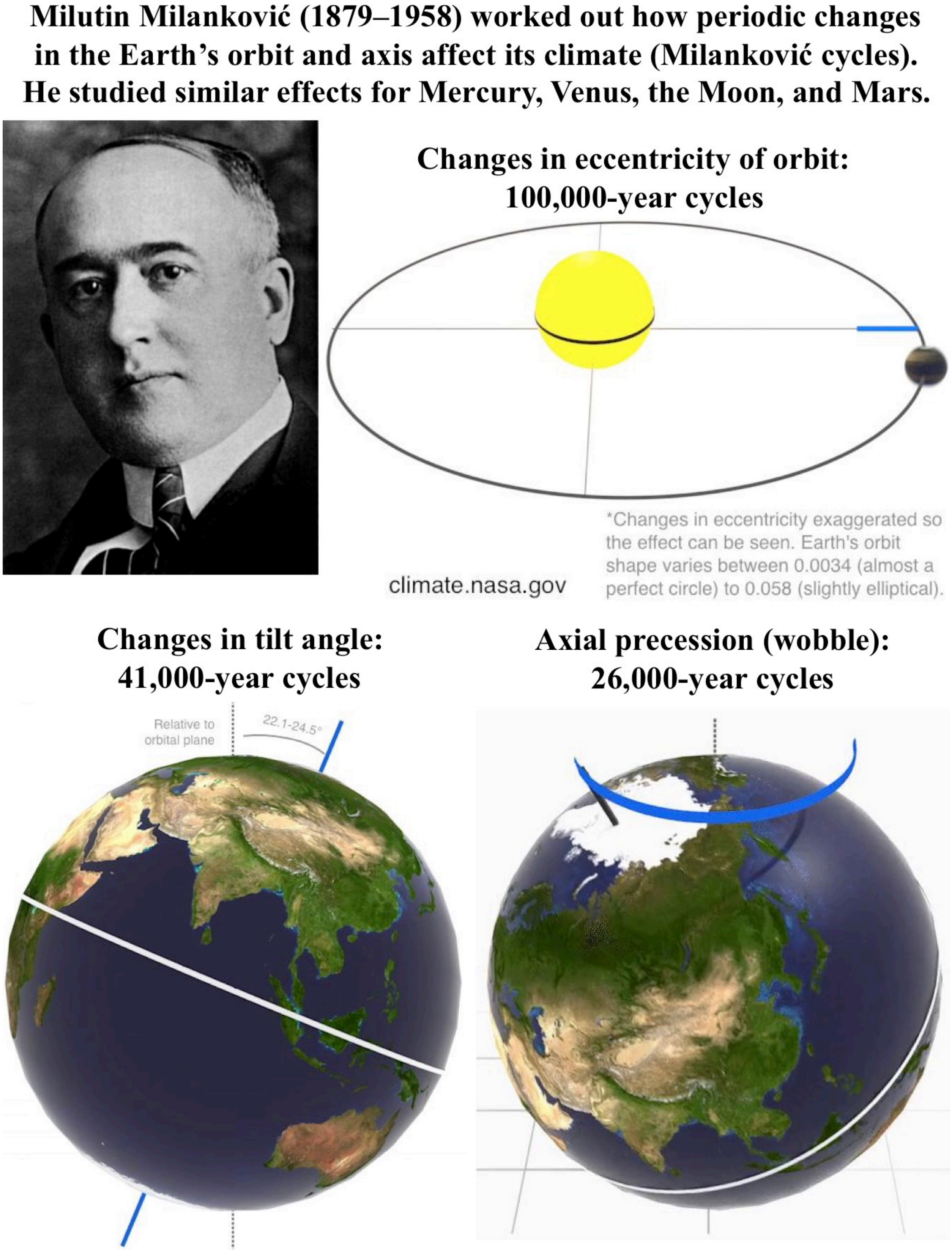


Figure 4.37: Johannes Kepler calculated the elliptical orbits of planets in the solar system.



Milutin Milanković (1879–1958) worked out how periodic changes in the Earth's orbit and axis affect its climate (Milanković cycles). He studied similar effects for Mercury, Venus, the Moon, and Mars.

Changes in eccentricity of orbit: 100,000-year cycles

*Changes in eccentricity exaggerated so the effect can be seen. Earth's orbit shape varies between 0.0034 (almost a perfect circle) to 0.058 (slightly elliptical).

climate.nasa.gov

Changes in tilt angle: 41,000-year cycles

Axial precession (wobble): 26,000-year cycles

Figure 4.38: Milutin Milanković (or Milankovitch) worked out how periodic changes in the Earth's orbit and axis affect its climate (Milanković or Milankovitch cycles). He also studied similar effects for Mercury, Venus, the Moon, and Mars.

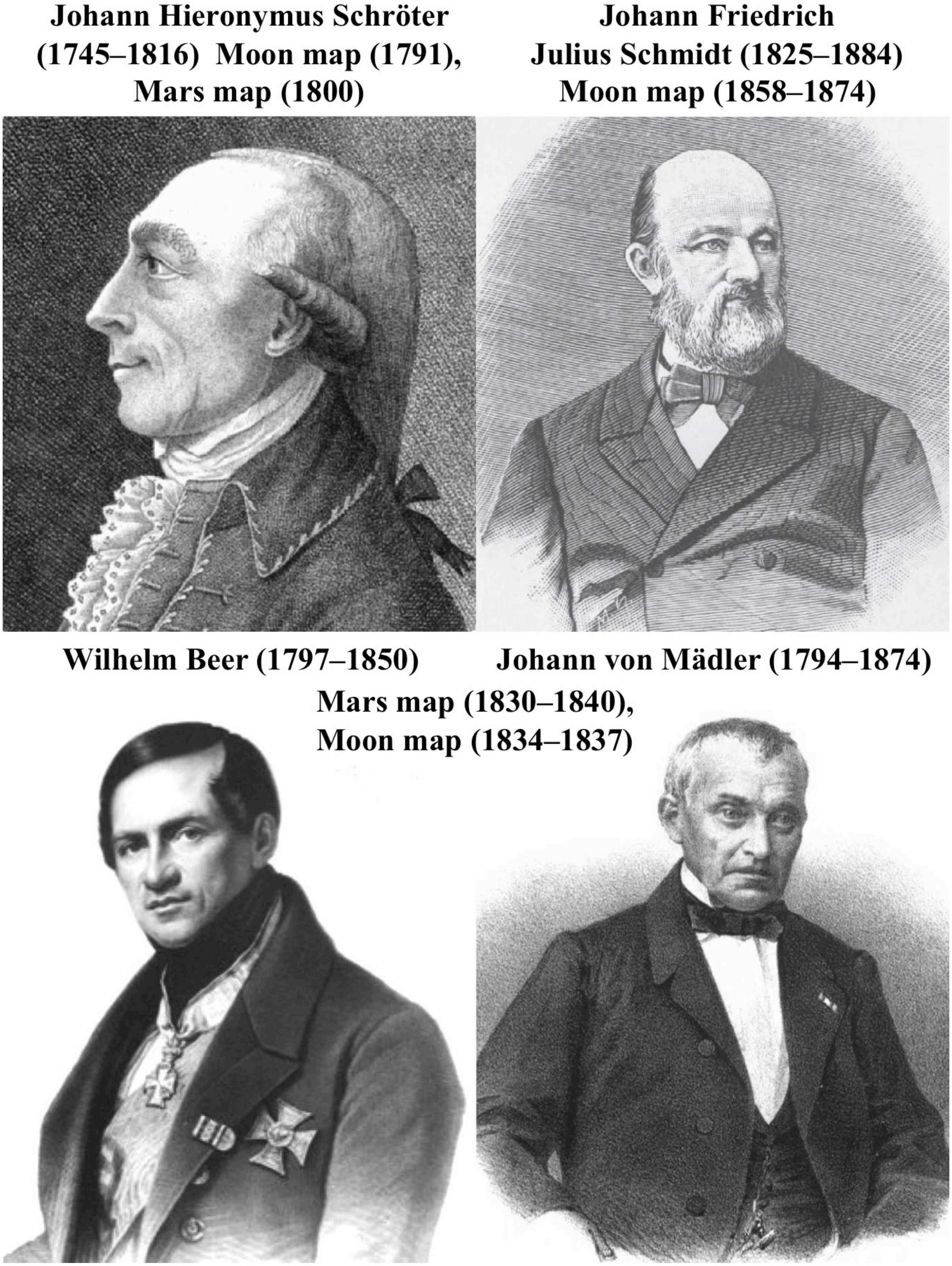


Figure 4.39: Creators who made important early detailed maps of the Moon and Mars included Johann Hieronymus Schröter, Wilhelm Beer and Johann von Mädler, and Johann Friedrich Julius Schmidt.

Moon map (1834–1837) by Wilhelm Beer and Johann von Mädler

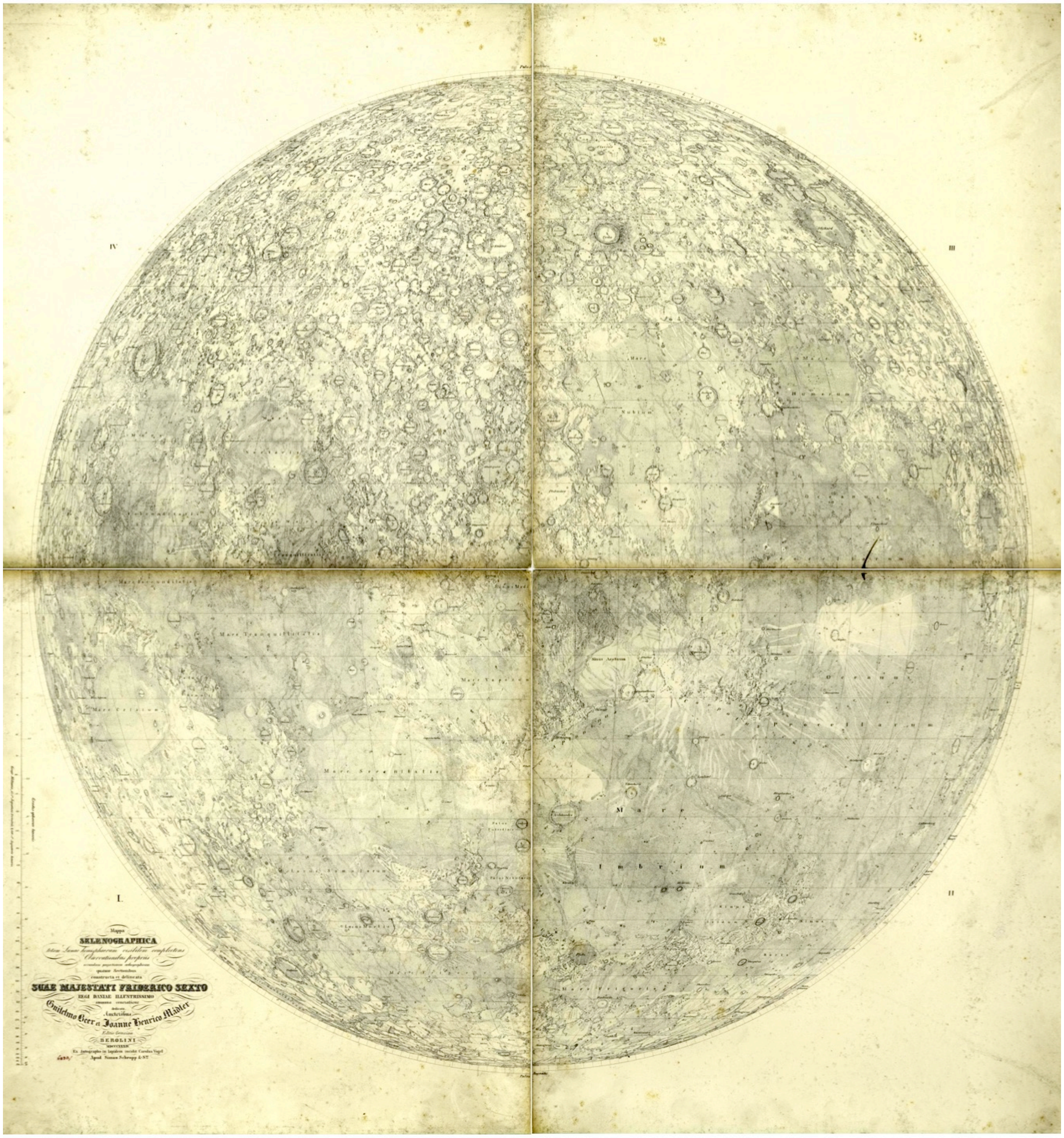


Figure 4.40: The Moon map (1834–1837) produced by Wilhelm Beer and Johann von Mädler.

Mars map (1830–1840) by
Wilhelm Beer and Johann von Mädler

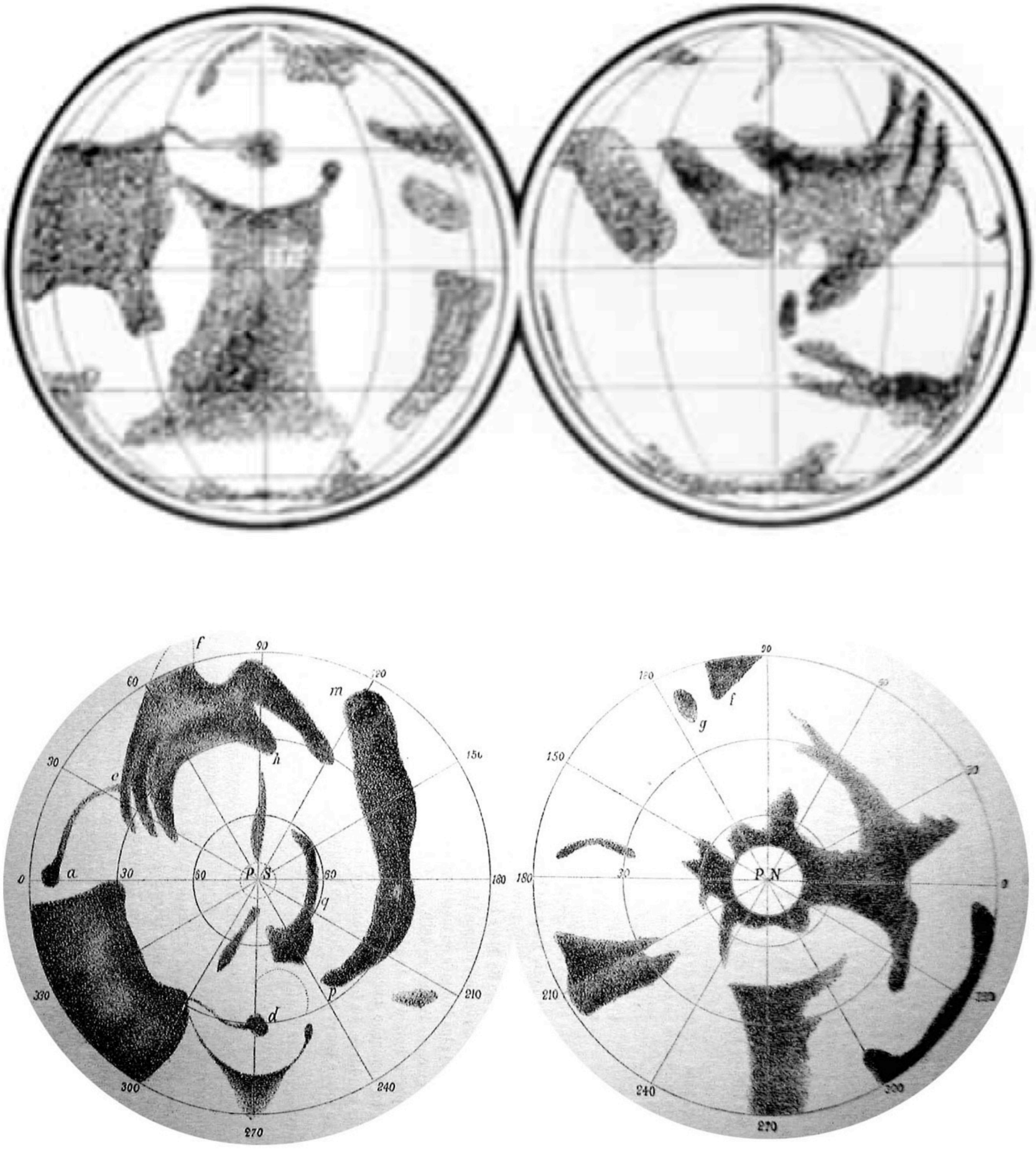


Figure 4.41: The Mars map (1830–1840) produced by Wilhelm Beer and Johann von Mädler.

4.5.3 Asteroids

As shown in Fig. 4.42, Ernst Chladni (German states, 1756–1827) discovered and published (in 1794) detailed evidence that meteorites come from space [Chladni 1794]. He also spent much of his career investigating the physics of vibrations, sound waves, and musical instruments.

German-speaking creators discovered many major asteroids, including the largest asteroids in the main asteroid belt between Mars and Jupiter (Figs. 4.43–4.46).

Franz Xaver von Zach (Hungarian, 1754–1832) organized astronomical searches for asteroids and was one of the astronomers (along with Heinrich Olbers, Carl Friedrich Gauss, and Giuseppe Piazzi) to spot the largest asteroid, Ceres, in 1801.

Heinrich Olbers (German states, 1758–1840) was one of the astronomers who spotted Ceres in 1801. He also discovered the very large asteroids Pallas in 1802 and Vesta in 1807. He discovered Olbers' comet in 1815, and proposed Olbers' paradox (Why is the night sky dark if there are an infinite number of stars in every direction, if you look far enough?) in 1823. Olbers also aided the career of the young Friedrich Bessel. For much of his life, Olbers was actually a practicing ophthalmologist in Bremen; he was also an early proponent of smallpox vaccination.

Carl Friedrich Gauss (German states, 1777–1855) developed revolutionary new methods for calculating orbits that led to the discovery and tracking of Ceres in 1801. He also calculated other asteroid orbits and developed methods of accounting for the perturbations of asteroid orbits by planets [Dunnington 1955]. (See also pp. 740, 828, 858, and 972.)

At the University of Göttingen, Karl Ludwig Harding (German states, 1765–1834) discovered the very large asteroid Juno in 1804. He also discovered several comets, created an important star catalog, and studied the behavior of variable stars.

Hermann Goldschmidt (German states, 1802–1866) found 14 asteroids and also made other astronomical discoveries regarding variable stars and atmospheric distortions during solar eclipses. In addition, he had a long and successful career as a painter.

Karl Robert Luther (German, 1822–1900) spent several decades working at an observatory in Düsseldorf; he discovered 24 asteroids.

Johann Palisa (Austrian, 1848–1925) was director of the Austrian Pula and Vienna observatories. He discovered 122 asteroids as well as some comets, and later collaborated with Maximilian Wolf on a photographic star atlas.

Friedrich Schwassmann (German, 1870–1964) worked at observatories in Potsdam and Hamburg, where he discovered 22 asteroids and 4 comets.

Maximilian Wolf (German, 1863–1932) was an important pioneer of astrophotography, and used that technique to discover hundreds of asteroids, including the first of the large population of 'Trojan asteroids' in orbit near Jupiter. He also discovered several nebulae, studied sunspots, carried out observations of Halley's comet, and invented the stereo-comparator tool for astronomical observations. Oxford University's *Biographical Dictionary of Scientists* explained the importance of Wolf's innovations [Porter 1994, p. 732]:

> One of his most successful innovations was a technique for discovering large numbers of asteroids. Until this time, asteroids had always been discovered visually[...] Wolf arranged for time-lapse photographs to be taken, using a camera mounted on a telescope whose clock mechanism followed as exactly as possible the proper motion of the 'fixed stars'. On the developed plate, the stars would appear as discrete spots—the size being a function of the star's magnitude—whereas any asteroids present would appear as short streaks in the foreground.
>
> The first asteroid Wolf discovered using this technique was number 323, afterwards named Brucia. He subsequently discovered more than 200 other asteroids using the same method. In September 1903, he discovered a special asteroid, number 588, later named Achilles. Its particular significance was that it was the first of the so-called 'Trojan satellites' whose orbits are in precise synchrony with that of Jupiter's; they form a gravitationally stable configuration between Jupiter and the Sun.

Many of Wolf's students at the University of Heidelberg made their own discoveries and had very productive careers in astronomy, including for example:

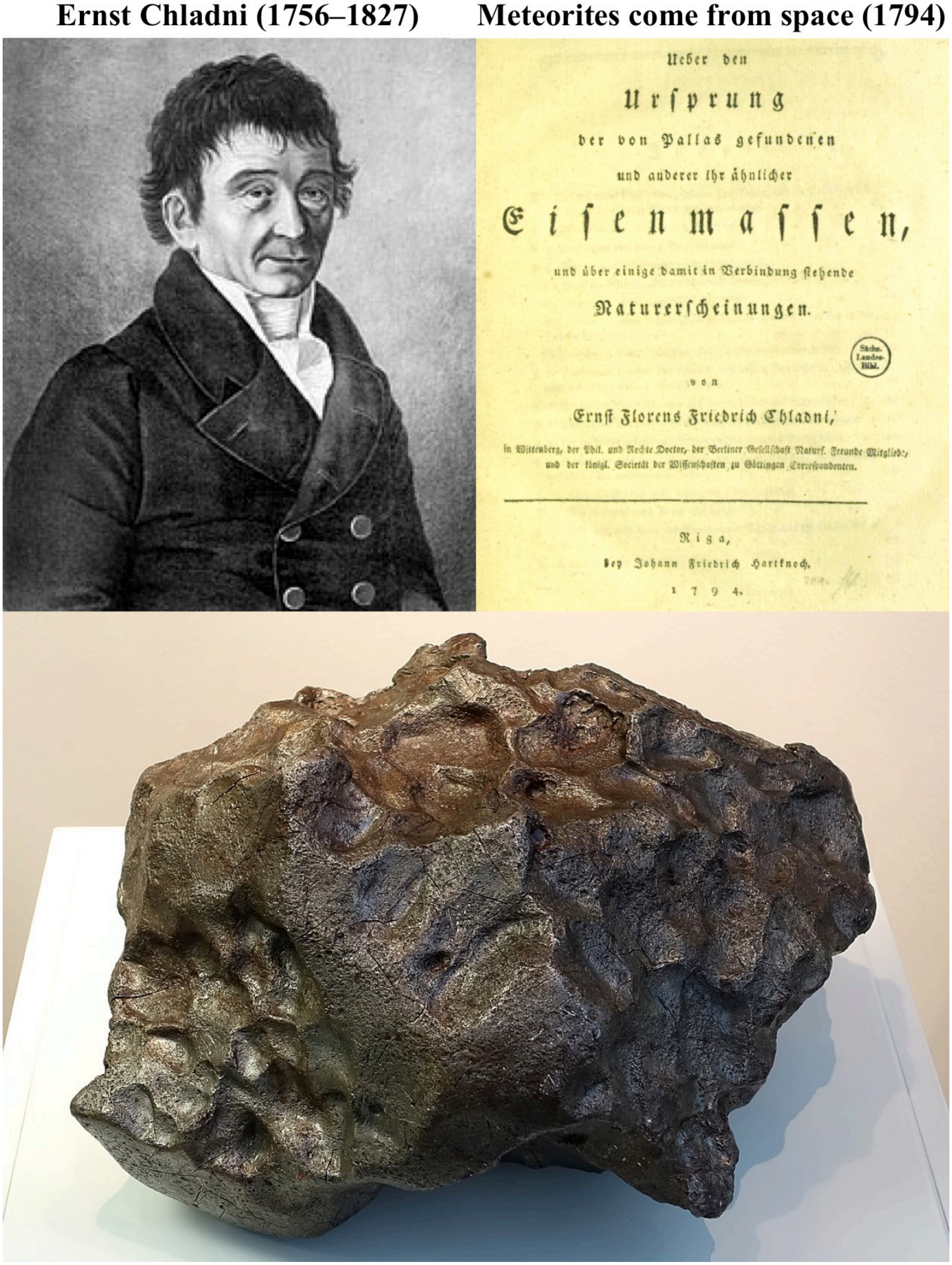
- Alfred Bohrmann (German, 1904–2000) discovered 9 asteroids and made extensive observations of many others.
- Paul Götz (German, 1883–1962) identified 20 asteroids.
- Joseph Helffrich (German, 1890–1971) found 13 asteroids.
- Franz Kaiser (German, 1891–1962) discovered 21 asteroids.
- August Kopff (German, 1882–1960) identified 68 asteroids and several comets.
- Karl Wilhelm Reinmuth (German, 1892–1979) found 395 asteroids plus some comets.

Antonín Mrkos (Czech/Austrian, 1918–1996) was one of the leading astronomers in Czechoslovakia; he discovered 274 asteroids and 13 comets.

Paul Wild (Swiss, 1925–2014) worked at the University of Bern and also with Fritz Zwicky at Caltech (p. 813). He found 94 asteroids, plus 41 supernovae and at least 7 comets.

Johann M. Baur (German, 1930–2007) founded a private observatory in northern Italy and discovered 15 asteroids.

Working at the Karl Schwarzschild Observatory in Tautenburg, Freimut Börngen (German, 1930–2021) discovered 538 asteroids and also made extensive studies of galaxies.



Ernst Chladni (1756–1827)

Meteorites come from space (1794)

Ueber den
Urſprung
der von Pallas gefundenen
und anderer ihr ähnlicher
Eiſenmaſſen,
und über einige damit in Verbindung ſtehende
Naturerſcheinungen.

von

Ernſt Florens Friedrich Chladni,

in Wittenberg, der Phil. und Rechte Doctor, der Berliner Geſellſchaft Naturf. Freunde Mitglied;
und der königl. Societät der Wiſſenſchaften zu Göttingen Correſpondenten.

Riga,
bey Johann Friedrich Hartknoch.
1794.

Figure 4.42: Ernst Chladni discovered and published detailed evidence that meteorites come from space (1794).

Johann M. Baur
(1930–2007)
15 asteroids

Alfred Bohrmann
(1904–2000)
9 asteroids +
observations of
many others

Freimut Börngen
(1930–2021)
538 asteroids

Carl Friedrich Gauss
(1777–1855)
Ceres (1801),
asteroid orbits
and perturbations
by planets

Hermann Goldschmidt
(1802–1866)
14 asteroids
+ other
astronomical
discoveries

Paul Götz
(1883–1962)
20 asteroids

Figure 4.43: Some creators who discovered many major asteroids included Johann M. Baur, Alfred Bohrmann, Freimut Börngen, Carl Friedrich Gauss, Hermann Goldschmidt, and Paul Götz.

Figure 4.44: Other creators who discovered many major asteroids included Karl Ludwig Harding, Joseph Helffrich, Franz Kaiser, August Kopff, Karl Robert Luther, Antonín Mrkos, and Heinrich Olbers.

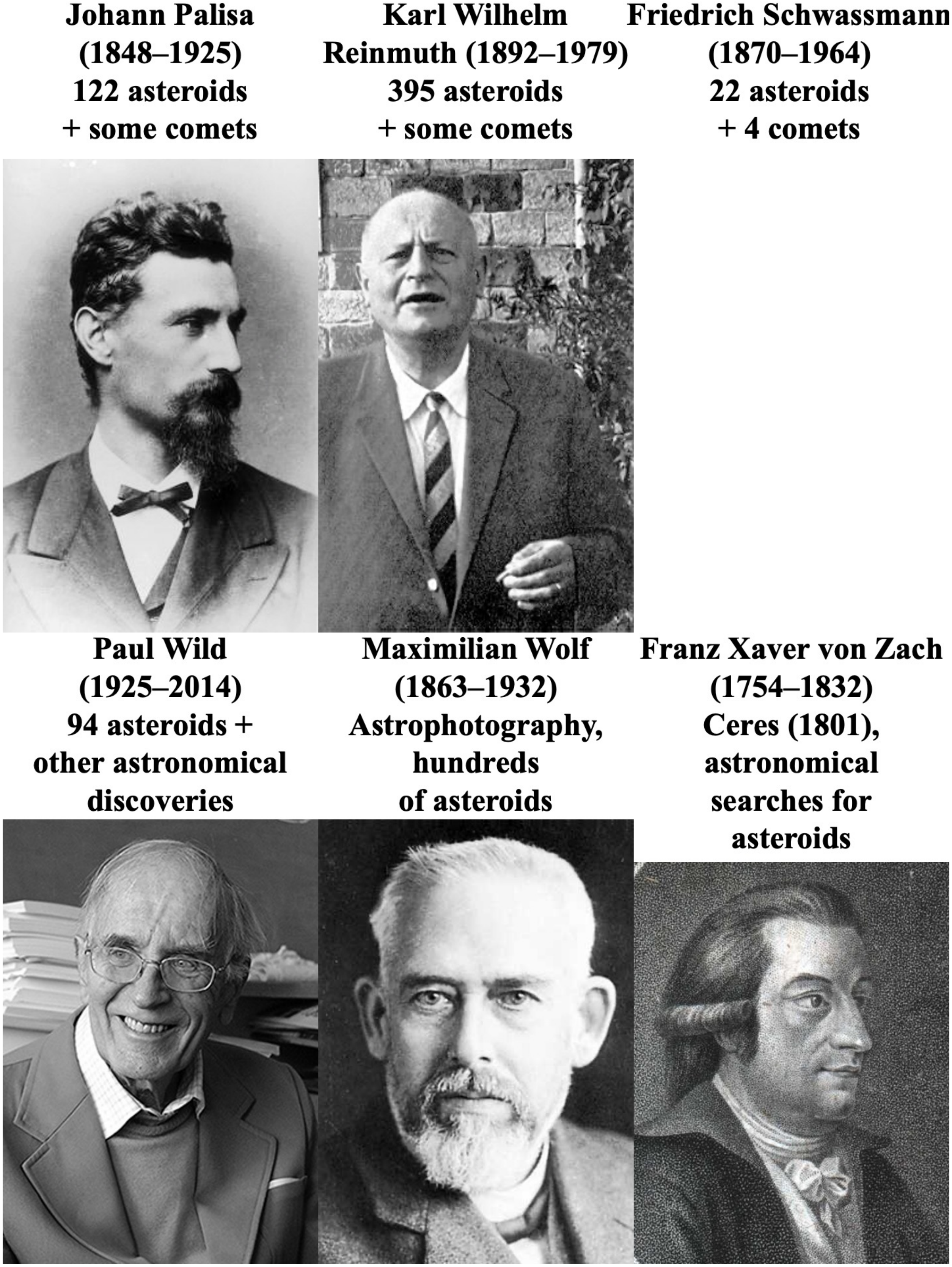


Figure 4.45: Other creators who discovered many major asteroids included Johann Palisa, Karl Wilhelm Reinmuth, Friedrich Schwassmann, Paul Wild, Maximilian Wolf, and Franz Xaver von Zach.

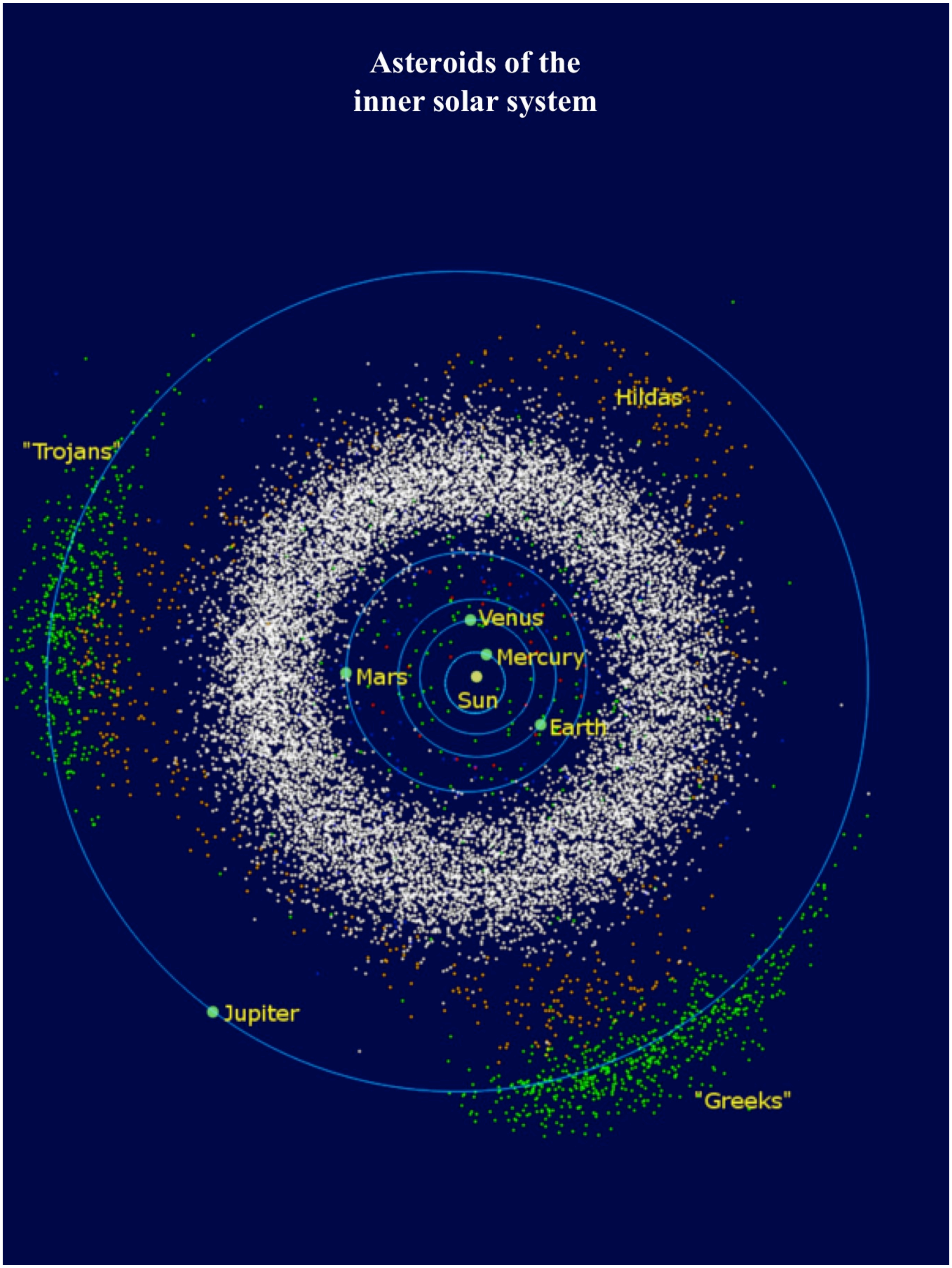


Figure 4.46: Asteroids of the inner solar system.

4.5.4 Outer Solar System

Creators from the greater German-speaking world made many major discoveries regarding the planets, moons, and comets of the outer solar system.

Johann Encke (German states, 1791–1865) and Theodor von Oppolzer (Austrian, 1841–1886) each carefully worked out the detailed orbits of many planets, asteroids, and comets (Fig. 4.47).

Friedrich Wilhelm Herschel (Hanover, 1738–1822, Fig. 4.48) discovered the planet Uranus in 1781, as well as two of its moons: Oberon (1787) and Titania (1787). He also discovered two additional moons of Saturn (Enceladus and Mimas, both in 1789) and studied the behavior of sunspots.

Friedrich Wilhelm Herschel's sister, Caroline Herschel (Hanover, 1750–1848), worked with him in those endeavors and also composed a very important early star catalog [Hoskin 2011; Lemonick 2008].

Friedrich Wilhelm Herschel's son, John Herschel (1792–1871), later discovered several other moons of Saturn and Uranus and conducted important research in other scientific fields.

In 1782, Johann Bode (German states, 1747–1826, Fig. 4.49) named and worked out the orbit of the planet Uranus following Friedrich Wilhelm Herschel's discovery.

Johann Galle (German, 1812–1910, Fig. 4.49) discovered the planet Neptune in 1846 [Galle and Wattenberg 1963].

Gerard Kuiper (Dutch, 1905–1973, Fig. 4.49) discovered the methane atmosphere of Saturn's moon Titan (1944), carbon dioxide in the atmosphere of Mars (1947), Uranus's moon Miranda (1948), Neptune's moon Nereid (1949), and evidence for the Kuiper belt of comets orbiting beyond Neptune (1951). The astronomer Carl Sagan eulogized him [Sagan 1980, p. 143]:

> Gerard Peter Kuiper, who in the 1940's and 1950's was the world's only full-time planetary astrophysicist. The subject was then considered by most professional astronomers to be at least slightly disreputable[...] I am grateful to have been Kuiper's student.

Jan Oort (Dutch, 1900–1992, Fig. 4.60) proposed the existence of the Oort cloud of comets in the outer reaches of our solar system.

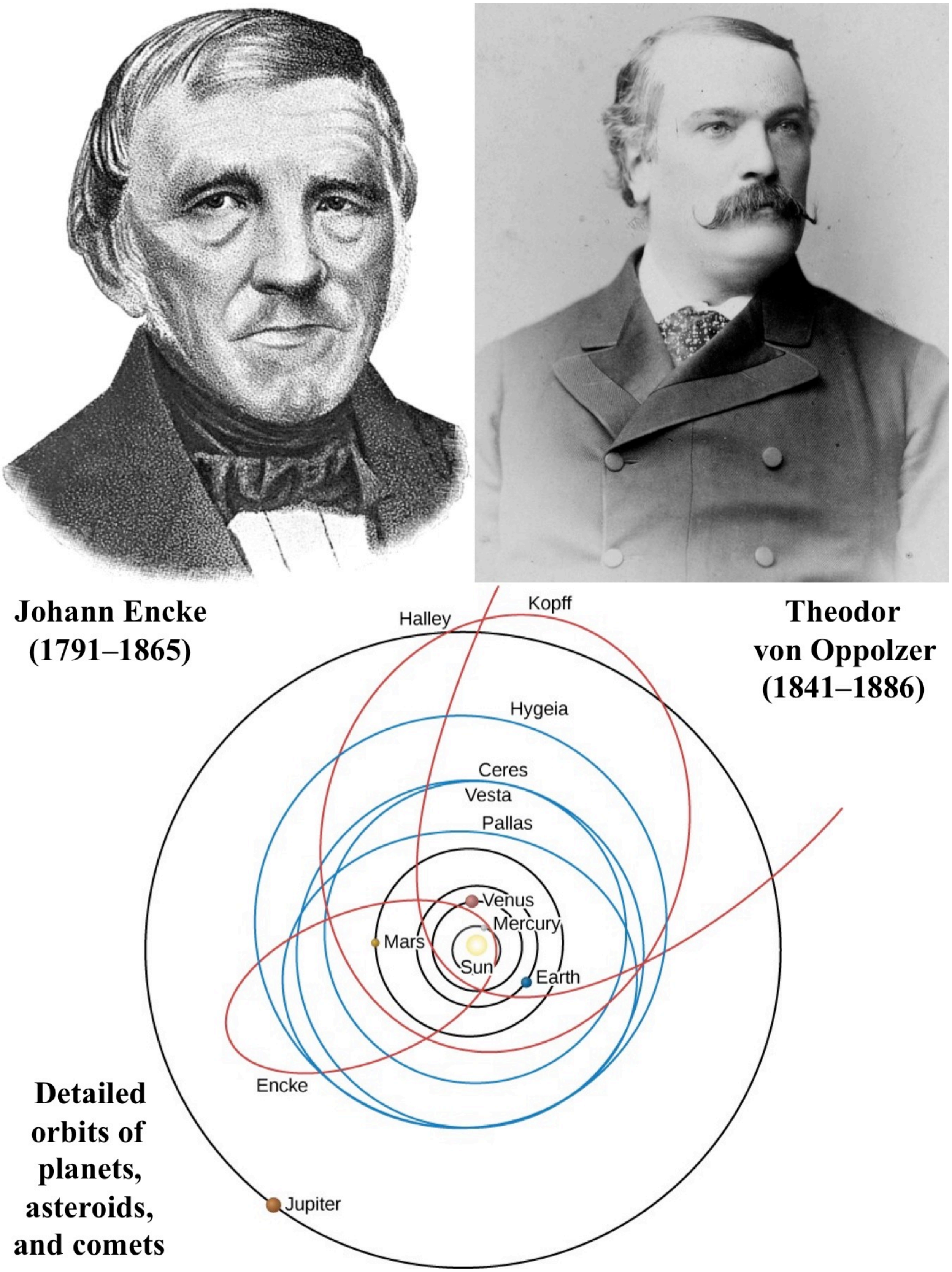


Figure 4.47: Johann Encke and Theodor von Oppolzer each carefully worked out the detailed orbits of many planets, asteroids, and comets.

Figure 4.48: Friedrich Wilhelm Herschel discovered the planet Uranus, two of its moons, and two additional moons of Saturn. His sister Caroline Herschel worked with him in those endeavors and also composed a very important early star catalog.

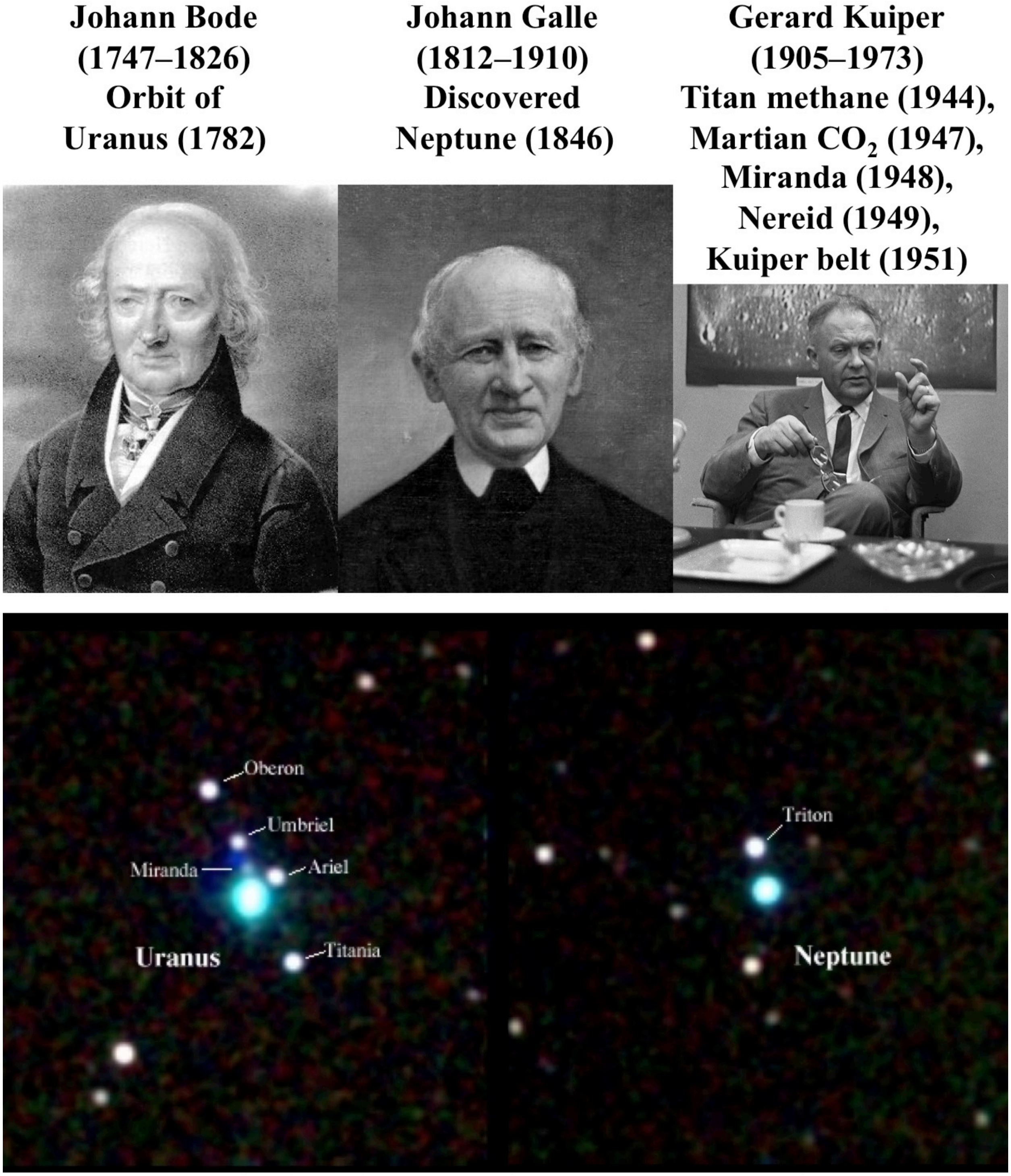


Figure 4.49: Some other creators who made major discoveries about Uranus, Neptune, and the outer solar system included Johann Bode, Johann Galle, and Gerard Kuiper.

4.6 Astrophysics

Scientists from the German-speaking world played a dominant role in the development of astrophysics, including:

4.6.1. Cosmic rays

4.6.2. Stellar physics

4.6.3. Maps of stars and galaxies

4.6.4. Cosmology

4.6.1 Cosmic Rays

Cosmic rays are high-energy radiation that is emitted by the sun or other objects further out in space and that strikes the Earth's atmosphere, which mostly shields the Earth's surface from the rays [L'Annunziata 2016; North 1995].

German-speaking creators made most of the major discoveries regarding cosmic rays (Figs. 4.50–4.51).

Theodor Wulf (German, 1868–1946) created electroscopes for measuring radiation (Fig. 4.51) and demonstrated in 1910 that they detected more radiation from high on the Eiffel Tower than on the ground, suggesting that radiation was coming from space.

Victor Franz Hess (Austrian, 1883–1964) carried some of Theodor Wulf's electroscopes up in his 1912 balloon flight to measure cosmic rays, and showed that the measured cosmic ray radiation increased with altitude (Fig. 4.51). Hess won the Nobel Prize in Physics in 1936 for this work. Professor H. Pleijel, Chairman of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences, praised Hess's discovery [https://www.nobelprize.org/prizes/physics/1936/ceremony-speech/]:

> Professor Hess. By virtue of your purposeful researches into the effects of radioactive radiation carried out with exceptional experimental skill you discovered the surprising presence of radiation coming from the depths of space, i.e. cosmic radiation. As you have proved, this new radiation possesses a penetrating power and an intensity of previously unknown magnitude; it has become a powerful tool of research in physics, and has already given us important new results with respect to matter and its composition. The presence of this cosmic radiation has offered us new, important problems on the formation and destruction of matter, problems which open up new fields for research. We congratulate you on your fine achievements.

Werner Kolhörster (German, 1887–1946) conducted more thorough balloon experiments in 1913–1914 and obtained more accurate data on cosmic ray radiation vs. altitude (Fig. 4.51).

Erich Regener (German, 1881–1955) developed improved radiation detectors and related instruments and launched them first in balloons and later in rockets.

Eduard Gottfried Steinke (German, 1899–1963) measured cosmic rays of different energies.

Georg Pfotzer (German, 1909–1981) was a student of Erich Regener and collaborated with him in his experiments.

Auguste Piccard (Swiss, 1884–1962) and Paul Kipfer (Swiss, 1905–1980) measured cosmic ray intensities up to the highest altitudes then possible in a balloon (Fig. 4.34).

For more information on the development of radiation detection methods in the German-speaking world, see Sections 8.1–8.2.

Cosmic rays

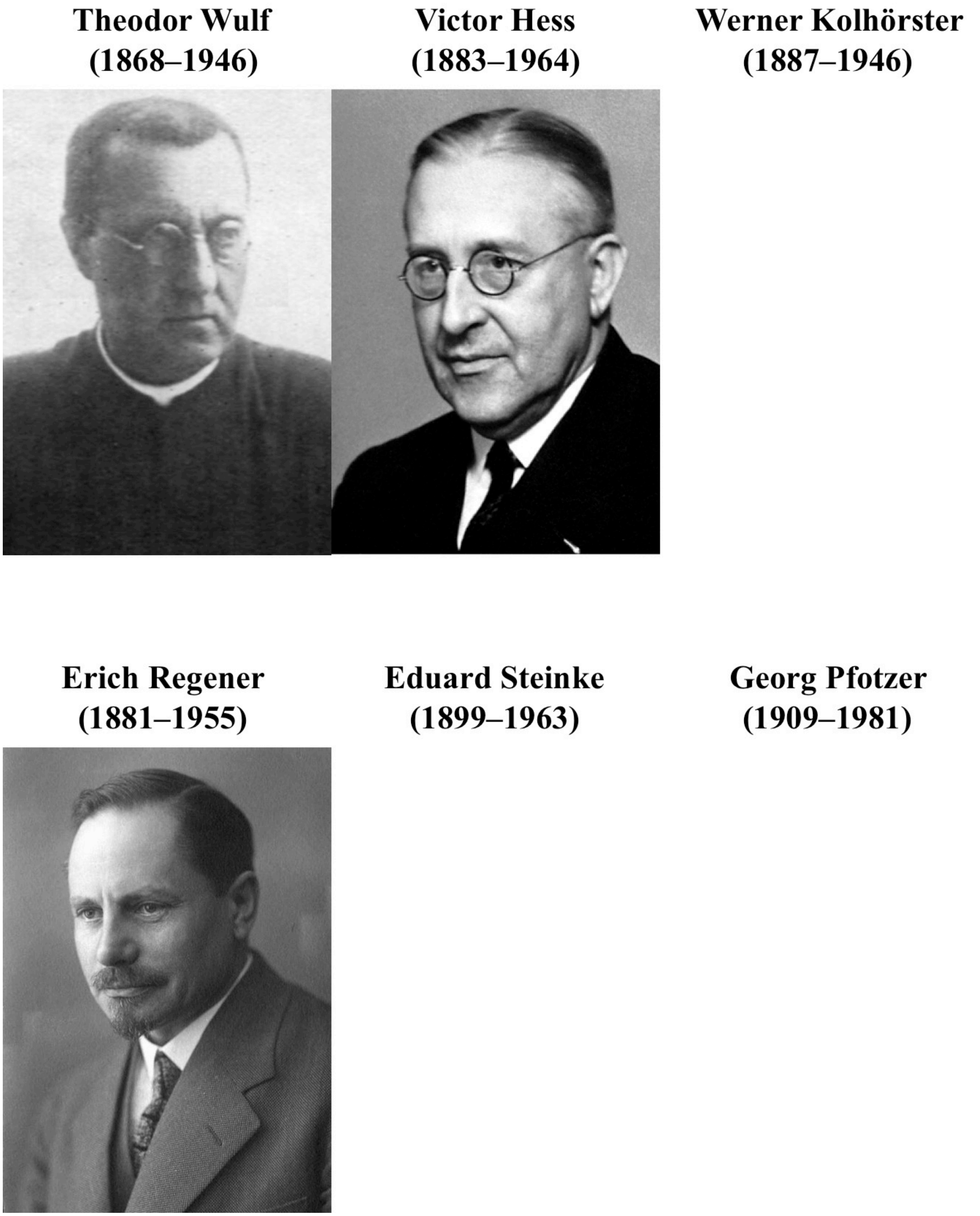
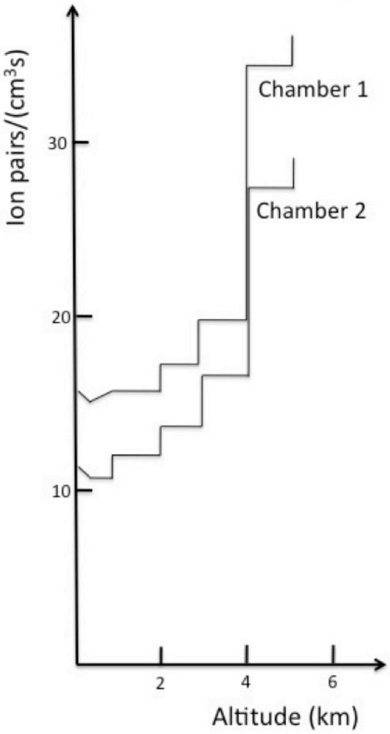


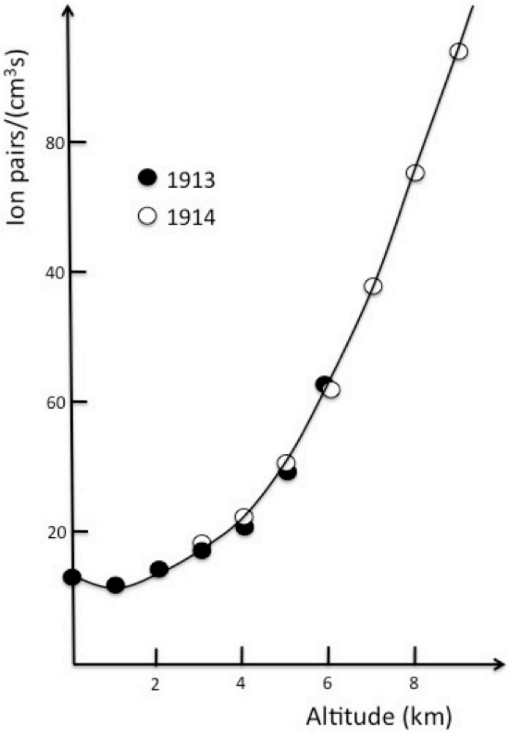
Figure 4.50: Some creators who discovered and studied cosmic rays included Theodor Wulf, Victor Hess, Werner Kolhörster, Erich Regener, Eduard Steinke, and Georg Pfotzer.

Electroscope by Theodor Wulf for measuring radiation



Victor Hess's data on radiation vs. altitude (1912)

Victor Hess's balloon flight to measure cosmic rays (1912)



Werner Kolhörster's data on radiation vs. altitude (1913–1914)

Figure 4.51: Theodor Wulf created electroscopes for measuring radiation, and Victor Hess carried them up in his 1912 balloon flight to measure cosmic rays. The graphs show Victor Hess's 1912 data on the measured cosmic ray radiation vs. altitude, and Werner Kolhörster's more accurate 1913–1914 data.

4.6.2 Stellar Physics

As illustrated in Fig. 4.52, stars such as the sun create such intense heat and pressure in the central core that they convert hydrogen into helium plus lots of energy. There are two parallel processes for that conversion, proton-proton fusion reactions and carbon-catalyzed fusion reactions.

Figures 4.53–4.54 show some of the creators who made major discoveries in stellar physics.[5]

Walter Baade (German, 1893–1960) identified and studied different types of stars.

Hans Bethe (German, 1906–2005) worked out the major fusion reactions in stars, for which he won the Nobel Prize in Physics in 1967 (p. 1542).

Ludwig Biermann (German, 1907–1986) studied the solar wind of charged particles streaming outward from the sun.

Robert Emden (Swiss, 1862–1940) developed the Emden equation describing the spatial variation of pressure inside a star.

Joseph von Fraunhofer (German states, 1787–1826) performed spectral analyses of the sun.

Fritz Houtermans (German, 1903–1966) first worked out some of the fusion reactions and reaction rates in stars.

Rudolph Minkowski (German, 1895–1976) used astrophotography to study supernovae.

J. Robert Oppenheimer (1904–1967) calculated the conditions involved in stellar collapse at the end of a star's life. Oppenheimer was born in the United States but had a German father and second-generation German-American mother, was raised speaking German, repeatedly visited family in Germany during his childhood, and received his Ph.D. in Germany under Max Born at Göttingen.

Samuel Heinrich Schwabe (German, 1789–1875) studied sunspots.

Martin Schwarzschild (German, 1912–1997) made major contributions to our understanding of stellar structure and evolution.

Hermann Carl (or Karl) Vogel (German, 1841–1907) performed spectral analyses of stars. Among other findings, he discovered spectroscopic binary stars—pairs of mutually orbiting stars that are so close together that they appear as one point of light when viewed from Earth, yet that can be distinguished from each other by the spectra of light that they emit.

Carl Friedrich von Weizsäcker (German, 1912–2007) worked out the major fusion reactions in stars.

For more information on fusion reactions, see Section 8.6.

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[5] Bethe 1991, 1997; Bird and Sherwin 2005; Brown and Lee 2006; Davis 1968; L'Annunziata 2016; North 1995; Schwarzschild 1958; Schweber 2012.

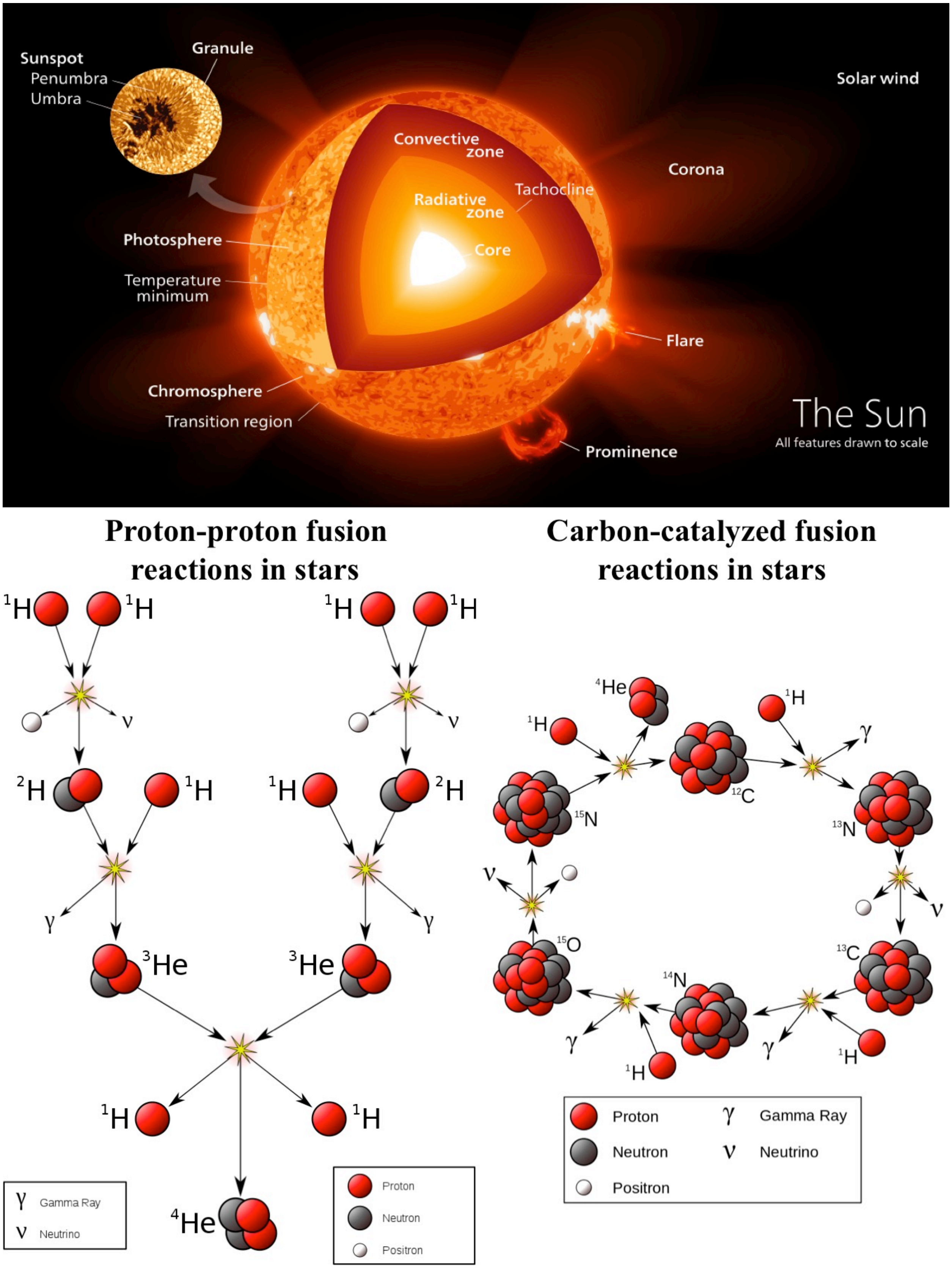


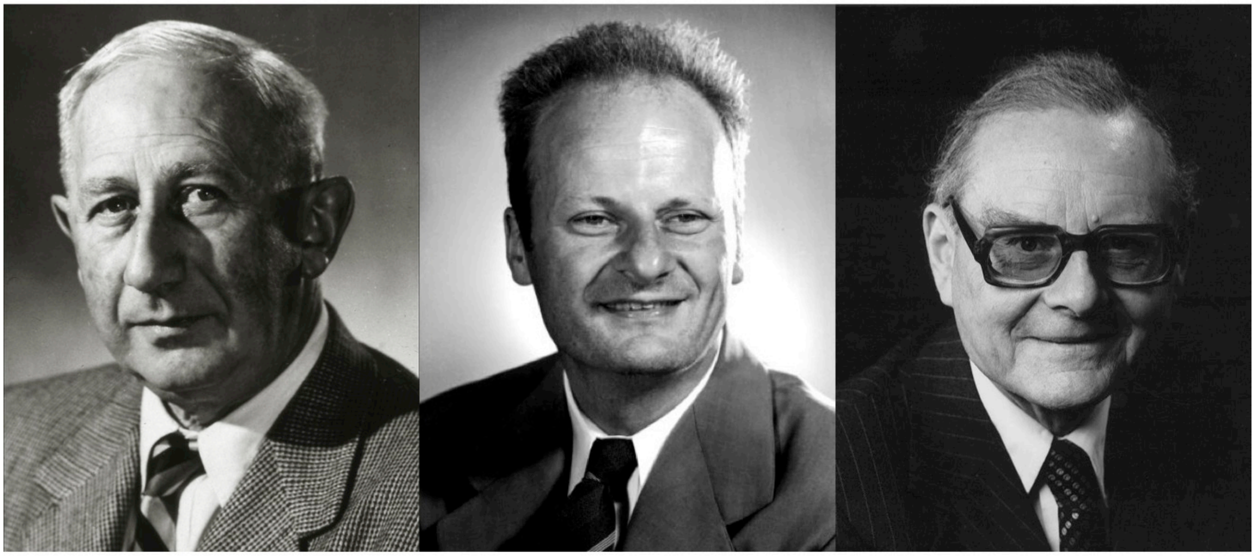
Figure 4.52: Stars such as the sun create such intense heat and pressure in the central core that they convert hydrogen into helium plus lots of energy, via both proton-proton fusion reactions and carbon-catalyzed fusion reactions.

Stellar physics

Walter Baade
(1893–1960)
Different types
of stars

Hans Bethe
(1906–2005)
Fusion reactions
in stars

Ludwig
Biermann
(1907–1986)
Solar wind



Robert Emden
(1862–1940)
Emden equation
for pressure
inside a star

Joseph von
Fraunhofer
(1787–1826)
Spectral analysis
of the sun

Fritz Houtermans
(1903–1966)
Fusion
reactions
in stars

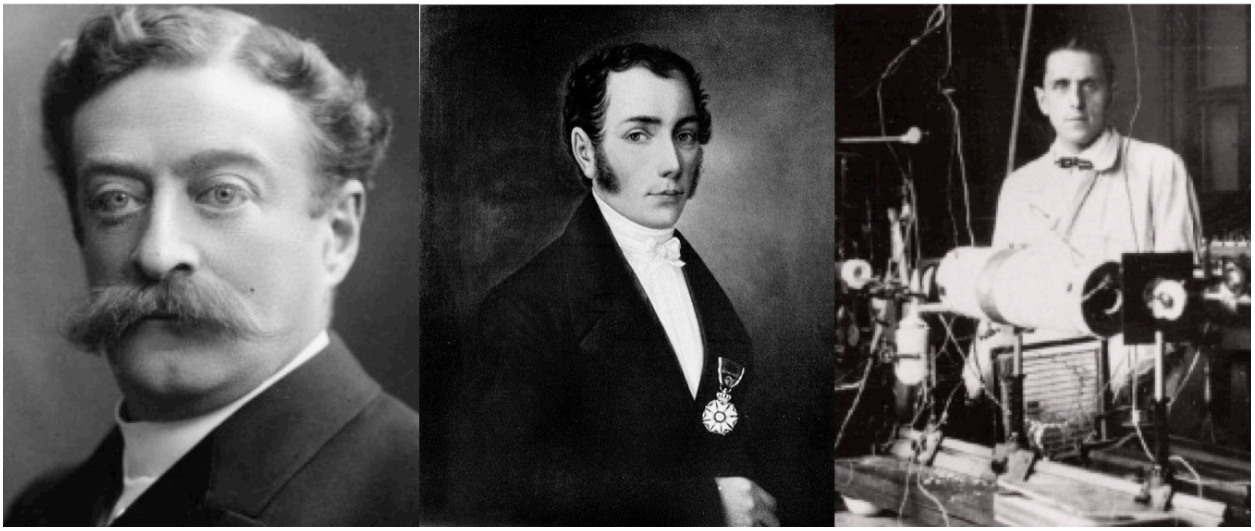


Figure 4.53: Some creators who made major discoveries in stellar physics included Walter Baade, Hans Bethe, Ludwig Biermann, Robert Emden, Joseph von Fraunhofer, and Fritz Houtermans.

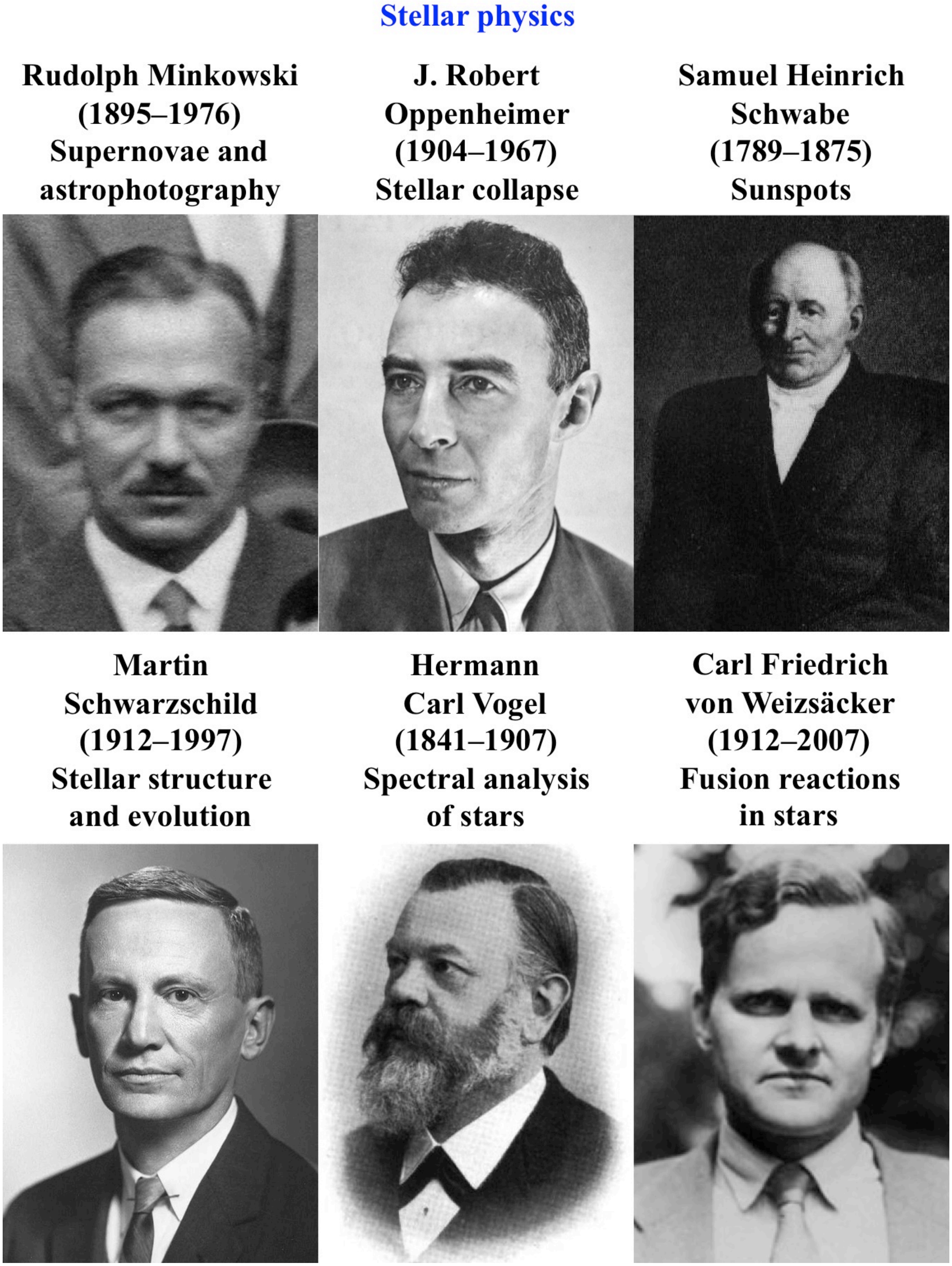


Figure 4.54: Other creators who made major discoveries in stellar physics included Rudolph Minkowski, J. Robert Oppenheimer, Samuel Heinrich Schwabe, Martin Schwarzschild, Hermann Carl Vogel, and Carl Friedrich von Weizsäcker.

4.6.3 Maps of Stars and Galaxies

Friedrich Bessel (German states, 1784–1846) developed the parallax method of measuring distances to stars (see Fig. 4.55), as well as Bessel mathematical functions. Based on geodetic observations, he approximated the figure of the Earth, and in 1841 he established the Bessel ellipsoid, which was used as an important geodetic reference system for over a century. His theory of observational errors was also highly influential in the physical sciences. The *Encyclopedia Britannica* explained the impact of Bessel's work [EB 2010]:

> Bessel was a scientist whose works laid the foundations for a better determination than any previous method had allowed of the scale of the universe and the sizes of stars, galaxies, and clusters of galaxies. In addition, he made fundamental contributions to accurate positional astronomy, the exact measurement of the positions of celestial bodies; to celestial mechanics, dealing with their movements; and to geodesy, the study of the Earth's size and shape. Further, he enlarged the resources of pure mathematics by his introduction and investigation of what are now known as Bessel functions, which he used first in 1817 to investigate the very difficult problem of determining the motion of three bodies moving under mutual gravitation. Seven years later he developed Bessel functions more fully for the treatment of planetary perturbations. Much credit for the final establishment of a scale for the universe in terms of solar system and terrestrial distances, which depends vitally on accurate measurement of the distances of the nearest starts from the Earth, must go to Bessel.

The multigenerational Baltic German Struve family of astronomers included (Fig. 4.56):

- Friedrich Georg Wilhelm von Struve (1793–1864), the son of German math teacher Jacob Struve (1755–1841), measured the distances to many stars using Bessel's parallax method, and also produced a catalog of binary stars (pairs of stars orbiting each other).

- Otto Wilhelm von Struve (1819–1905), the son of Friedrich Georg Wilhelm von Struve, made many important astronomical observations, including precession measurements for the solar system.

- Karl Hermann von Struve (1854–1920), a son of Otto Wilhelm von Struve, made detailed measurements of the positions of many moons and stars, and also devised the mathematical Struve function in 1882.

- Gustav Wilhelm Ludwig von Struve (1858–1920), another son of Otto Wilhelm von Struve, measured accurate positions of stars and the rotation rate of our Milky Way galaxy.

- Georg Otto Hermann Struve (1886–1933), the son of Karl Hermann von Struve, carefully measured the orbits of several moons of Saturn and Uranus. He also made important observations of stars and asteroids.

- Otto Struve (1897–1963), the son of Gustav Wilhelm Ludwig von Struve, studied interstellar matter and stellar physics.

Creators such as Friedrich Argelander (German, 1799–1875), Eduard Schönfeld (German, 1828–1891), Adalbert Krüger (German, 1832–1896), and Robert Trümpler (Swiss, 1886–1956) composed important catalogs of stars that are visible from Earth; see Fig. 4.57. Figure 4.58 shows examples of star catalogs by Argelander from 1843, and by Argelander, Schönfeld, and Krüger from 1859.

Bart Bok (Dutch, 1906–1983, Fig. 4.59) pioneered the study of interstellar matter and the structure of our Milky Way galaxy.

4.6.4 Cosmology

Several creators discovered and analyzed dark matter, a mysterious, invisible substance that only interacts with other things via gravity and that surrounds normal matter such as galaxies (Fig. 4.60):

- Jacobus Kapteyn (Dutch, 1851–1922) developed astrophotography, measured galactic rotation rates, and used that data to deduce the existence of dark matter.
- Fritz Zwicky (Swiss, 1898–1974) conducted experimental observations and theoretical analyses of dark matter and stellar physics, and also helped to develop jets and rockets in the United States [John Johnson, Jr., 2019; Stöckli and Müller 2008].
- Jan Oort (Dutch, 1900–1992) studied dark matter and the structure of the Milky Way galaxy, and also proposed the existence of the Oort cloud of comets in the outer reaches of our solar system.

Albert Einstein (German, 1879–1955) predicted the possible existence of dark energy (which he called the cosmological constant) in 1917 [Pais 1982]. As shown in Fig. 4.61, dark energy currently appears to make up approximately 68% of the universe and acts as an antigravitational force to push the universe apart. Approximately 27% of the universe seems to be dark matter, and only about 5% of the universe is atoms or other ordinary matter.

In 1917, Einstein and Willem de Sitter (Dutch, 1872–1934) showed that Einstein's equations of general relativity predicted that the universe should be expanding (or possibly contracting).

In a series of 1918–1924 publications (p. 882), Carl Wilhelm Wirtz (German, 1876–1939) measured the distances and velocities (based on the red-shifting of light) of other galaxies. He demonstrated that the universe was indeed expanding, and that more distant galaxies were moving away from us faster than galaxies closer to us, in agreement with Einstein's and de Sitter's predictions [Wirtz 1918, 1922a, 1922b, 1924, 1936].

For more information on relativity and cosmology, see Section 5.3.

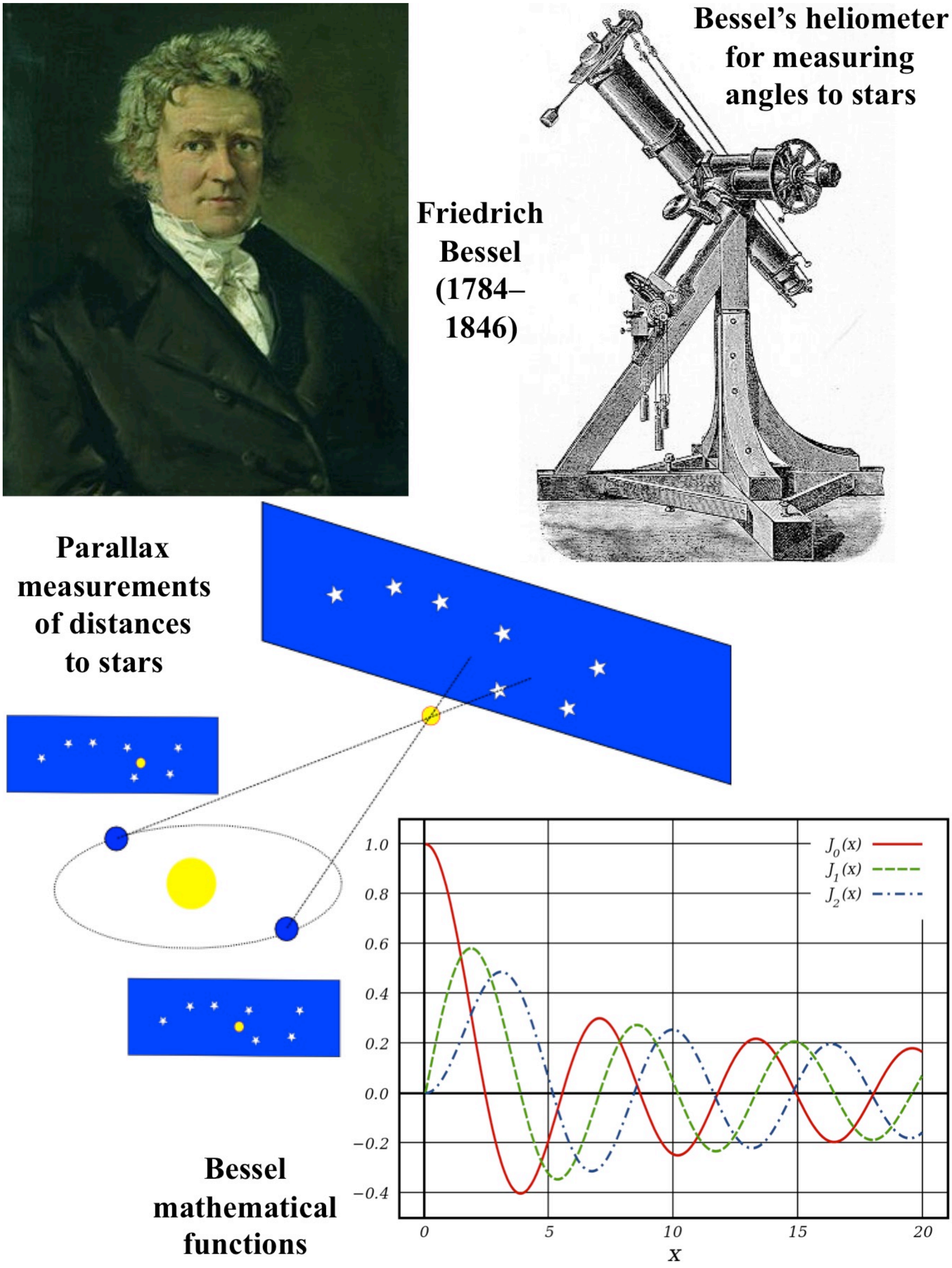


Figure 4.55: Friedrich Bessel developed the parallax method of measuring distances to stars, as well as Bessel mathematical functions.

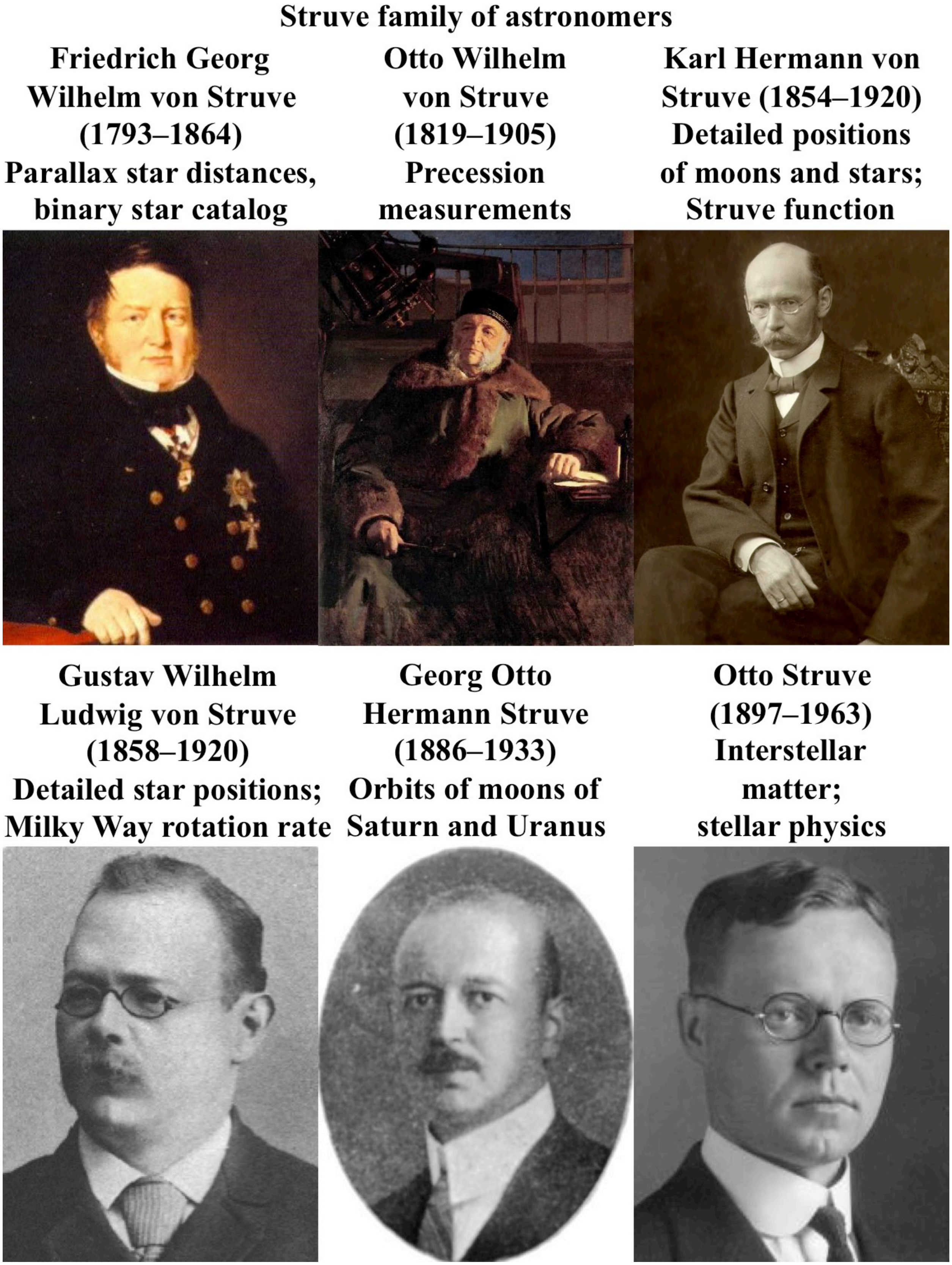


Figure 4.56: The multigenerational Struve family of astronomers included Friedrich Georg Wilhelm von Struve, Otto Wilhelm von Struve, Karl Hermann von Struve, Gustav Wilhelm Ludwig von Struve, Georg Otto Hermann Struve, and Otto Struve.

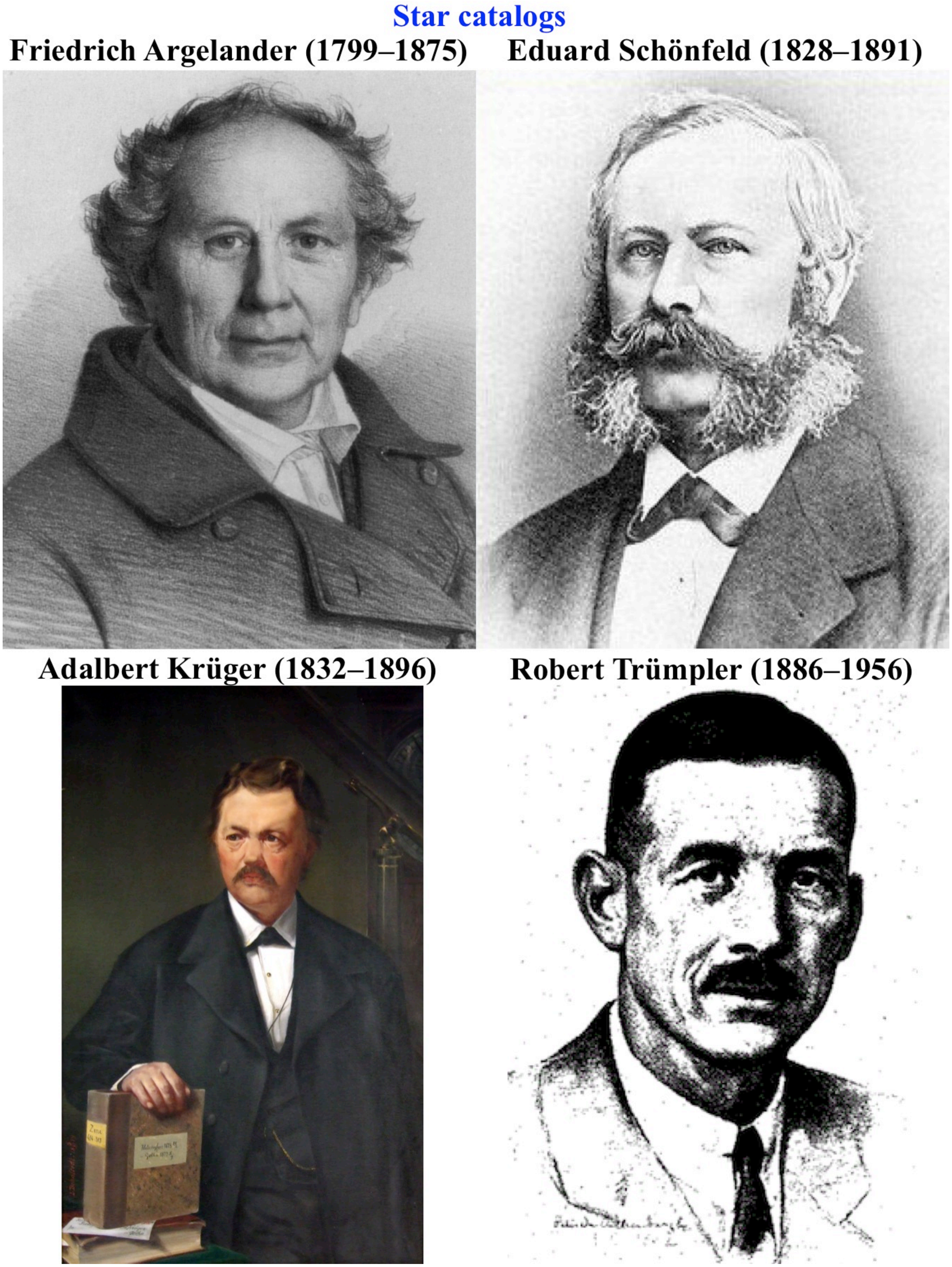
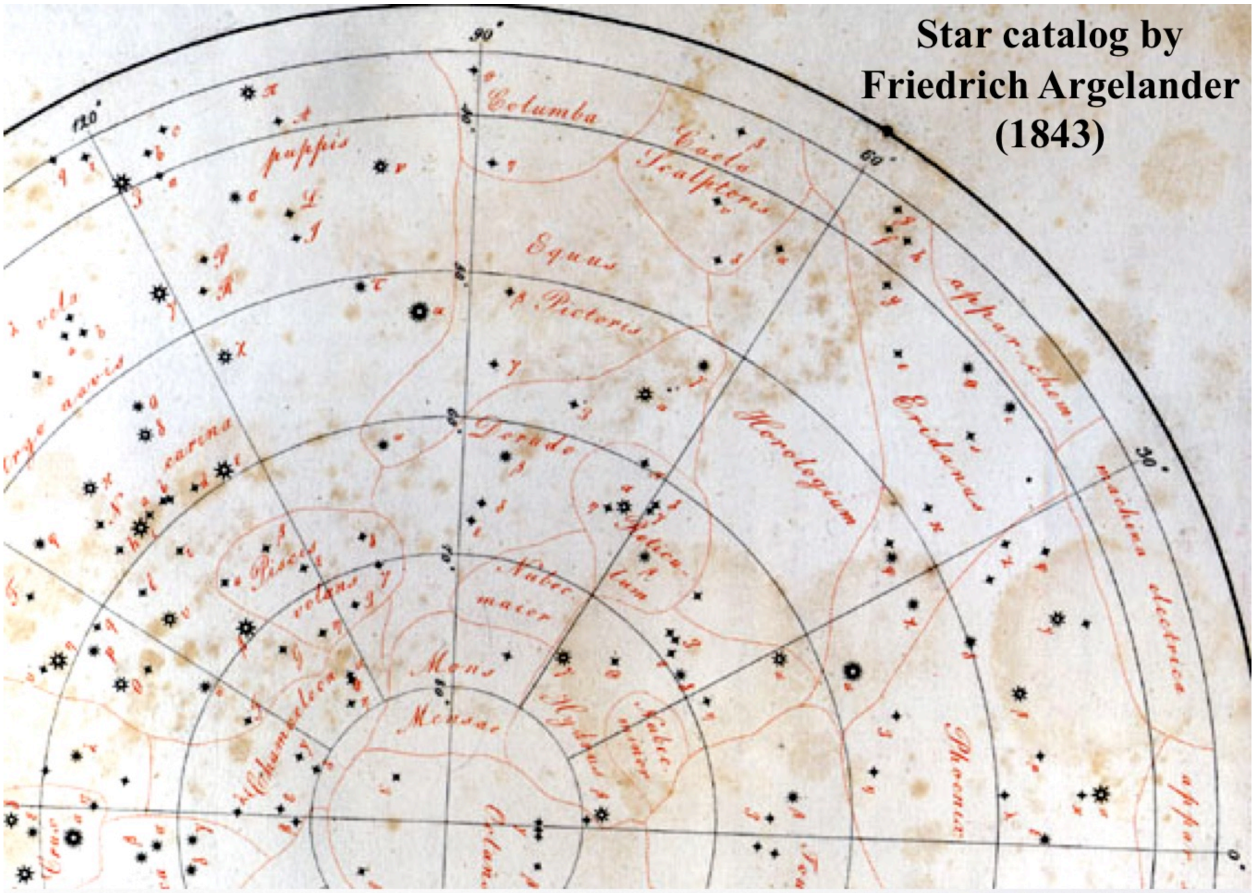
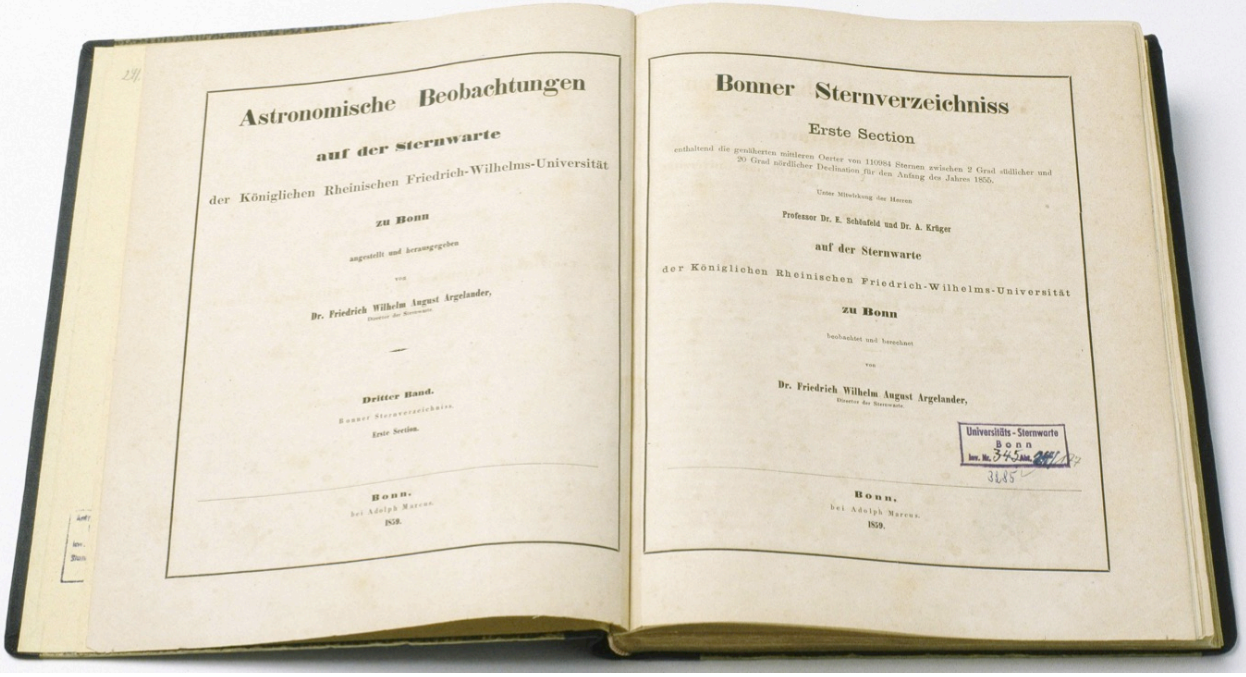


Figure 4.57: Creators such as Friedrich Argelander, Eduard Schönfeld, Adalbert Krüger, and Robert Trümpler composed important catalogues of stars that are visible from Earth.



Star catalog by Friedrich Argelander,
Eduard Schönfeld, and Adalbert Krüger (1859)



Astronomische Beobachtungen

auf der Sternwarte

der Königlichen Rheinischen Friedrich-Wilhelms-Universität

zu Bonn

angestellt und herausgegeben

von

Dr. Friedrich Wilhelm August Argelander,
Director der Sternwarte.

Dritter Band.

Bonner Sternverzeichniss.

Erste Section.

Bonn,
bei Adolph Marcus.
1859.

Bonner Sternverzeichniss

Erste Section

enthaltend die genäherten mittleren Oerter von 110984 Sternen zwischen 2 Grad südlicher und 20 Grad nördlicher Declination für den Anfang des Jahres 1855.

Unter Mitwirkung der Herren

Professor Dr. E. Schönfeld und Dr. A. Krüger

auf der Sternwarte

der Königlichen Rheinischen Friedrich-Wilhelms-Universität

zu Bonn

beobachtet und berechnet

von

Dr. Friedrich Wilhelm August Argelander,
Director der Sternwarte.

Bonn,
bei Adolph Marcus.
1859.

Figure 4.58: Star catalogs by Friedrich Argelander (1843), and by Argelander, Eduard Schönfeld, and Adalbert Krüger (1859).

Figure 4.59: Bart Bok pioneered the study of interstellar matter and the structure of our Milky Way galaxy.

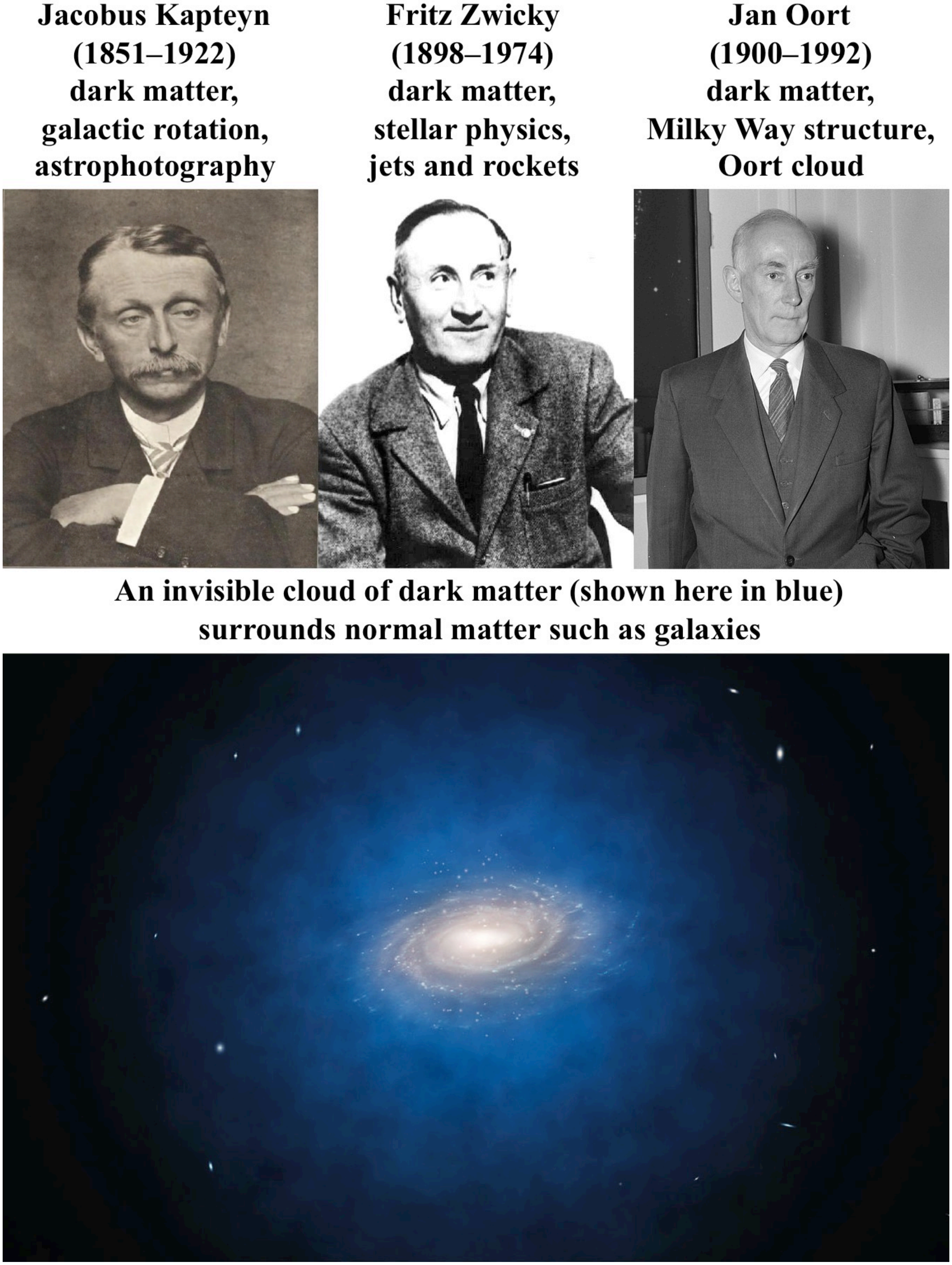


Figure 4.60: Jacobus Kapteyn, Fritz Zwicky, and Jan Oort discovered and analyzed dark matter, a mysterious, invisible substance that only interacts with other things via gravity and surrounds normal matter such as galaxies.

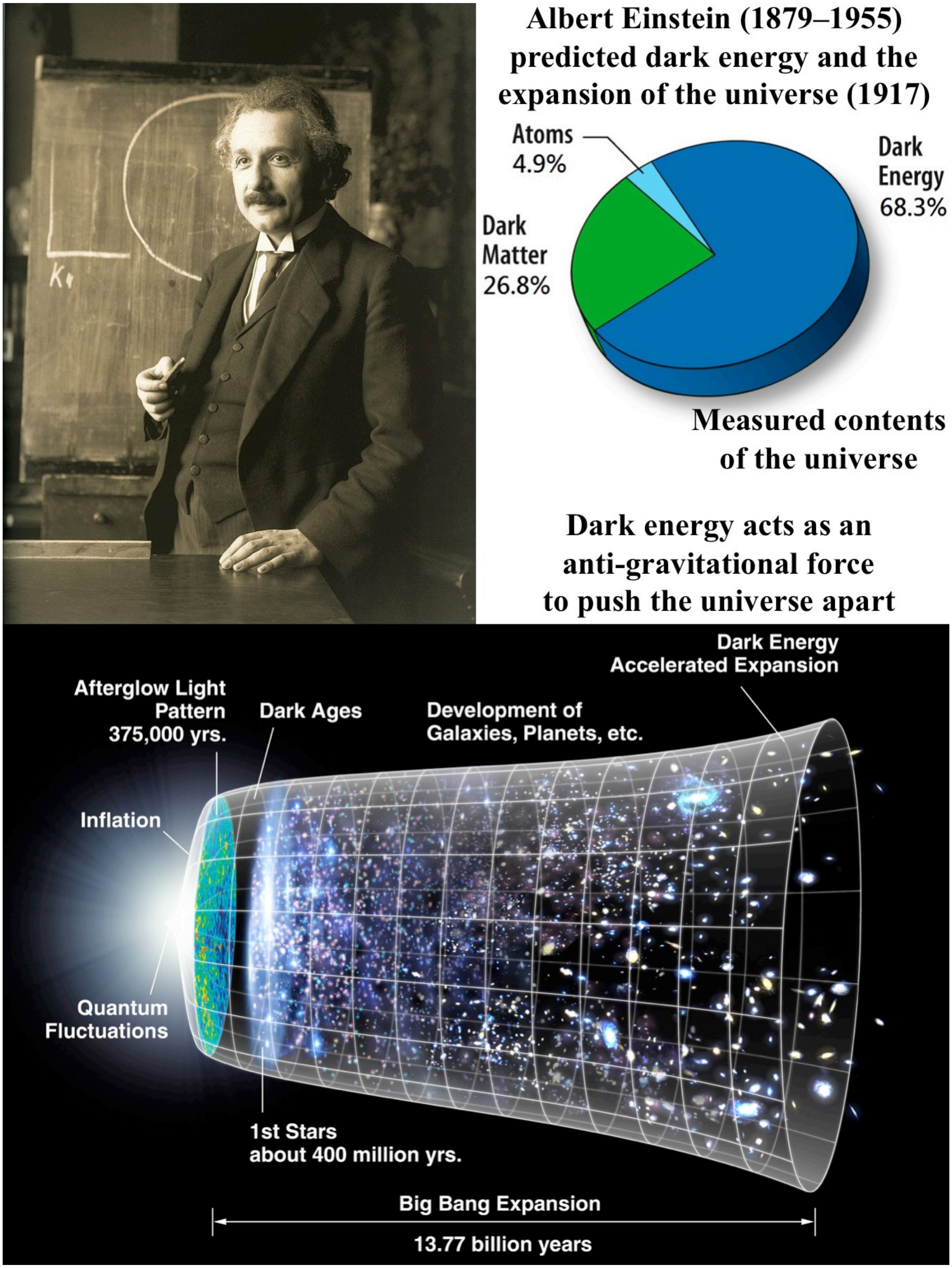


Figure 4.61: Albert Einstein predicted dark energy and the expansion of the universe in 1917. Dark energy currently appears to make up approximately 68% of the universe and acts as an antigravitational force to push the universe apart.

Chapter 5

Creators and Creations in Physics and Mathematics

Nicht die Wahrheit, in deren Besitz irgendein Mensch ist oder zu sein vermeinet, sondern die aufrichtige Mühe, die er angewandt hat, hinter die Wahrheit zu kommen, macht den Wert des Menschen. Denn nicht durch den Besitz, sondern durch die Nachforschung der Wahrheit erweitern sich seine Kräfte, worin allein seine immer wachsende Vollkommenheit bestehet.	The true value of a man is not determined by his possession, supposed or real, of Truth, but rather by his sincere exertion to get to the Truth. It is not possession of the Truth, but rather the pursuit of Truth by which he extends his powers and in which his ever-growing perfectibility is to be found.

Gotthold Lessing. 1777. Über die Wahrheit [About the Truth].

This chapter gives an overview of some physics and applied mathematics innovations that have played major roles in the modern world and that were invented or discovered by scientists and engineers who were trained in the predominantly German-speaking central European research world in the nineteenth and early twentieth centuries.

By the mid- to late-nineteenth century, intellectual leadership in applied mathematics and physics research had passed from primarily French and British scientists to German-speaking scientists:[1]

- Prior to that time, many giants of mathematical physics came out of the French intellectual tradition: Pierre-Simon Laplace (1749–1827), Joseph Fourier (1768–1830), André-Marie Ampère (1775–1836), Claude-Louis Navier (1785–1836), Sadi Carnot (1796–1832), and others. However, their numbers declined after that time, perhaps due to the nearly a century of continual political upheaval that followed the French Revolution.
- Several scientists from the United Kingdom made major physics contributions both before this point in time [e.g., Michael Faraday (1791–1867), James Clerk Maxwell (1831–1879), etc.] and after it [e.g., William Henry Bragg (1862–1942), William Lawrence Bragg (1890–1971), Ernest Rutherford (1871–1937), Paul Dirac (1902–1984), etc.]. Nonetheless, their relatively small numbers were soon dwarfed by the large numbers of talented German-speaking physicists.

As covered in this chapter, creators from the German-speaking world made major contributions to:

5.1. Applied mathematics and classical mechanics

5.2. Electromagnetism

5.3. Special and general relativity

5.4. Non-relativistic quantum physics

5.5. Statistical and thermal physics

5.6. Relativistic quantum physics

Scientists from the German-speaking world also made numerous contributions to other physics-related areas listed in Chapters 6 (applied electromagnetic technologies), 8 (nuclear physics), and 9 (applied physics in aerodynamics and spaceflight).

---

[1] In addition to specific references that are cited in different areas throughout this chapter, this chapter makes use of general biographical and project information from: ACLS 2000; Albrecht et al. 1992; Ash and Söllner 1996; Bar-Zohar 1967; Bower 1987; Bunch and Hellemans 2004; Challoner 2009; Cornwell 2003; Crim 2018; EB 1911, 2010; Gillispie 1970–1990; Gimbel 1990a; Glatt 1994; Hall 2019a; István Hargittai 2006, 2011; Linda Hunt 1991; Impey et al. 2008; Jacobsen 2014; Koertge 2007; Kurowski 1982; Lasby 1971; Lusar 1956, 1971; Medawar and Pyke 2000; Mick 2000; Murray 2003; Nachmansohn 1979; NDB 1953–2020; Neufeld 2012; Nouzille and Huwart 1999; O'Reagan 2014, 2019; Porter 1994; Charles Walker 1946; Peter Watson 2010; Weitensfelder 2009.

For general overviews of large portions of the history of physics in the German-speaking world, see: Laurie Brown et al. 1995; István Hargittai 2002, 2006, 2011; Jungnickel and McCormmach 1986, 2017; Kragh 2002; von Meÿenn 1997; Teichmann 2008; Weber 1988.

I have deliberately left a blank space where images of some creators or creations should go. Those are people or projects that I felt were important enough that they should definitely be shown in this book, yet I have not yet been able to locate a suitable image that I have permission to use, despite my searches in Europe and in the United States. If readers have any relevant images and could send them to me, I would be very grateful and will include them in future editions of this book. Even where a suitable photo cannot be located, I believe that leaving a blank space pays tribute both to the scientific importance of that creator or creation and to how that historical fact has been very nearly forgotten.

5.1 Applied Mathematics and Classical Mechanics

Beginning in the nineteenth century, applied mathematics and classical mechanics were dominated by a long list of creators from the German speaking world, as shown by the examples in this section. Today, mathematicians, physicists, and engineers still use Bessel functions, Christoffel symbols, Jacobians, Kronecker delta functions, Noether's theorem, Riemannian geometry, and other contributions made by those scientists and mathematicians. Even children learn about Möbius strips and Klein bottles, and university students still learn from the two-volume mathematical textbook of Courant and Hilbert.

5.1.1 Creators and Creations Before 1800

Although the German-speaking mathematics and physics research world became more established after 1800, there were some very important earlier creators in applied math and physics that must be mentioned.

Nicolaus Copernicus (Prussian, 1473–1543, p. 786) proposed that the planets orbit around the sun and conducted other research in physics and math.

Tycho Brahe (Danish but educated and worked in the German-speaking world, 1546–1601, p. 787) made detailed astronomical observations that were used by Johannes Kepler to calculate planetary orbits.

Johannes Kepler (Weil der Stadt, 1571–1630, p. 788) worked out the physics of planetary orbits and also did other work in physics and math.

Otto von Guericke (also spelled von Gericke; German states, 1602–1686, p. 1488) established the physics of water and air pressure, and also studied the electrostatic force and other forces. He used those discoveries to create several ingenuous inventions [Harsch 2007b].

Christiaan Huygens (Dutch, 1629–1695, Fig. 5.1) derived mathematical formulas describing centripetal force, pendulums, optics, and other important aspects of mathematics and classical mechanics [Andriesse 2005].

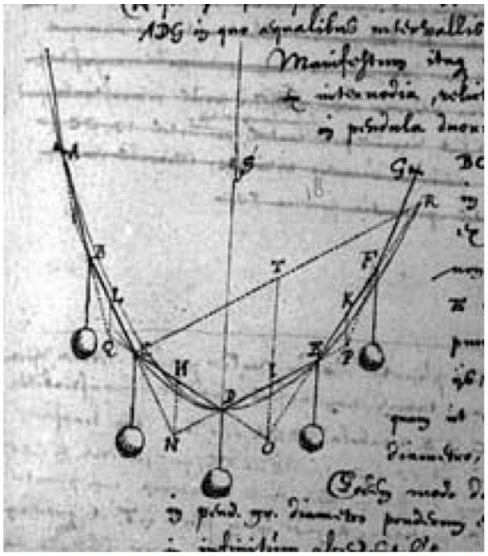
Gottfried Leibniz (Saxony, 1646–1716, Fig. 5.1) developed differential and integral calculus and made numerous other contributions to mathematics and classical mechanics (including the conservation of energy and the idea that time and space could be relative instead of absolute). Leibniz also developed binary mathematics and built calculating machines (p. 1160). He designed other hardware from mining equipment to prototype submarines and proposed very prescient theories regarding everything from biological evolution to the interior structure of the Earth [Antognazza 2009].

Daniel Bernoulli (Swiss, 1700–1782, p. 1659) derived the Bernoulli equation for incompressible, inviscid fluid flow, and published it in 1738. He also made important contributions to the theory of flexible beams, probability, statistics, and economic theory.

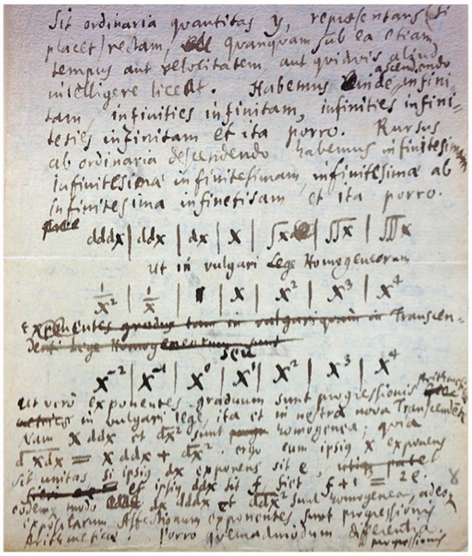
Leonhard Euler (Swiss, 1707–1783, Fig. 5.1) made extensive contributions to calculus, complex number theory, topology and graph theory, mechanical stress and strain calculations, astronomy, optics, fluid mechanics, logic, and other topics [Calinger 2015; Richeson 2008].

Applied mathematics and classical mechanics

Christiaan Huygens (1629–1695)



Gottfried Leibniz (1646–1716)



Sit ordinaria quantitas y, repraesentans (si placet) rectam, ~~vel~~ quanquam sub ea etiam tempus aut velocitatem aut quidvis aliud intelligere liceat. Habemus inde ascendendo infinitam, infinities infinitam, infinities infinities infinitam et ita porro. Rursus ab ordinaria descendendo habemus infinitesimam infinitesimam infinitesimam, infinitesima ab infinitesima infinetisam et ita porro.

$$dddx \mid ddx \mid dx \mid x \mid \int x \mid \int\int x \mid \int\int\int x$$

ut in vulgari Lege Homogeneorum

$$\frac{1}{x^2} \mid \frac{1}{x} \mid 1 \mid x \mid x^2 \mid x^3 \mid x^4$$

Exponentes ~~graduum tam in vulgari quam in Transcendenti lege Homogeneorum sunt~~ seu

$$x^{-2} \mid x^{-1} \mid x^0 \mid x^1 \mid x^2 \mid x^3 \mid x^4$$

Ut vero exponentes graduum sunt progressionis Arithmeticae in vulgari lege, ita et in nostra nova Transcendenti. Nam $x\,ddx$ et dx^2 sunt homogenea; quia $d\,xdx = x\,ddx + dx^2$. ergo cum ipsius x exponens sit unitas, si ipsius dx exponens sit e, ~~utique patet~~ et ipsius ddx sit f, fiet $f+1 = 2e$. eodem modo $dx\,dddx$ et ddx^2 sunt homogenea, adeoque ipsarum Affectionum exponentes sunt progressionis Arithmeticae. Porro quemadmodum differentiae progressionis

Leonhard Euler (1707–1783)

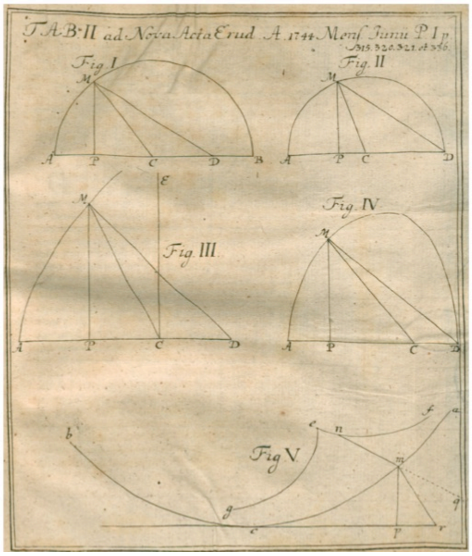


Figure 5.1: Early creators who made significant contributions to applied mathematics and classical mechanics included Christiaan Huygens, Gottfried Leibniz, and Leonhard Euler.

5.1.2 Creators and Creations After 1800

From around 1800 onward, the number and importance of people in the greater German-speaking world who made major contributions to mathematics and classical mechanics steadily increased until they dominated these fields.[2] In fact, the number of contributors was so great that this section will only briefly list some of the more notable ones (shown in Figs. 5.2–5.17) and their accomplishments in alphabetical order.

Emil Artin (Austrian, 1898–1962) made major contributions in algebraic number theory, class field theory, and other areas of mathematics, and is also remembered for his Artin's conjectures on certain mathematical problems.

Stefan Banach (Polish, 1892–1945) developed the general theory of functional analysis and introduced many mathematical concepts that still bear his name, such as Banach algebras, the Banach fixed-point theorem, Banach measures, Banach space, the Banach-Alaoglu theorem, the Banach-Mazur game, the Banach-Steinhaus theorem, the Banach-Tarski paradox, the Hahn-Banach theorem, etc.

Paul Bernays (Swiss, 1888–1977) made important discoveries in axiomatic set theory, mathematical logic, and complex analysis. He worked closely with David Hilbert, for example on what is now known as the Hilbert-Bernays paradox.

In addition to fundamental discoveries in astronomy, Friedrich Bessel (Minden, 1784–1846) made major contributions to applied mathematics, which he used to analyze his astronomical data. In particular, he developed what are now called Bessel functions, which are especially useful for describing waves (such as electromagnetic waves, sound waves, or quantum waves) in cylindrical geometries like pipes and waveguides.

János Bolyai (Hungarian, 1802–1860) helped to develop non-Euclidean geometry, or mathematics describing dimensions that are warped, such as Albert Einstein later used in analyzing how gravity warps the dimensions of space and time. He was the son of Wolfgang Farkas Bolyai.

Wolfgang Farkas Bolyai (Hungarian, 1775–1856) did important work on new methods of analysis in geometry and on iterative and convergent solutions to mathematical problems. He was the father of János Bolyai.

Bernardus Bolzano (Bohemian, 1781–1848) contributed in the areas of math analysis, analytic proofs, and mathematical limits, and his name is remembered in theorems such as Bolzano's theorem and the Bolzano-Weierstrass theorem.

Alexander von Brill (German, 1842–1935) worked in the area of algebraic geometry and functions, and is perhaps best remembered for Brill-Noether theory. One of his students was Max Planck, who went on to help found the field of quantum physics (p. 890).

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[2] For good overviews of this area, see especially: Grattan-Guinness 1998; Jungnickel and McCormmach 1986, 2017; Kragh 2002. On the end of this era, see Segal 2003. For a much more extensive list, with excellent details about each mathematician, see: https://mathshistory.st-andrews.ac.uk/Countries/.

Luitzen Brouwer (Dutch, 1881–1966) did important work in complex analysis, measure theory, set theory, and topology. His name is still attached to concepts such as the Brouwer fixed-point theorem and the Phragmen-Brouwer theorem.

Karl Hermann Brunn (German, 1862–1939) conducted research in convex geometry and knot theory. He is known for Brunnian links and the Brunn-Minkowski inequality.

Heinrich Burkhardt (German, 1861–1914) worked on Fourier analysis, real-variable analysis, and group theory.

Georg Cantor (born in Russia but educated and worked in Germany, 1845–1918) developed the theory of mathematical sets and applied it to a wide range of cases, greatly influencing later mathematicians such as John von Neumann. He also made major contributions to Fourier analysis and the foundations of real analysis.

Constantin Carathéodory (German, 1873–1950) made important findings regarding the calculus of variations, conformal representations, measure theory, and real analysis.

Elwin Christoffel (German, 1829–1900) worked in complex variable analysis, differential geometry, number analysis, and Abelian functions and integrals. He is best remembered for creating certain tensors or matrices that are now called Christoffel symbols, which describe warped dimensions and were later incorporated into the theory of general relativity by Albert Einstein.

Rudolf Alfred Clebsch (German, 1833–1872) made useful discoveries in algebraic geometry and invariant theory. His name is still remembered in Clebsch surfaces, Clebsch representations and Clebsch potentials, and (with Paul Gordan) the Clebsch-Gordon coefficients that physicists later found useful for describing the quantum behavior of electron clouds in atoms.

Lothar Collatz (German, 1910–1990) specialized in developing novel numerical methods for finding approximate solutions to difficult equations. Among other creations, he is remembered for the Collatz conjecture and the Collatz-Wielandt formula.

Richard Courant (German, 1888–1972) made a wide range of contributions to mathematics during his long career. In modern times, he is especially remembered for developing finite element methods to produce approximate numerical solutions of differential equations to any desired accuracy, which became especially useful once computers were available. In collaboration with David Hilbert, he wrote a two-volume textbook, *Methods of Mathematical Physics*, that is still widely used in university courses today.

Richard Dedekind (German, 1831–1916) did important work in abstract algebra, algebraic number theory, the axiomatic foundation for the natural numbers, real numbers, and other areas of mathematics. He was the last doctoral student of Carl Friedrich Gauss.

Max Dehn (German, 1878–1952) made useful innovations in geometry, group theory, and topology, and his name is attached to concepts such as Dehn's algorithm, Dehn functions, and the Dehn-Nielsen theorem.

Peter Gustav Lejeune Dirichlet (Prussian, 1805–1859) made so many vital contributions to mathematics, especially in the areas of number theory, Fourier series, and mathematical analysis, that his name remains attached to well over two dozen different mathematical concepts that are still in use. Those mathematical innovations named after him include: Dirichlet's approximation theorem, the Dirichlet beta function, Dirichlet boundary conditions, Dirichlet's box principle, Dirichlet characters, Dirichlet conditions, Dirichlet convolution, the Dirichlet density, Dirichlet distributions of several types, the Dirichlet divisor problem, the Dirichlet eigenvalue, Dirichlet's ellipsoidal function, Dirichlet's energy, the Dirichlet form, the Dirichlet function, Dirichlet integrals, Dirichlet kernels, the Dirichlet L-function, the Dirichlet principle, the Dirichlet problem, Dirichlet processes of different types, the Dirichlet ring, Dirichlet series, Dirichlet space, the Dirichlet stability criterion, Dirichlet tessellation or cells, Dirichlet's test, Dirichlet's theorem on arithmetic progressions, and Dirichlet's unit theorem.

Paul du Bois Reymond (German, 1831–1889) worked in the areas of differential equations, Fourier analysis, and real-variable analysis.

Walther von Dyck (German, 1856–1934) made many contributions to group theory and Riemann surfaces. His name remains attached to Dyck graphs, Dyck groups, Dyck language, Dyck paths, Dyck's surface, Dyck tessellations, and Dyck's theorem.

Samuel Eilenberg (Polish, 1913–1998) worked in algebraic topology and automata theory, developed category theory, and is remembered for mathematical constructs such as the Eilenberg swindle and the Eilenberg-Steenrod axioms.

Andreas von Ettingshausen (Austrian, 1796–1878) made important contributions to combinatorial analysis that are widely used in probability and physics, and also conducted extensive research in electromagnetism and optics.

Alfred Enneper (German, 1830–1885) worked in several areas of mathematics and is especially remembered for Enneper's minimal surfaces and Enneper-Weierstrass parameterization.

Erwin Fehlberg (German, 1911–1990) developed improved numerical methods for finding approximate solutions to differential equations, most notably the Runge-Kutta-Fehlberg method. Fehlberg moved to the United States after World War II and was ultimately awarded NASA's Exceptional Scientific Achievement Medal for his work calculating trajectories for the Apollo missions to the moon.

William Feller (Austro-Hungarian Croatian, 1906–1970) did most of his work in probability and statistics, but also contributed to mathematical analysis, geometry, and other areas. His name is attached to Feller's explosion test, Feller-Brown movement, Feller processes, and the Lindeberg-Feller theorem.

Abraham Fränkel (German, 1891–1965) worked in axiomatic set theory; his name is still remembered in the Zermelo-Fränkel axioms.

Friedrich Gottlob Frege (German, 1848–1925) focused on the field of mathematical logic; his name is tied to the Frege-Church ontology, the Frege-Geach problem, Frege's puzzles, the Frege-Russell view, and Frege's theorem.

Robert Fricke (German, 1861–1930) worked in the areas of automorphic functions and elliptic functions. He is perhaps best remembered for Fricke involution and for his collaborative writings with Felix Klein.

Georg Frobenius (German, 1849–1917) made many contributions to differential equations, elliptic functions, group theory, and number theory. His name is attached to concepts such as Frobenius manifolds, the Frobenius matrix, the Frobenius method, and the Frobenius-Stickelberger formulae.

Lazarus Immanuel Fuchs (German, 1833–1902) made important innovations in complex variable analysis and Abelian functions and integrals. He focused especially on methods of solving differential equations, and is remembered for Fuchs's conditions, Fuchsian groups, Fuchs's theorem, and the Picard-Fuchs equation. He was the father of Maximilian Fuchs.

Maximilian Ernst Richard Fuchs (German, 1873–1944), the son of Lazarus Fuchs, continued and significantly extended his father's work on differential equations.

Karl Rudolf Fueter (Swiss, 1880–1950) worked on algebraic number theory and quaternions, and is known for the Fueter-Pólya theorem.

Carl Friedrich Gauss (German states, 1777–1855) made discoveries in mathematics, science, and engineering that were staggering in both their number and importance [Dunnington 1955]. Among other mathematical accomplishments, he proved several important theorems in algebra, was the first to consider non-Euclidean geometries, and discovered four-dimensional complex numbers (quaternions) in 1819. (See also pp. 740, 793, 858, and 972.)

Kurt Gödel (Austrian, 1906–1978) made revolutionary contributions to mathematical logic and set theory. His name is immortalized with Gödel's incompleteness and completeness theorems, the Gödel metric, Gödel numbering, the Gödel ontological proof, and Gödel-Dummett logic.

Paul Gordan (German, 1837–1912) made many contributions to invariant theory as well as Abelian functions and integrals, developed the Clebsch-Gordan coefficients with Rudolf Clebsch, and is also known for Gordan's lemma. He was the doctoral advisor of Emmy Noether.

Hermann Grassmann (German, 1809–1877) developed a whole field that is now known as Grassmann algebra; it combines algebra, geometry, and group theory in an approach that is useful for solving a wide variety of problems.

Hermann Hankel (German, 1839–1873) worked in complex analysis and other areas of mathematics. He is especially remembered for the Hankel contour, Hankel functions, the Hankel matrix, and the Hankel transform.

Carl Gustav Axel Harnack (Baltic German, 1851–1888) made contributions in the areas of real-variable analysis and also algebraic geometry and functions. He is still remembered for Harnack's inequality, Harnack's principle, and Harnack's theorem.

Friedrich Hartogs (German, 1874–1943) developed many important concepts in set theory and complex analysis, such as the Hartogs domain, Hartogs's extension theorem, Hartogs's function, Hartogs's lemma, the Hartogs number, Hartogs's theorem, the Hartogs-Laurent expansion, and the Hartogs-Rosenthal theorem.

Felix Hausdorff (German, 1868–1942) made major contributions in topology, set theory, measure theory, and functional analysis. He is known for the Hausdorff dimension, Hausdorff distance, the Hausdorff maximal principle, the Hausdorff measure, the Hausdorff moment problem, the Hausdorff paradox, Hausdorff space, and the Hausdorff-Young inequality.

Heinrich Eduard Heine (German, 1821–1881, not to be confused with the earlier German poet Heinrich Heine) worked in real analysis and introduced important innovations regarding spherical harmonics, Legendre functions, hypergeometric series, and other mathematical approaches. His name remains known via the Heine-Borel theorem, the Heine-Cantor theorem, Heine-Stieltjes polynomials, the Heine definition of continuity, Heine functions, Heine's identity, and the Mehler-Heine formula.

David Hilbert (German, 1862–1943) made huge contributions to many areas of mathematics, including algebraic number theory, the calculus of variations, commutative algebra, Euclidean and non-Euclidean geometry, and invariant theory. His name remains associated with Hilbert's axioms, Hilbert's basis theorem, Hilbert's problems, Hilbert's program, and Hilbert space. In collaboration with Richard Courant, he wrote a two-volume textbook, *Methods of Mathematical Physics*, that is still widely used.

Heinz Hopf (German, 1894–1971) worked in topology and geometry, and is known for many concepts, such as Hopf algebra, the Hopf conjecture, Hopf fibration, the Hopf invariant, the Hopf link, the Hopf manifold, the Hopf map, Hopf surfaces, the Hopf theorem, and the Killing-Hopf theorem.

Adolf Hurwitz (German, 1859–1919) contributed to complex variable analysis, elliptic functions, real-variable analysis, and Riemann surfaces. He is remembered for Hurwitz's automorphisms theorem, Hurwitz quaternions, the Riemann-Hurwitz formula, and the Routh-Hurwitz stability criterion.

Carl Gustav Jacobi (Prussian, 1804–1851) introduced important innovations in the classical mechanics of orbits, differential equations, elliptic functions, and number theory. His name is widely recognized from concepts such as the Jacobian, the Jacobi ellipsoid, Jacobi's elliptic functions, the Jacobi identity, the Jacobi method, Jacobi operators, Jacobi polynomials, Jacobi symbols, the Jacobi transform, and the Hamilton-Jacobi equation.

Theodor Kaluza (German, 1885–1954) produced very creative ideas regarding non-Euclidean geometries and extra dimensions that proved useful in some versions of relativity and unified field theories. His son Theodor Kaluza Jr. (German, 1910–1994) was also a mathematician.

Wilhelm Killing (German, 1847–1923) made numerous important contributions to group theory. His name is attached to many concepts, such as the Killing equation, the Killing form, the Killing-Hopf theorem, the Killing horizon, the Killing spinor, the Killing tensor, and the Killing vector field.

Christian Felix Klein (German, 1849–1925) made a large number of discoveries in algebraic geometry and functions, automorphic functions, elliptic functions, and Riemann surfaces. His mathematical innovations found many later applications in theoretical physics. He also created the structure now known as a Klein bottle, somewhat like a three-dimensional Möbius strip.

Sofia Kovalevskaya (Russian but educated in Germany, 1850–1891) did important work in differential equations, as well as Abelian functions and integrals. She is still known from the Cauchy-Kowalevski theorem.

Leopold Kronecker (German, 1823–1891) made research advances in algebra, mathematical logic, and number theory. Today is he remembered from the Kronecker delta function, Kronecker's lemma, the Kronecker product, the Kronecker symbol, Kronecker's theorem, and the Kronecker-Weber theorem.

Ernst Kummer (German, 1810–1893) worked on Bessel functions, class field theory, hypergeometric series, and other topics. His name remains linked to Kummer extensions of fields, the Kummer surface, and Kummer theory.

Martin Wilhelm Kutta (German, 1867–1944) developed practical methods of extracting useful answers from very complicated physics and engineering equations, especially in aerodynamics. He collaborated with Carl Runge to create the Runge-Kutta methods of producing approximate but sufficiently accurate numerical solutions to differential equations. He also developed complex analysis transformations for solving the equations for airflow around wings and other objects.

Daniel Christian Ludolph Lehmus (German, 1780–1863) worked in geometry and is especially remembered for the Steiner-Lehmus theorem.

Sophus Lie (Norwegian but studied and worked in Germany, 1842–1899) made huge contributions to differential equations and group theory that are now widely used in theoretical physics. His name is immortalized in concepts such as Lie algebra, Lie groups, Lie symmetries, and Lie theorems.

Carl Ferdinand von Lindemann (German, 1852–1939) worked in algebraic geometry and functions, and became famous for proving that π is a transcendental number. He was also the doctoral advisor for prominent mathematicians and physicists such as David Hilbert, Martin Kutta, Alfred Loewy, Hermann Minkowski, Oskar Perron, Arthur Rosenthal, and Arnold Sommerfeld.

Rudolf Lipschitz (German, 1832–1903) made important contributions to differential equations, real-variable analysis, and Fourier analysis. Perhaps most importantly, he independently discovered "Clifford algebras" at approximately the same time or earlier than William Clifford (English, 1845–1879), but with far less fame. He is remembered with the Lipschitz continuity condition, the Lipschitz integral condition, and the Lipschitz quaternion.

Alfred Loewy (German, 1873–1935) focused on representation theory and introduced innovations now known as Loewy decomposition, the Loewy length, Loewy rings, and Loewy series.

Gustav Ferdinand Mehler (German, 1835–1895) worked in several areas of mathematics, and is noted for Mehler's formula, Mehler functions, the Mehler kernel, the Mehler-Fock transform, and the Mehler-Heine formula.

Friedrich Wilhelm Franz Meyer (German, 1856–1934) spent his career investigating algebraic geometry and functions.

Hermann Minkowski (German, 1864–1909) did important work in geometry and number theory, and also contributed to the development of the theory of relativity. His name is still attached to concepts such as Minkowski addition, Minkowski content, Minkowski diagrams, Minkowski's question mark function, Minkowski space, the Minkowski functional, the Minkowski inequality, the Minkowski problem, Minkowski's bound, Minkowski's theorem in geometry of numbers, and the Brunn-Minkowski inequality.

Richard von Mises (Austro-Hungarian, 1883–1953) developed mathematical methods of solving equations in aerodynamics and the mechanics of materials, working with differential equations, complex analysis, probability, and statistics.

August Möbius (Saxony, 1790–1868) worked in topology and geometry as well as astronomy. He is particularly famous for the Möbius strip (a figure-8 formed from a strip of paper, which effectively only has one side), but he is also known for the Möbius function, the Möbius inversion formula, Möbius transformations, the Möbius-Kantor configuration, and the Möbius-Kantor graph.

Carl Neumann (German, 1832–1925), the son of physicist Franz Ernst Neumann, developed mathematical methods for analyzing physics problems. He is especially remembered for the Neumann boundary condition and Neumann series.

John von Neumann (Hungarian, 1903–1957) contributed a vast number of innovations to mathematics, physics, engineering, computer science, and economics [Macrae 1992]. Among many other contributions, he is known for von Neumann algebra, von Neumann architecture, the von Neumann bicommutant theorem, the von Neumann cardinal assignment, the von Neumann cellular automaton, the von Neumann conjecture, the von Neumann entropy, the von Neumann equation, the von Neumann ergodic theorem, the von Neumann extractor, von Neumann's inequality, von Neumann interpretation, the von Neumann measurement scheme, the von Neumann neighborhood, von Neumann ordinals, the von Neumann paradox, the von Neumann regular ring, the von Neumann spectral theorem, von Neumann stability analysis, the von Neumann universal constructor, the von Neumann universe, and von Neumann-Bernays-Gödel set theory.

Rolf Nevanlinna (Finnish but an active part of the German research world, 1895–1980) worked in complex analysis and developed what are now known as Nevanlinna theory and Nevanlinna class functions.

Emmy Noether (German, 1882–1935), the daughter of Max Noether, made revolutionary discoveries in both mathematics and theoretical physics. In mathematics, she worked on algebraic invariants, number fields, abstract algebra, noncommutative algebras, hypercomplex numbers, group theory, and topology. In physics, she is most famous for discovering Noether's theorem, which explains the relationship between conservation laws (such as the conservation of energy or the conservation of momentum) and symmetries (ways that variables such as time and space can be shifted without altering the fundamental laws of physics). Noether's theorem has been employed in many areas of physics since she first articulated it.

Max Noether (German, 1844–1921) conducted research on algebraic functions, algebraic geometry, and Riemann surfaces. His full name (to distinguish him from his even more famous daughter) is attached to Max Noether's inequality, Max Noether's residual intersection theorem, Max Noether's theorem on canonical curves, Max Noether's theorem on the Cremona group, Max Noether's theorem on curves on algebraic surfaces, and Max Noether's theorem on rationality for surfaces.

Moritz Pasch (German, 1843–1930) focused on algebraic geometry and functions and the foundations of geometry. He is most noted for Pasch's axiom.

Oskar Perron (German, 1880–1975) worked on differential equations and continued fractions, and is known for the Perron method for solving elliptic differential equations and for Perron's paradox.

Ernst Peschl (German, 1906–1986) made important contributions to complex analysis, the solution of partial differential equations, and differential geometry.

Michel Plancherel (Swiss, 1885–1967) worked in mathematical analysis and algebra, and is remembered for the Plancherel measure, the Plancherel theorem for harmonic analysis, and the Plancherel theorem for spherical functions.

Julius Plücker (German states, 1801–1868) contributed to geometry and also physics. In mathematics, he is known for Plücker's conoid, Plücker coordinates, Plücker embedding, the Plücker formula, the Plücker matrix, the Plücker relations, and the Plücker surface.

George Pólya (Hungarian, 1887–1985) worked in many areas of mathematics, including algebra, combinatorics, geometry, mathematical analysis, number theory, probability, and series. He is associated with numerous concepts such as the Pólya-Aeppli distribution, the Pólya conjecture, the Pólya distribution, the Pólya enumeration theorem, the Pólya inequality, the Pólya urn model, the Fueter-Pólya theorem, and the Hilbert-Pólya conjecture.

Alfred Pringsheim (German, 1850–1941) contributed to real-variable analysis, the foundations of real analysis, and Fourier analysis.

Bernhard Riemann (Kingdom of Hanover, 1826–1866) made enormous contributions to differential geometry, mathematical analysis, number theory, and other fields of mathematics. In particular, his methods of using tensors in differential geometry later proved especially useful to describe how gravity warps space and time, as Albert Einstein found. Riemann's name is attached to dozens of concepts, including Riemann bilinear relations, Riemann conditions, Riemann's differential equation, Riemann's existence theorem, Riemann's explicit formula, the Riemann form, the Riemann function, Riemannian geometry, the Riemann-Hurwitz formula, the Riemann hypothesis, the Riemann integral, the Riemann invariant, the Riemann matrix, Riemann's minimal surface, the Riemann operator, the Riemann series theorem, the Riemann singularity theorem, the Riemann sum, the Riemann surface, Riemann's theorem on removable singularities, the Riemann theta function, the Riemann Xi function, and the Riemann zeta function.

Arthur Rosenthal (German, 1887–1959) worked in geometry, mathematical analysis, and dynamical systems analysis. He is perhaps best known for the Hartogs-Rosenthal theorem.

Carl Runge (German, 1856–1927) made important contributions to numerical analysis and spectroscopy. He collaborated with Martin Wilhelm Kutta to develop the Runge-Kutta methods of numerically solving differential equations. He is also known for Runge's phenomenon, the behavior of certain errors that occur when finding approximate answers for functions. Carl Runge's son, Wilhelm Runge, was one of the developers of radar (p. 1220).

Ludwig Schlesinger (German, 1864–1933) conducted research in the areas of automorphic functions and differential equations. His name remain attached to the Schlesinger equations and Schlesinger transformations.

Arthur Schönflies (German, 1853–1928) made major contributions to group theory, set theory, and topology. His name is still widely known from Schönflies notation, Schönflies displacement, and Schönflies problems.

Friedrich Schottky (German, 1851–1935) worked on Abelian functions and integrals, complex variable analysis, and elliptic functions. He is remembered for the Schottky form, the Schottky-Klein prime form, Schottky groups, the Schottky problem, and Schottky's theorem. He was the father of Walter Schottky, one of the pioneers of semiconductor microelectronics (p. 1050).

Issai Schur (Russian but studied and worked in Germany, 1875–1941) performed innovative research in group theory, number theory, and combinatorics. He is best remembered for Schur decomposition and Schur's lemma.

Karl Hermann Amandus Schwarz (German, 1843–1921) made many contributions to complex variable analysis and differential equations. His name remains well known from concepts such as the additive Schwarz method, the Schwarz alternating method, the Schwarzian derivative, the Schwarz lantern, the Schwarz lemma, Schwarz's list, the Schwarz minimal surface, the Schwarz theorem, the Schwarz integral formula, Schwarz-Christoffel mapping, the Schwarz reflection principle, the Schwarz triangle, and the Cauchy-Schwarz inequality.

Jakob Steiner (Swiss, 1796–1863) carried out work in geometry and other areas of mathematics. He is remembered in names such as the Steinerian, the Steiner chain, Steiner's conic problem, the Steiner inellipse, the Steiner point, Steiner's problem, the Steiner surface, the Steiner system, the Steiner tree, the Steiner-Lehmus theorem, and the Poncelet-Steiner theorem.

Ludwig Stickelberger (Swiss, 1850–1936) made important contributions to linear algebra and number theory, such as the Stickelberger relation and the Frobenius-Stickelberger theorem.

Thomas Joannes Stieltjes (Dutch, 1856–1894) worked in mathematical analysis, continued fractions, and number theory. His name is attached to the Riemann-Stieltjes integral.

Otto Stolz (Austrian, 1842–1905) did innovative research in complex variable analysis and the foundations of real analysis.

Oswald Teichmüller (German, 1913–1943) made important contributions in complex analysis and is best known for Teichmüller space and Teichmüller theory.

B. L. van der Waerden (Dutch, 1903–1996) contributed to abstract algebra and algebraic geometry. He is remembered for concepts such as van der Waerden's conjecture, van der Waerden notation, the van der Waerden number, the van der Waerden test, and van der Waerden's theorem.

Heinrich Martin Weber (German, 1842–1913) did work in algebra, mathematical analysis, and number theory. His name is associated with Weber functions, Weber's theorem, and the Kronecker-Weber theorem.

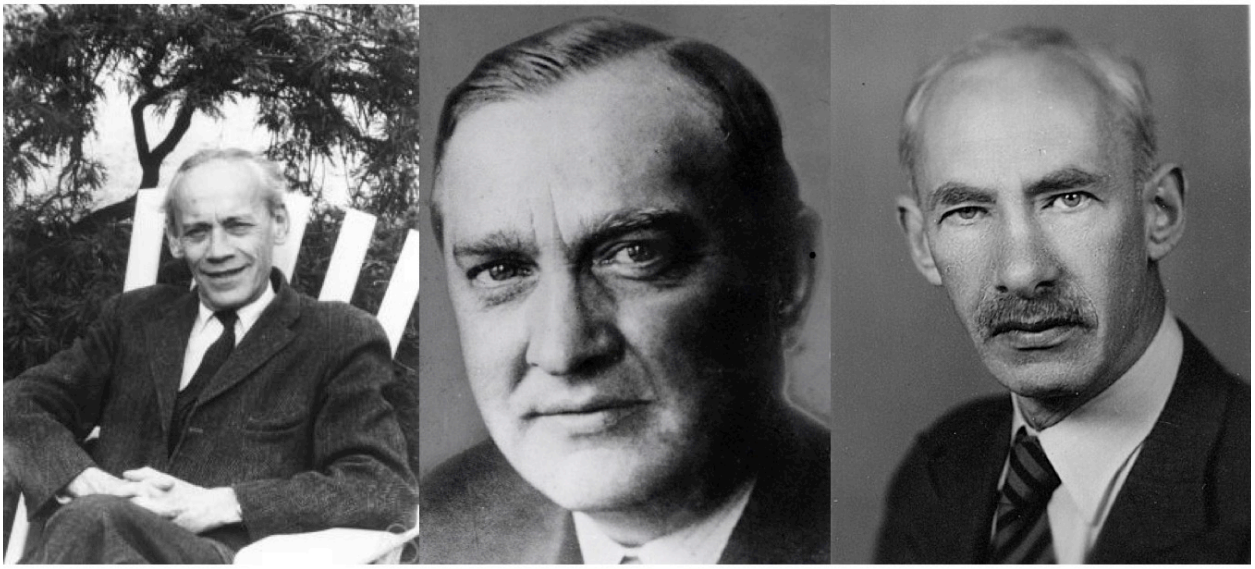
Karl Weierstrass (German, 1815–1897) made major advances in a wide range of areas, including Abelian functions and integrals, complex variable analysis, elliptic functions, the foundations of real analysis, and real-variable analysis. He is known for concepts such as the Weierstrass approximation theorem, Weierstrass coordinates, Weierstrass's elliptic functions, the Weierstrass equation, the Weierstrass factorization theorem, the Weierstrass function, the Weierstrass M-test, the Weierstrass point, the Weierstrass preparation theorem, the Weierstrass product inequality, the Weierstrass ring, and the Weierstrass transform.

Hermann Weyl (German, 1885–1955) introduced important innovations in group theory, number theory, and non-Euclidean geometry, as well as general relativity. His name remains attached to countless concepts such as Weyl algebra, the Weyl basis of the gamma matrices, the Weyl chamber, the Weyl character formula, the Weyl equation, Weyl fermions, the Weyl gauge, Weyl gravity, Weyl notation, Weyl quantization, Weyl spinors, Weyl sums, Weyl symmetry, Weyl tensors, Weyl transformations, the Weyl-Schouten theorem, Weyl's criterion, and Weyl's lemmas.

Hans Zassenhaus (German, 1912–1991) worked in abstract algebra and group theory, and helped to develop computer algebra and number theory.

Ernst Zermelo (German, 1871–1953) made many contributions to set theory and mathematical logic, such as Zermelo-Fränkel set theory, Zermelo's navigation problem, the Zermelo ordinal, and Zermelo's theorem.

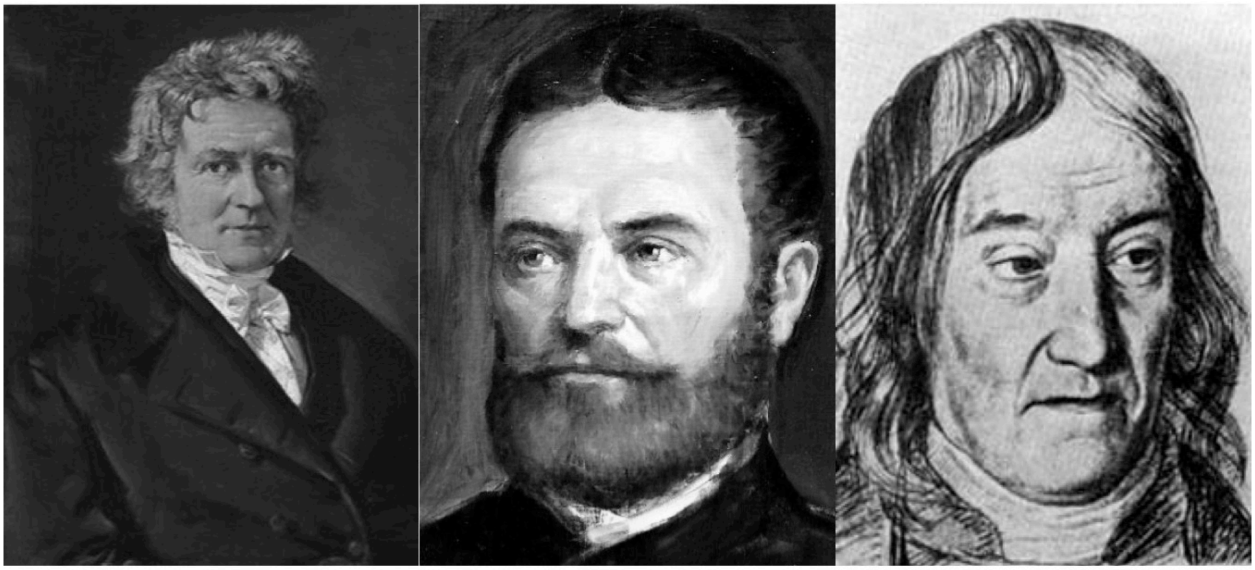
Applied mathematics and classical mechanics



Emil Artin (1898–1962)

Stefan Banach (1892–1945)

Paul Bernays (1888–1977)



Friedrich Bessel (1784–1846)

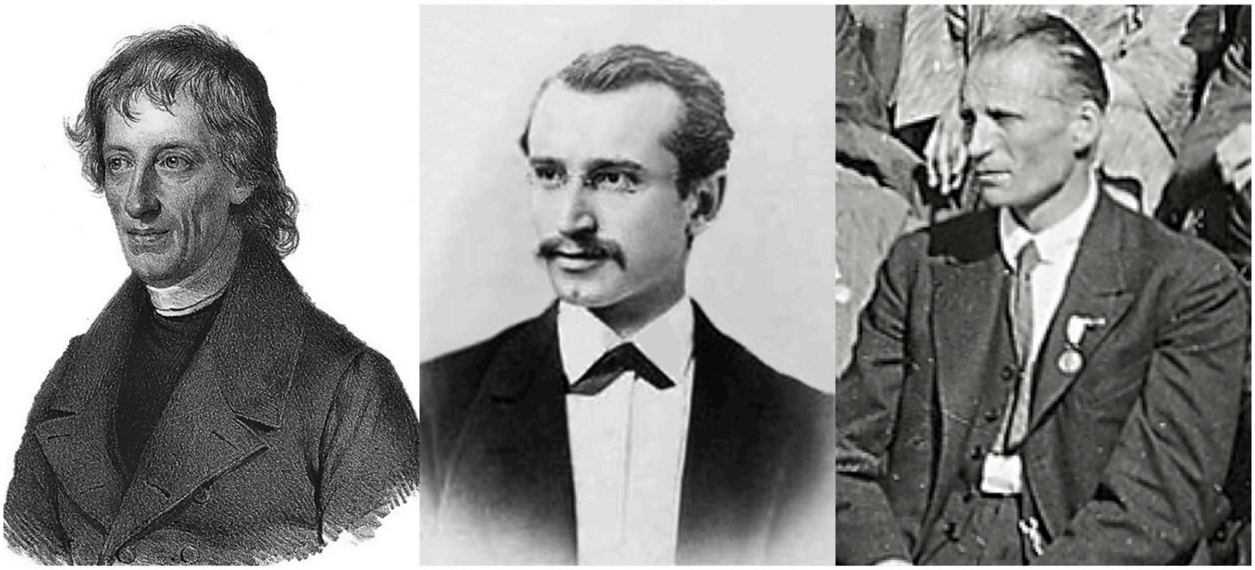
János Bolyai (1802–1860)

Wolfgang Bolyai (1775–1856)

Figure 5.2: Some creators who made significant contributions to applied mathematics and classical mechanics included Emil Artin, Stefan Banach, Paul Bernays, Friedrich Bessel, János Bolyai, and Wolfgang Bolyai.

Applied mathematics and classical mechanics

Bernardus Bolzano (1781–1848) **Alexander von Brill (1842–1935)** **Luitzen Brouwer (1881–1966)**



Karl Hermann Brunn (1862–1939) **Heinrich Burkhardt (1861–1914)** **Georg Cantor (1845–1918)**

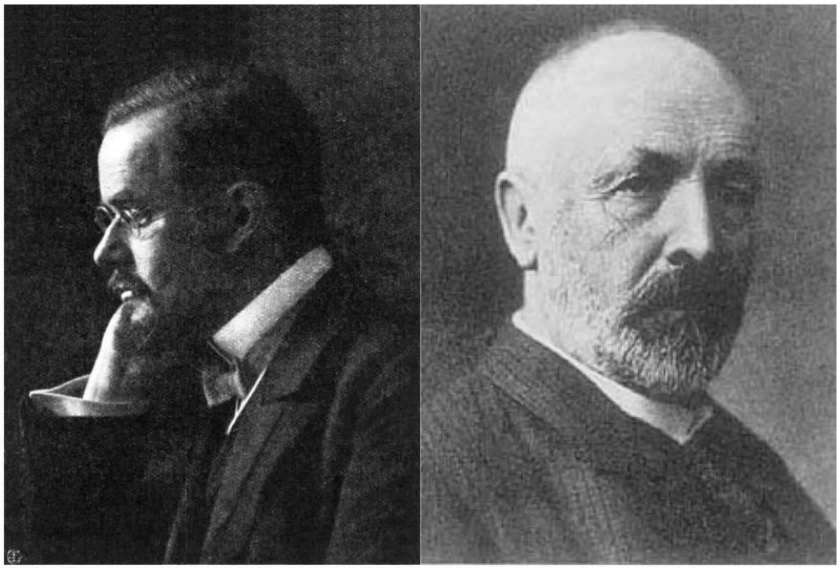


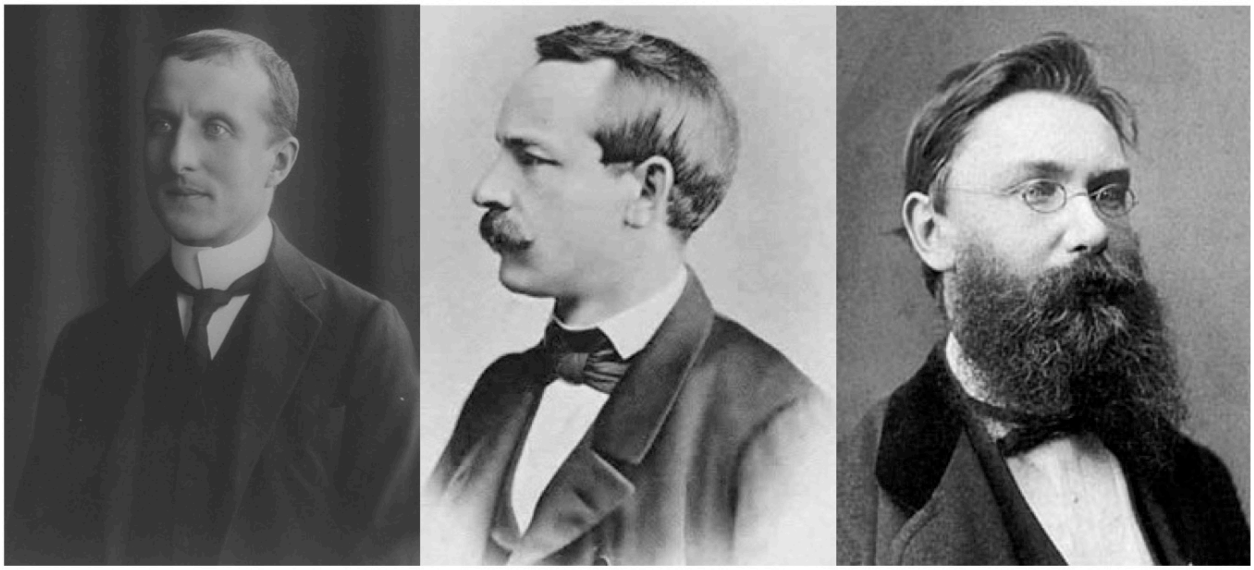
Figure 5.3: Other creators who made significant contributions to applied mathematics and classical mechanics included Bernardus Bolzano, Alexander von Brill, Luitzen Brouwer, Karl Hermann Brunn, Heinrich Burkhardt, and Georg Cantor.

Applied mathematics and classical mechanics

Constantin Carathéodory (1873–1950)

Elwin Christoffel (1829–1900)

Rudolf Alfred Clebsch (1833–1872)



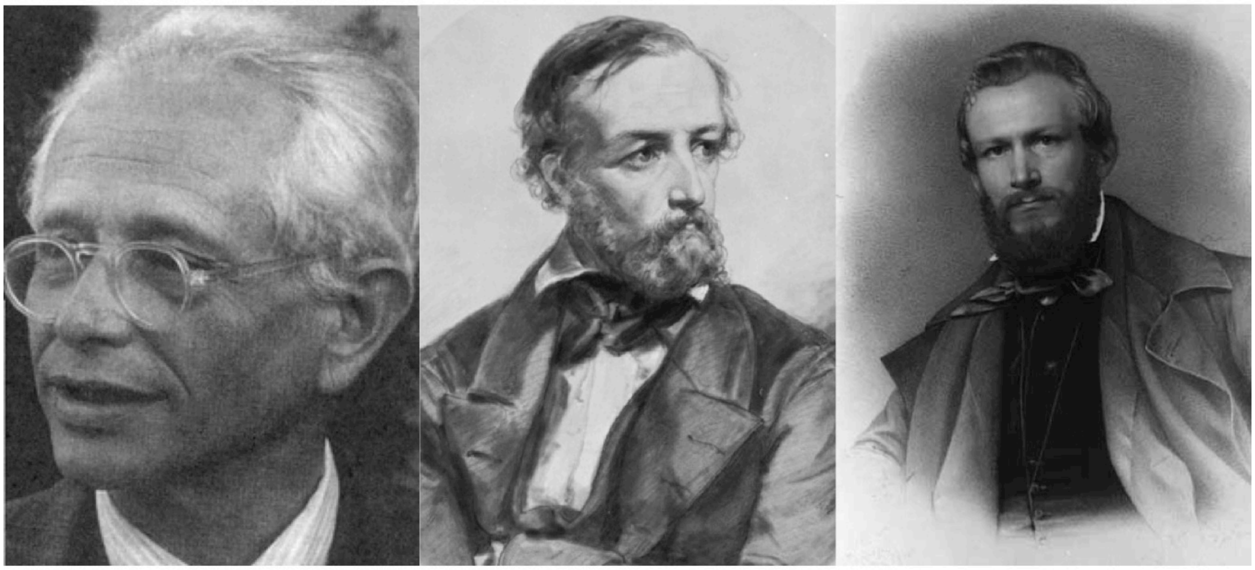
Lothar Collatz (1910–1990)

Richard Courant (1888–1972)

Richard Dedekind (1831–1916)

Figure 5.4: Other creators who made significant contributions to applied mathematics and classical mechanics included Constantin Carathéodory, Elwin Christoffel, Rudolf Alfred Clebsch, Lothar Collatz, Richard Courant, and Richard Dedekind.

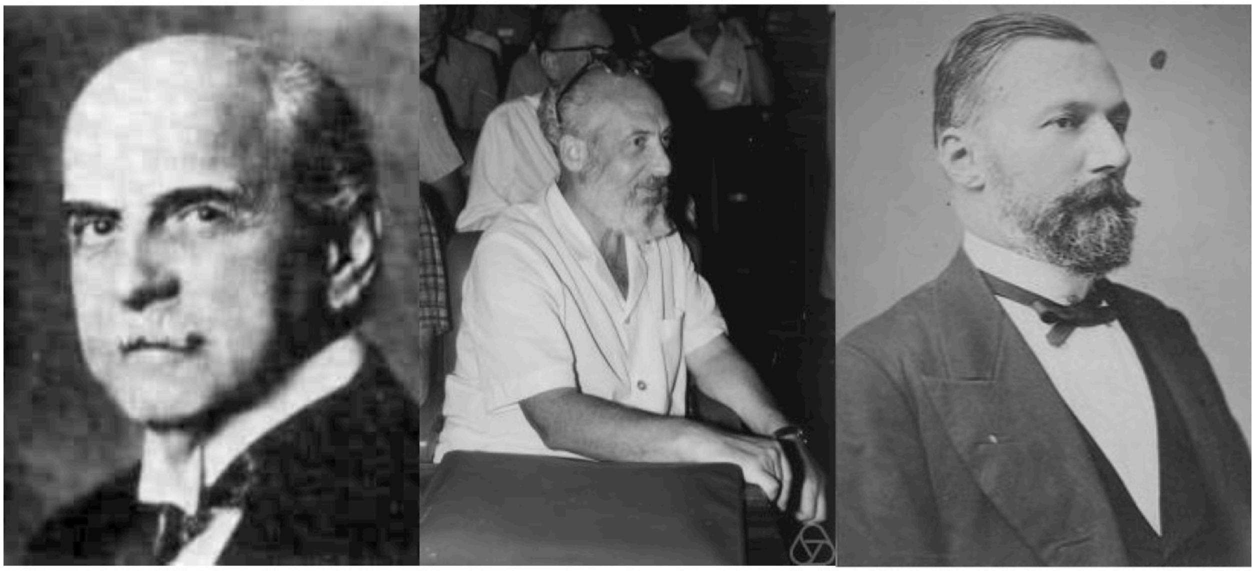
Applied mathematics and classical mechanics



Max Dehn
(1878–1952)

Peter Gustav
Lejeune Dirichlet
(1805–1859)

Paul du Bois
Reymond
(1831–1889)



Walther von Dyck
(1856–1934)

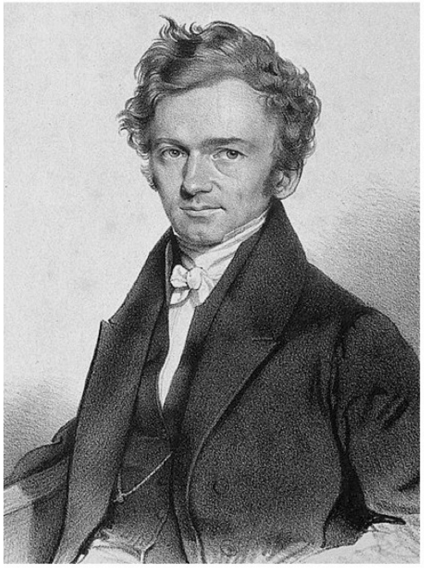
Samuel Eilenberg
(1913–1998)

Alfred Enneper
(1830–1885)

Figure 5.5: Other creators who made significant contributions to applied mathematics and classical mechanics included Max Dehn, Peter Dirichlet, Paul du Bois Reymond, Walther von Dyck, Samuel Eilenberg, and Alfred Enneper.

Applied mathematics and classical mechanics

Andreas von Ettingshausen (1796–1878)



Erwin Fehlberg (1911–1990)

William Feller (1906–1970)

Abraham Fränkel (1891–1965)

Friedrich Gottlob Frege (1848–1925)

Robert Fricke (1861–1930)

Figure 5.6: Other creators who made significant contributions to applied mathematics and classical mechanics included Andreas von Ettingshausen, Erwin Fehlberg, William Feller, Abraham Fränkel, Friedrich Gottlob Frege, and Robert Fricke.

Applied mathematics and classical mechanics

Georg Frobenius (1849–1917)

Lazarus Immanuel Fuchs (1833–1902)

Maximilian Richard Fuchs (1873–1944)

Karl Rudolf Fueter (1880–1950)

Carl Friedrich Gauss (1777–1855)

Kurt Gödel (1906–1978)

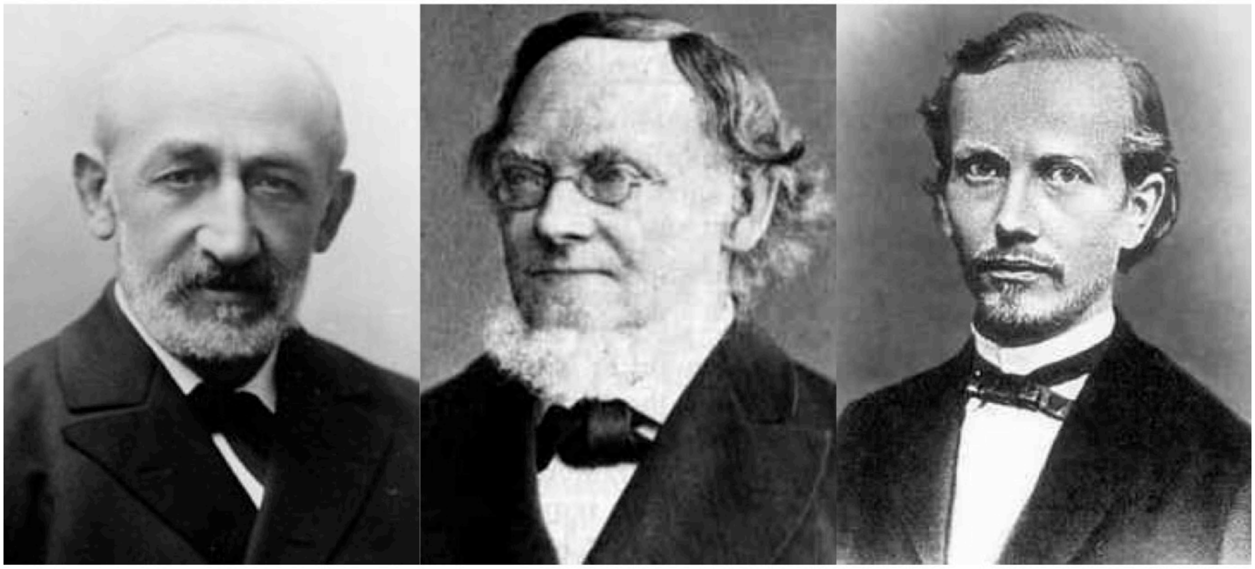
Figure 5.7: Other creators who made significant contributions to applied mathematics and classical mechanics included Georg Frobenius, Lazarus Immanuel Fuchs, Maximilian Richard Fuchs, Karl Rudolf Fueter, Carl Friedrich Gauss, and Kurt Gödel.

Applied mathematics and classical mechanics

Paul Gordan (1837–1912)

Hermann Grassmann (1809–1877)

Hermann Hankel (1839–1873)



Carl Gustav Axel Harnack (1851–1888)

Friedrich Hartogs (1874–1943)

Felix Hausdorff (1868–1942)

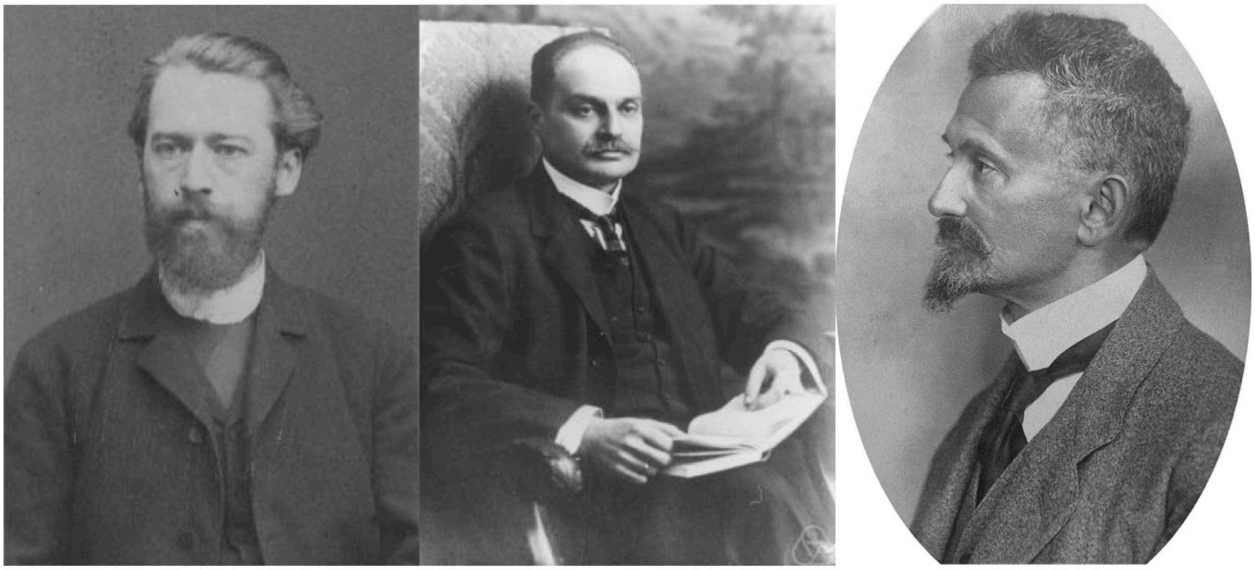
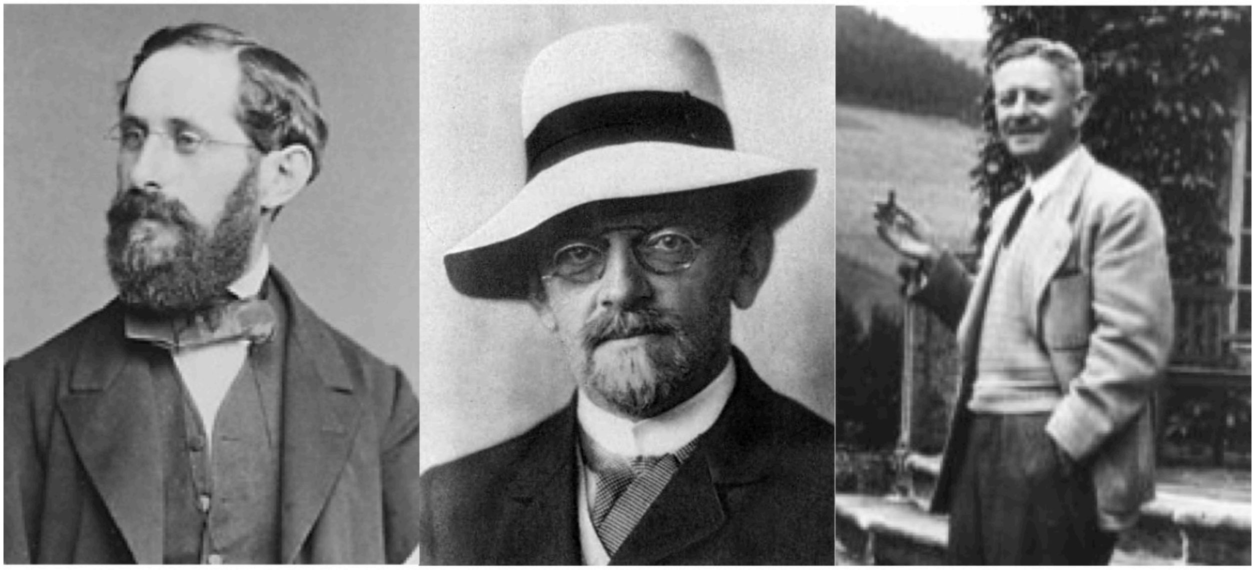


Figure 5.8: Other creators who made significant contributions to applied mathematics and classical mechanics included Paul Gordan, Hermann Grassmann, Hermann Hankel, Carl Gustav Axel Harnack, Friedrich Hartogs, and Felix Hausdorff.

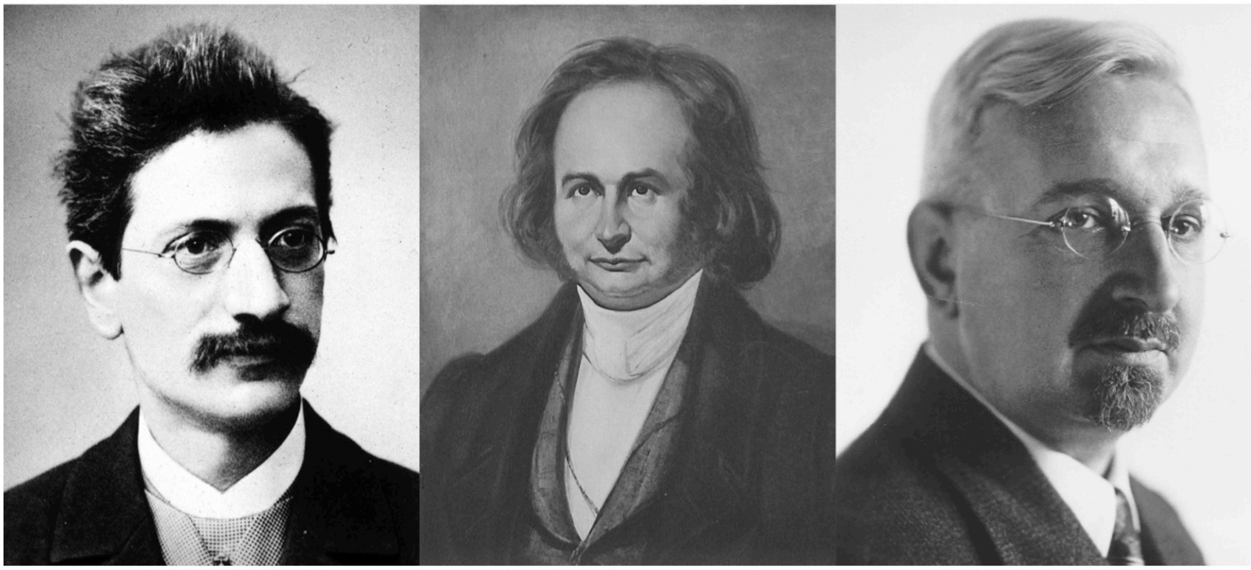
Applied mathematics and classical mechanics



Heinrich Eduard Heine (1821–1881)

David Hilbert (1862–1943)

Heinz Hopf (1894–1971)



Adolf Hurwitz (1859–1919)

Carl Gustav Jacobi (1804–1851)

Theodor Kaluza (1885–1954)

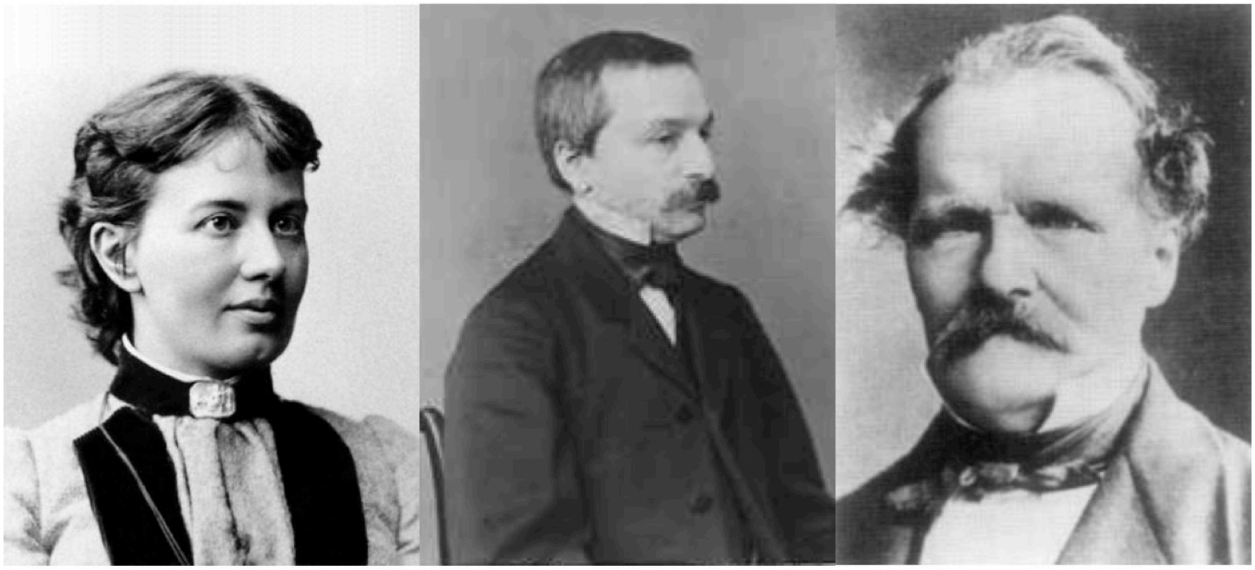
Figure 5.9: Other creators who made significant contributions to applied mathematics and classical mechanics included Heinrich Eduard Heine, David Hilbert, Heinz Hopf, Adolf Hurwitz, Carl Gustav Jacobi, and Theodor Kaluza.

Applied mathematics and classical mechanics

Theodor Kaluza, Jr.
(1910–1994)

Wilhelm Killing
(1847–1923)

Christian Felix Klein
(1849–1925)



Sofia Kovalevskaya
(1850–1891)

Leopold Kronecker
(1823–1891)

Ernst Kummer
(1810–1893)

Figure 5.10: Other creators who made significant contributions to applied mathematics and classical mechanics included Theodor Kaluza, Jr., Wilhelm Killing, Christian Felix Klein, Sofia Kovalevskaya, Leopold Kronecker, and Ernst Kummer.

Applied mathematics and classical mechanics

Martin Wilhelm Kutta
(1867–1944)

Daniel Christian
Ludolph Lehmus
(1780–1863)

Sophus Lie
(1842–1899)

Carl Ferdinand
von Lindemann
(1852–1939)

Rudolf Lipschitz
(1832–1903)

Alfred Loewy
(1873–1935)

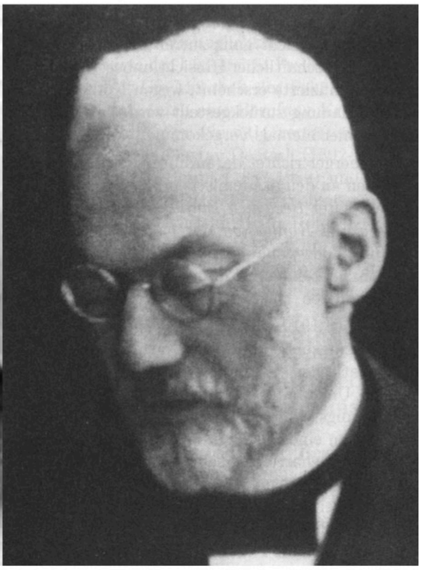


Figure 5.11: Other creators who made significant contributions to applied mathematics and classical mechanics included Martin Wilhelm Kutta, Daniel Christian Ludolph Lehmus, Sophus Lie, Carl Ferdinand von Lindemann, Rudolf Lipschitz, and Alfred Loewy.

Applied mathematics and classical mechanics

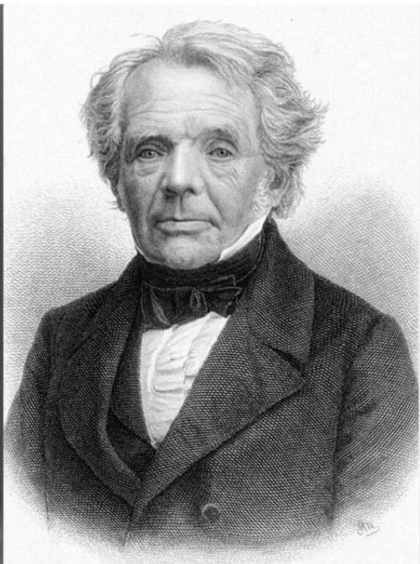
Gustav Ferdinand Mehler (1835–1895)

Friedrich Wilhelm Franz Meyer (1856–1934)

Hermann Minkowski (1864–1909)

Richard von Mises (1883–1953)

August Möbius (1790–1868)



Carl Neumann (1832–1925)

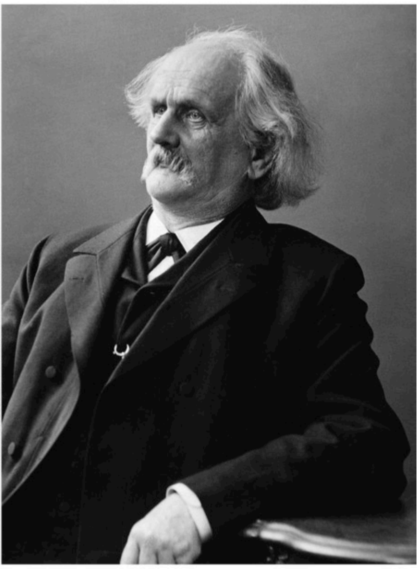


Figure 5.12: Other creators who made significant contributions to applied mathematics and classical mechanics included Gustav Ferdinand Mehler, Friedrich Meyer, Hermann Minkowski, Richard von Mises, August Möbius, and Carl Neumann.

Applied mathematics and classical mechanics

John von Neumann
(1903–1957)

Rolf Nevanlinna
(1895–1980)

Emmy Noether
(1882–1935)

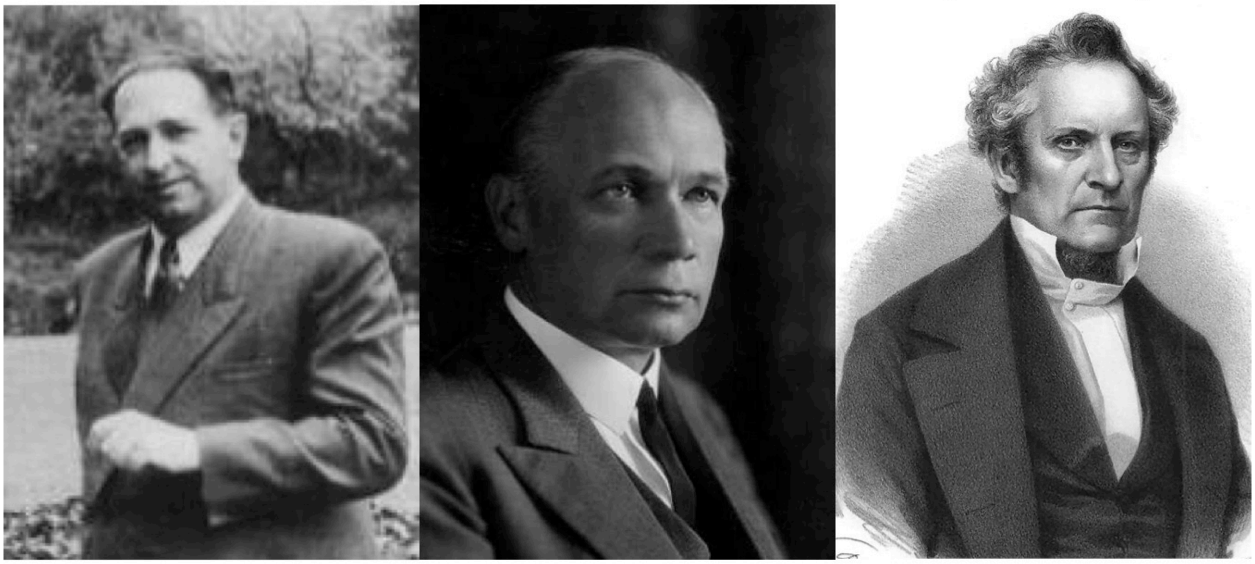
Max Noether
(1844–1921)

Moritz Pasch
(1843–1930)

Oskar Perron
(1880–1975)

Figure 5.13: Other creators who made significant contributions to applied mathematics and classical mechanics included John von Neumann, Rolf Nevanlinna, Emmy Noether, Max Noether, Moritz Pasch, and Oskar Perron.

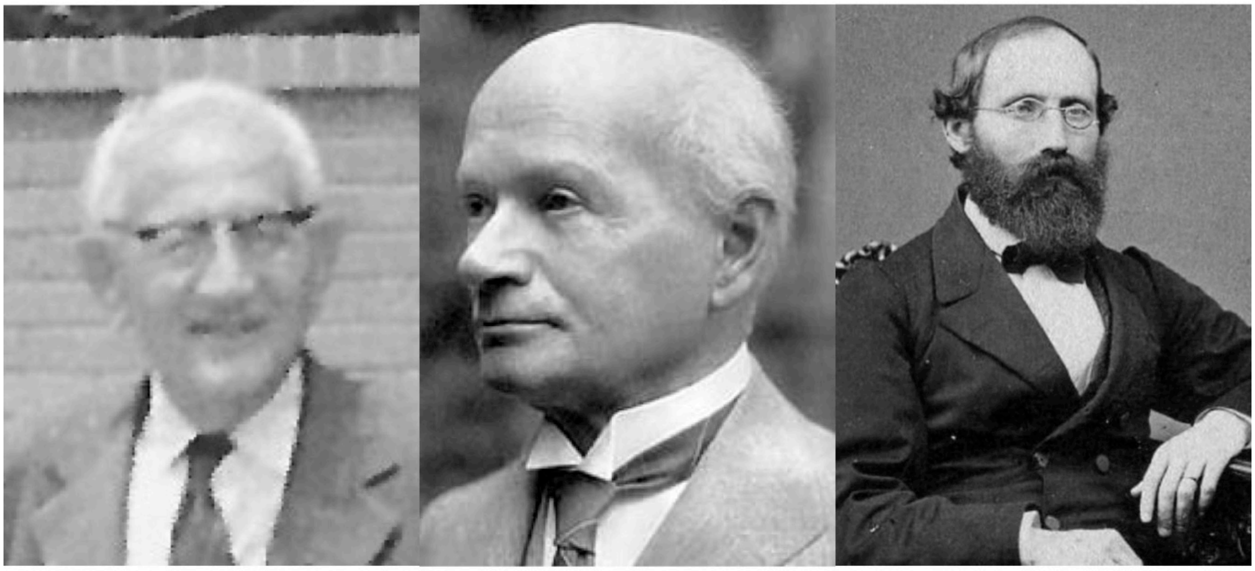
Applied mathematics and classical mechanics



Ernst Ferdinand Peschl (1906–1986)

Michel Plancherel (1885–1967)

Julius Plücker (1801–1868)



George Pólya (1887–1985)

Alfred Pringsheim (1850–1941)

Bernhard Riemann (1826–1866)

Figure 5.14: Other creators who made significant contributions to applied mathematics and classical mechanics included Ernst Ferdinand Peschl, Michel Plancherel, Julius Plücker, George Pólya, Alfred Pringsheim, and Bernhard Riemann.

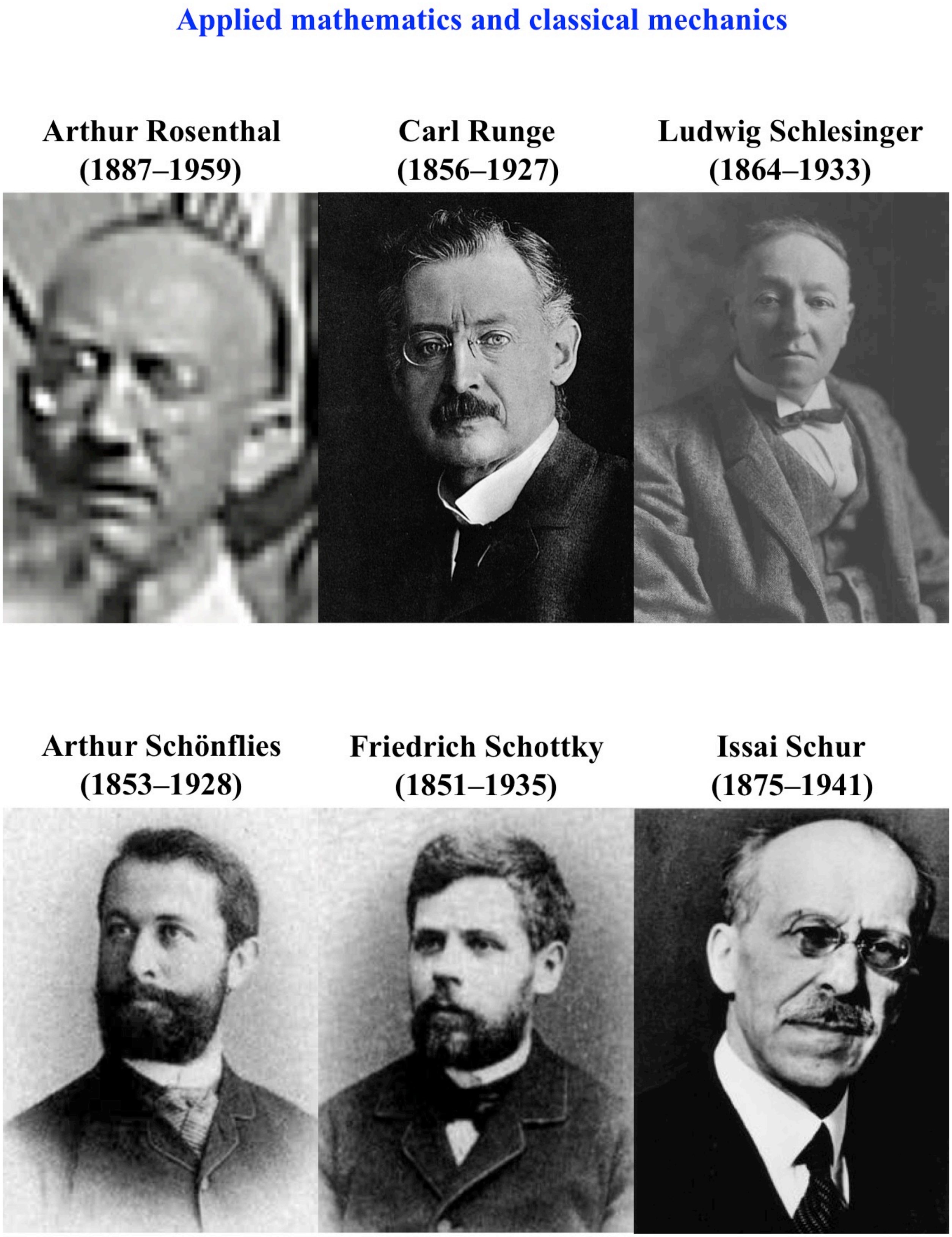


Figure 5.15: Other creators who made significant contributions to applied mathematics and classical mechanics included Arthur Rosenthal, Carl Runge, Ludwig Schlesinger, Arthur Schönflies, Friedrich Schottky, and Issai Schur.

Applied mathematics and classical mechanics

Karl Hermann Amandus Schwarz (1843–1921)

Jakob Steiner (1796–1863)

Ludwig Stickelberger (1850–1936)

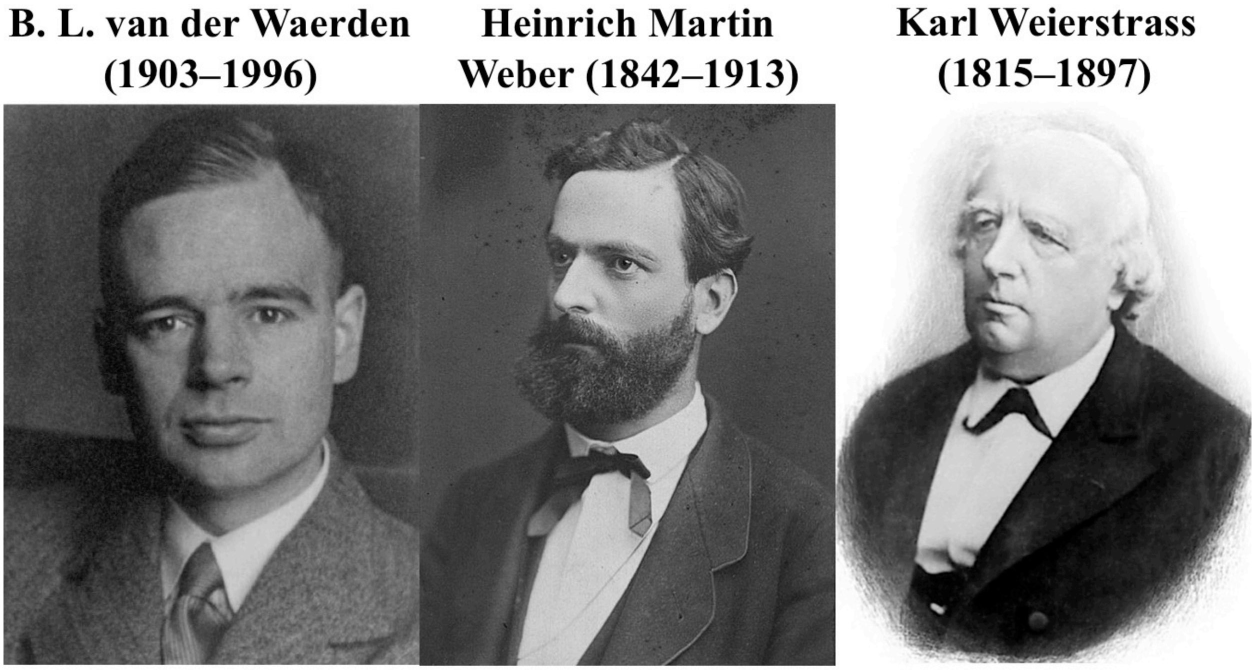
Thomas Stieltjes (1856–1894)

Otto Stolz (1842–1905)

Oswald Teichmüller (1913–1943)

Figure 5.16: Other creators who made significant contributions to applied mathematics and classical mechanics included Karl Hermann Amandus Schwarz, Jakob Steiner, Ludwig Stickelberger, Thomas Stieltjes, Otto Stolz, and Oswald Teichmüller.

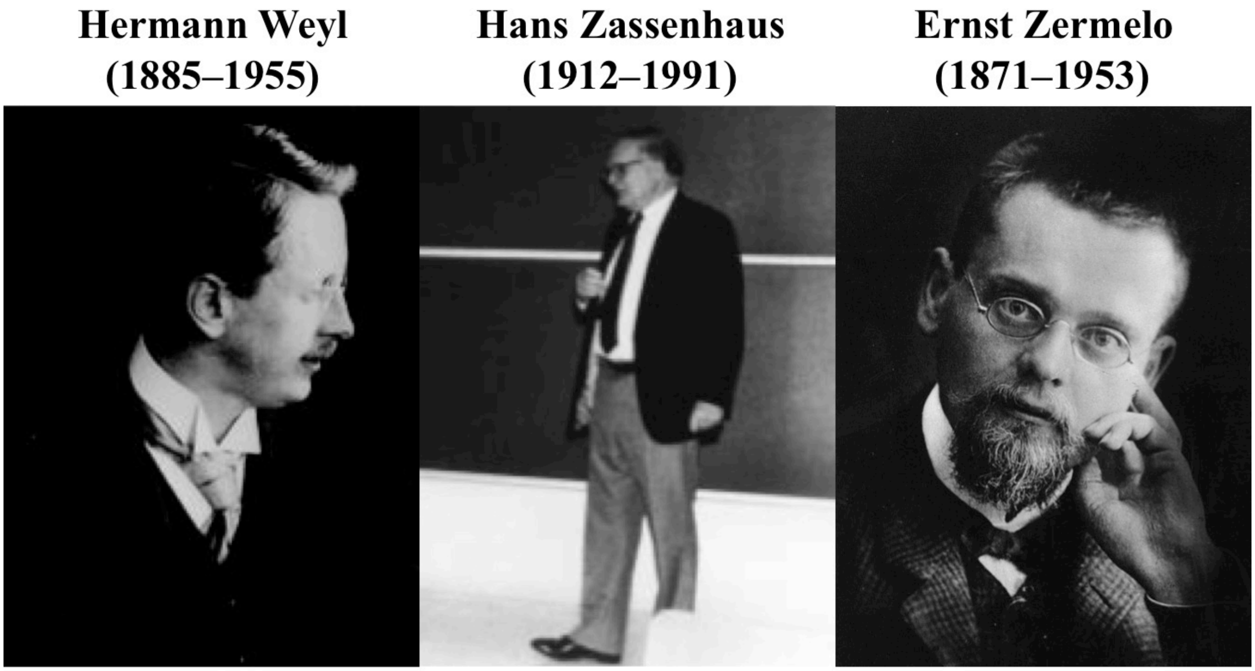
Applied mathematics and classical mechanics



B. L. van der Waerden (1903–1996)

Heinrich Martin Weber (1842–1913)

Karl Weierstrass (1815–1897)



Hermann Weyl (1885–1955)

Hans Zassenhaus (1912–1991)

Ernst Zermelo (1871–1953)

Figure 5.17: Other creators who made significant contributions to applied mathematics and classical mechanics included B. L. van der Waerden, Heinrich Martin Weber, Karl Weierstrass, Hermann Weyl, Hans Zassenhaus, and Ernst Zermelo.

5.2 Electromagnetism

Electromagnetic theory describes the behavior of electric fields, electric currents, magnetic fields, and electromagnetic waves (such as light and radio waves). The German-speaking scientific world slowly ramped up during the nineteenth century, and before then scientists had already begun working out the laws of electromagnetism. Therefore, most of the major early electromagnetic discoveries came from scientists outside the German-speaking world, including:

- Italian scientists (e.g., Luigi Galvani and Alessandro Volta).
- British scientists (e.g., Michael Faraday and James Clerk Maxwell).
- French scientists (e.g., André-Marie Ampère and Charles-Augustin de Coulomb).
- Hans Christian Ørsted in Denmark.
- Benjamin Franklin in the United States.

As the German-speaking scientific world became larger and more advanced over the course of the nineteenth century, German-speaking scientists came to increasingly dominate new discoveries in electromagnetism; see Figs. 5.18–5.23 for some examples.[3] That dominance is reflected in the modern physics terminology of Doppler shifts, Gauss's law, Helmholtz coils, Kirchhoff's laws, Lenz's law, Lorentz force, Ohm's law, and various physics quantities measured in Gauss, Hertz, Ohms, Siemens, Teslas, and Webers.

For convenience, the creators and creations in this section are divided into the following broad (and somewhat overlapping) categories:

5.2.1. Electric currents and magnetic fields

5.2.2. Electromagnetic waves

5.2.3. Electron beams and proton beams

The fundamental physics discoveries in electromagnetism led to a vast range of applications, which is the field of electrical and electromagnetic engineering; see Chapter 6 for more information.

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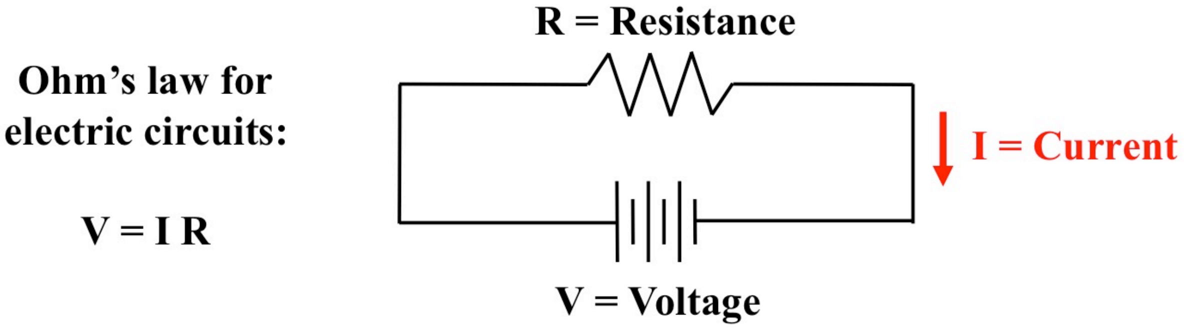
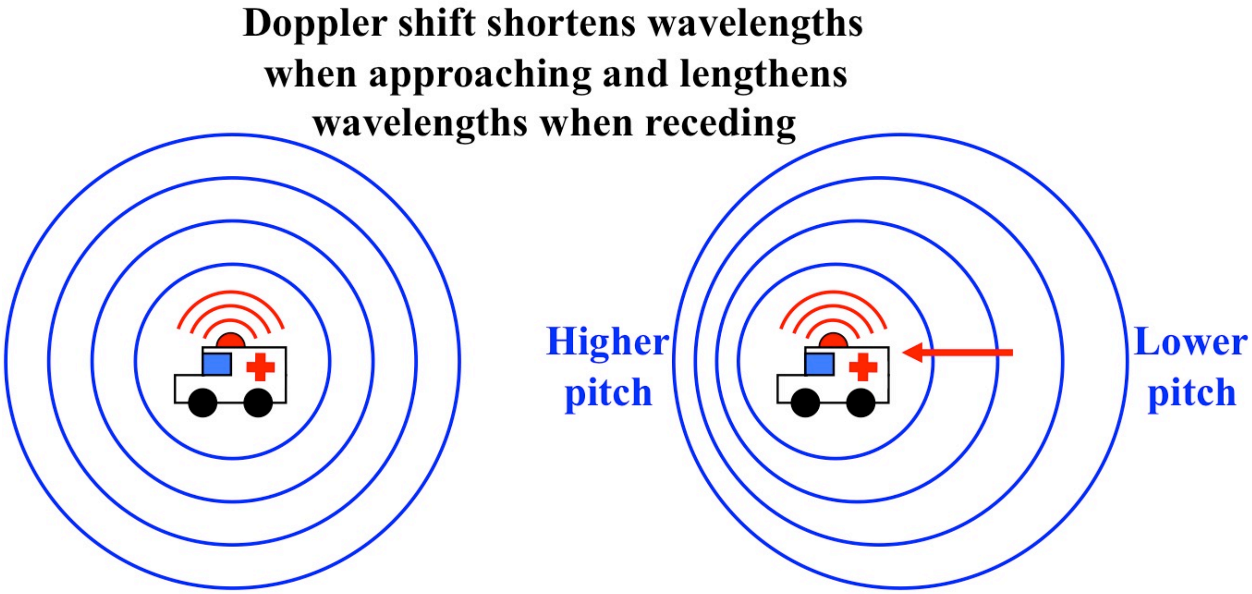
[3] For good overviews of this area, see especially: Jungnickel and McCormmach 1986, 2017; Kragh 2002; von Meÿenn 1997; Sarkar et al. 2006; Teichmann 2008; https://www.crtsite.com.





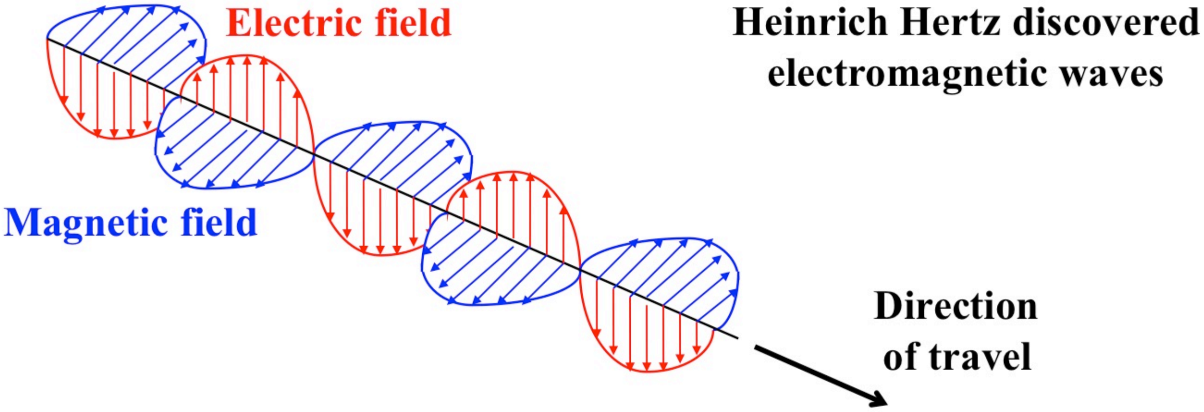


Figure 5.18: Examples of major German-speaking contributions to electromagnetism include Ohm's law for the relationship among voltage, current, and resistance in an electrical circuit; Christian Doppler's explanation for why the frequency and wavelength of waves change when their source is moving; and Heinrich Hertz's demonstration of electromagnetic waves.

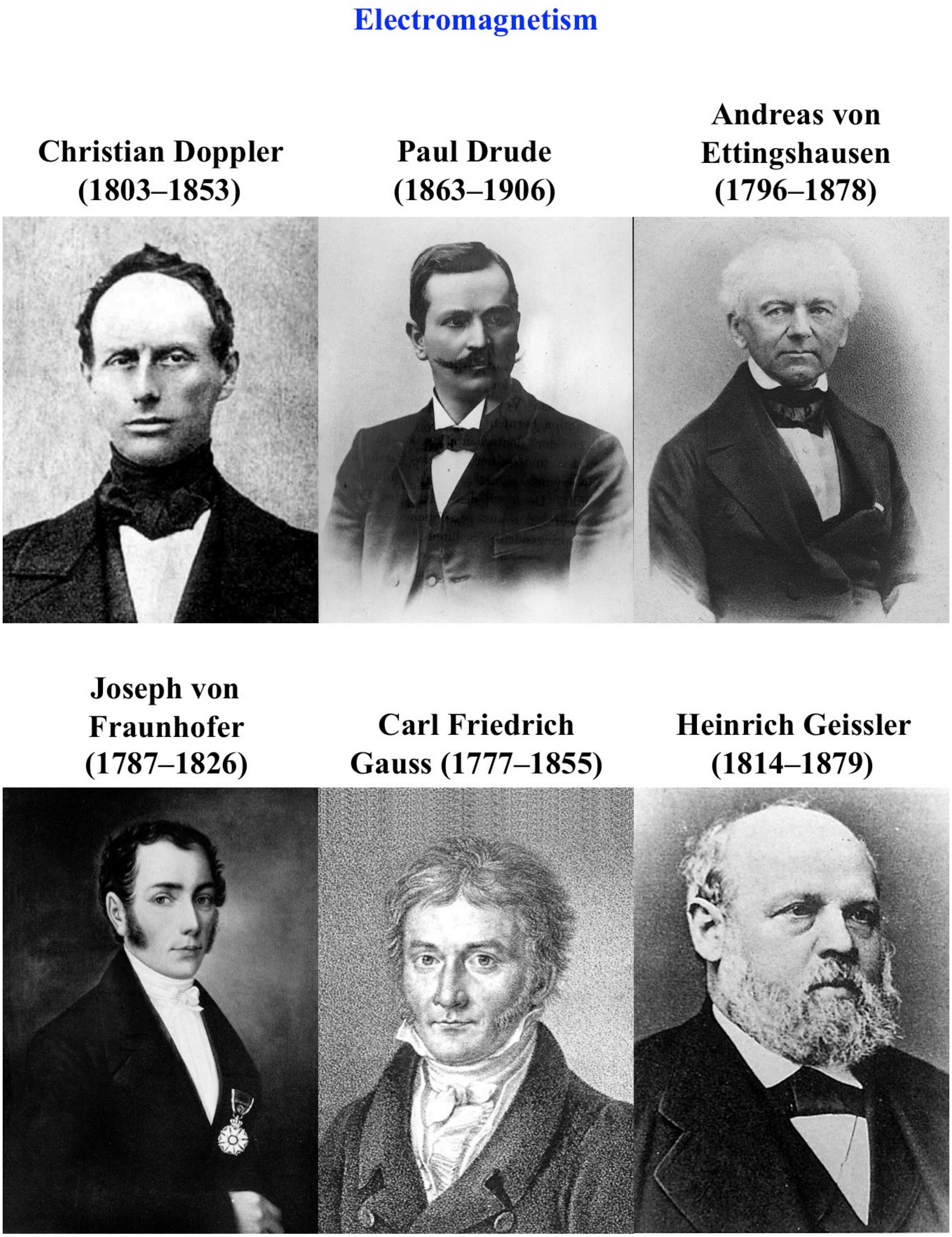
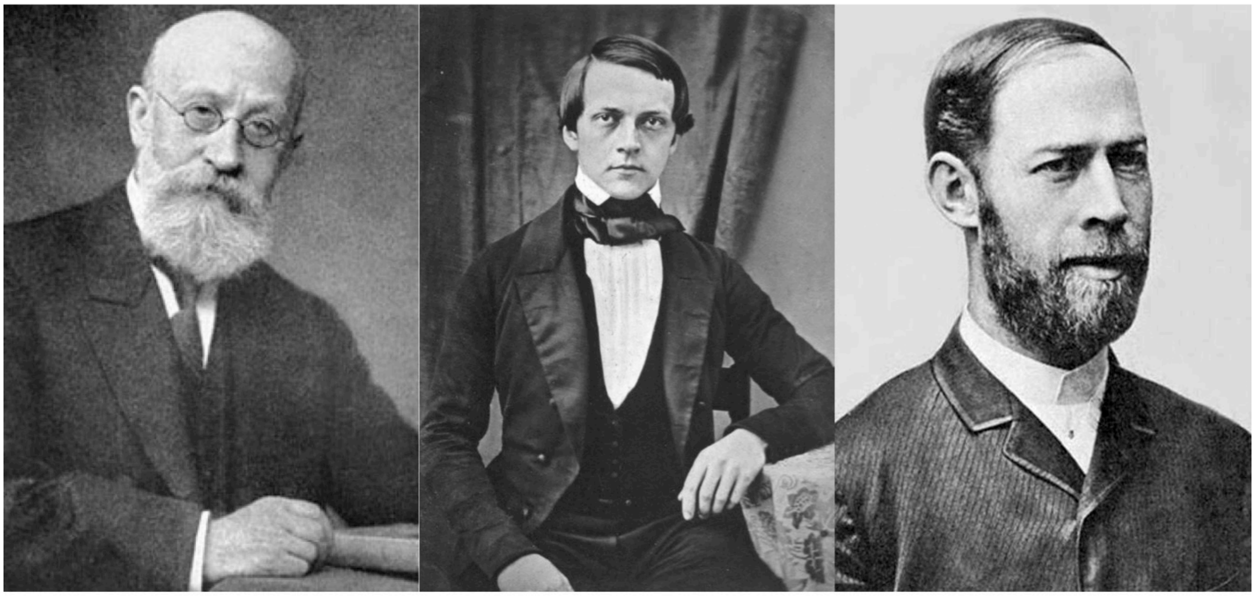


Figure 5.19: Some creators who made significant contributions to electromagnetism included Christian Doppler, Paul Drude, Andreas von Ettingshausen, Joseph von Fraunhofer, Carl Friedrich Gauss, and Heinrich Geissler.

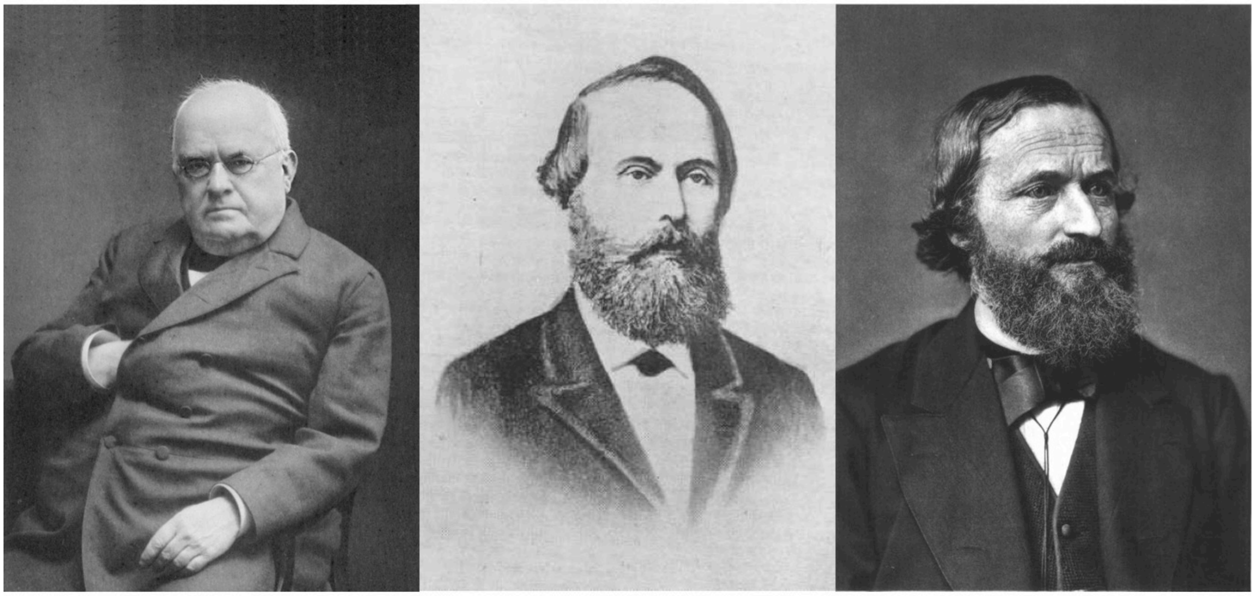
Electromagnetism



Eugen Goldstein (1850–1930)

Hermann von Helmholtz (1821–1894)

Heinrich Hertz (1857–1894)



Johann Wilhelm Hittorf (1824–1914)

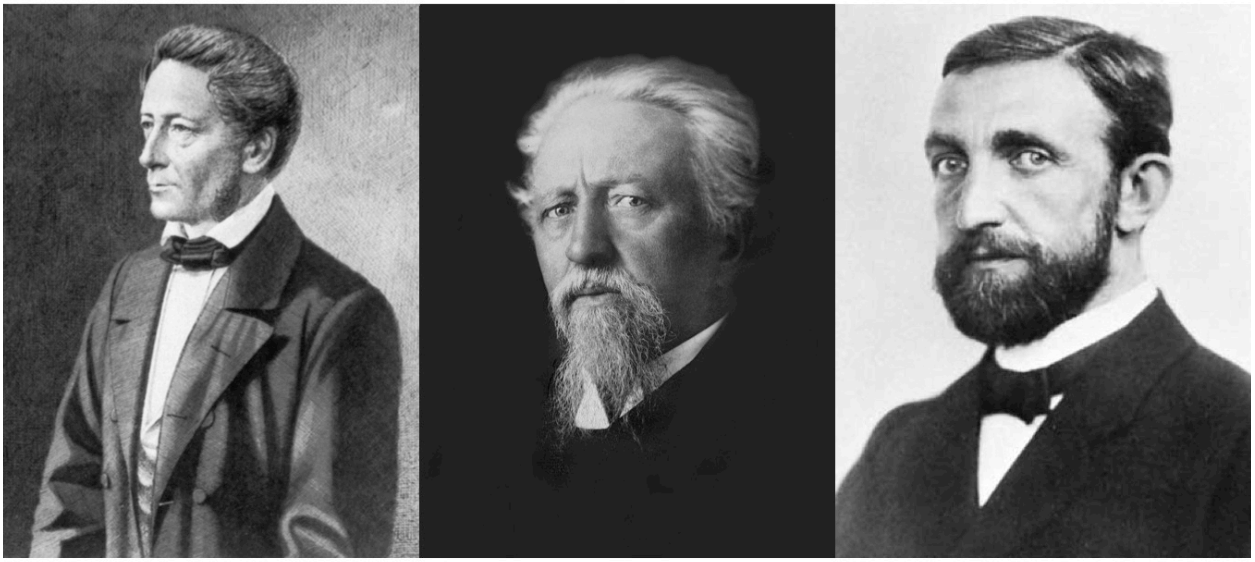
Wilhelm Holtz (1836–1913)

Gustav Kirchhoff (1824–1887)

Figure 5.20: Other creators who made significant contributions to electromagnetism included Eugen Goldstein, Hermann von Helmholtz, Heinrich Hertz, Johann Wilhelm Hittorf, Wilhelm Holtz, and Gustav Kirchhoff.

Electromagnetism

Rudolf Kohlrausch (1809–1858)
Ernst Lecher (1856–1926)
Philipp Lenard (1862–1947)



Heinrich Lenz (1804–1865)
Hendrik Lorentz (1853–1928)
Albert Michelson (1852–1931)

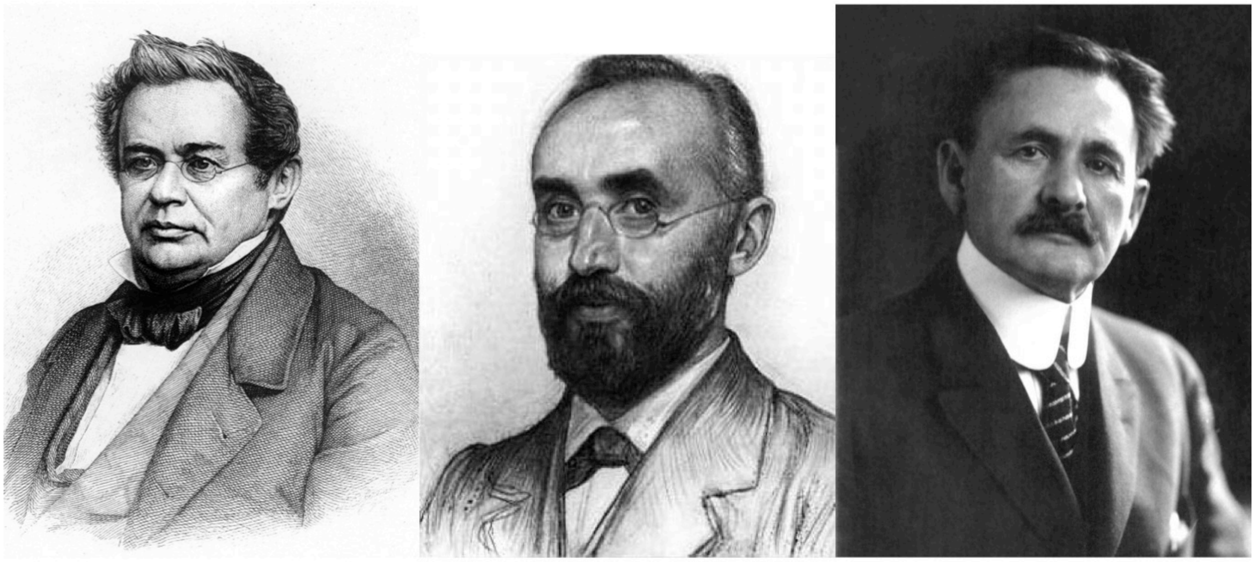


Figure 5.21: Other creators who made significant contributions to electromagnetism included Rudolf Kohlrausch, Ernst Lecher, Philipp Lenard, Heinrich Lenz, Hendrik Lorentz, and Albert Michelson.

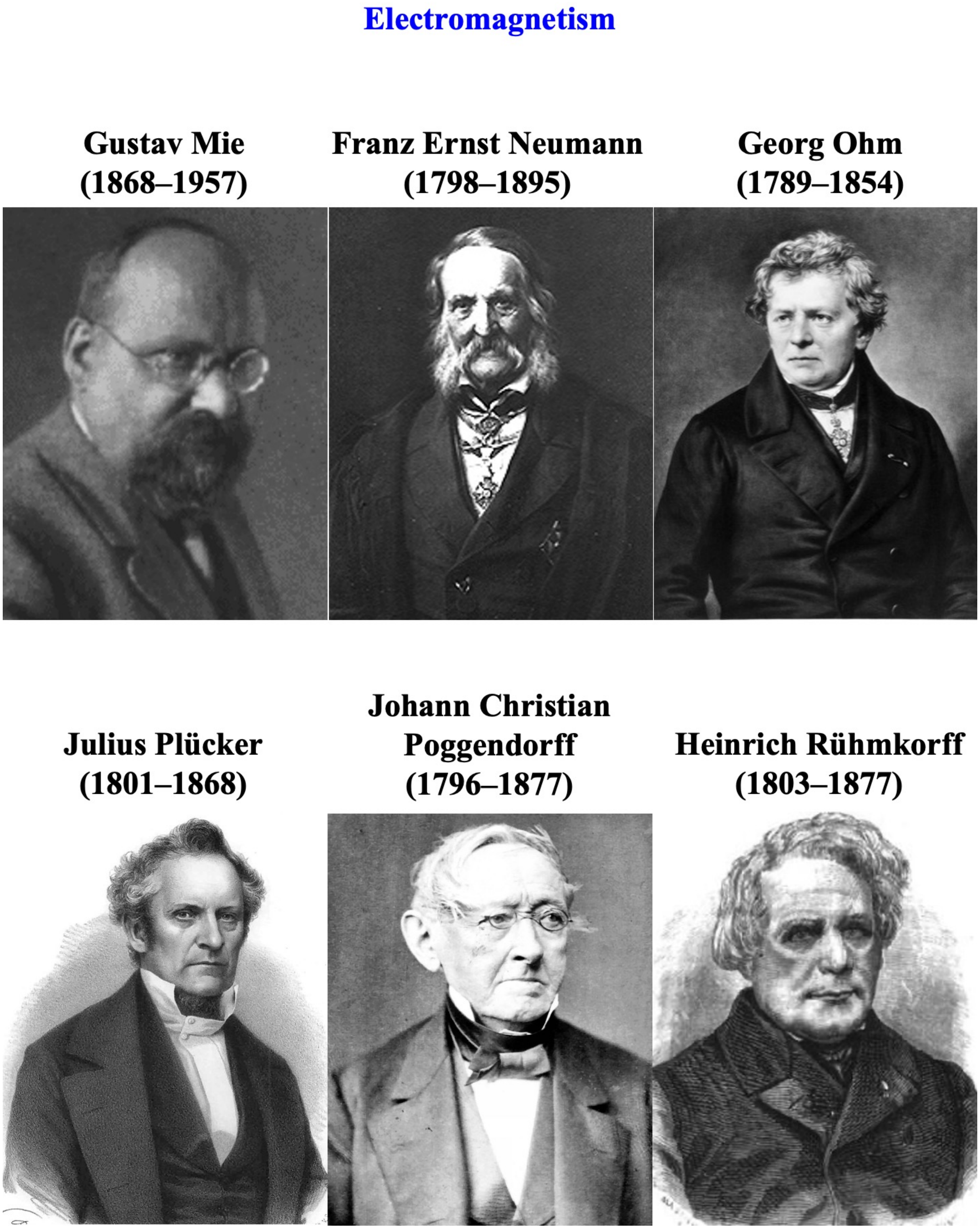
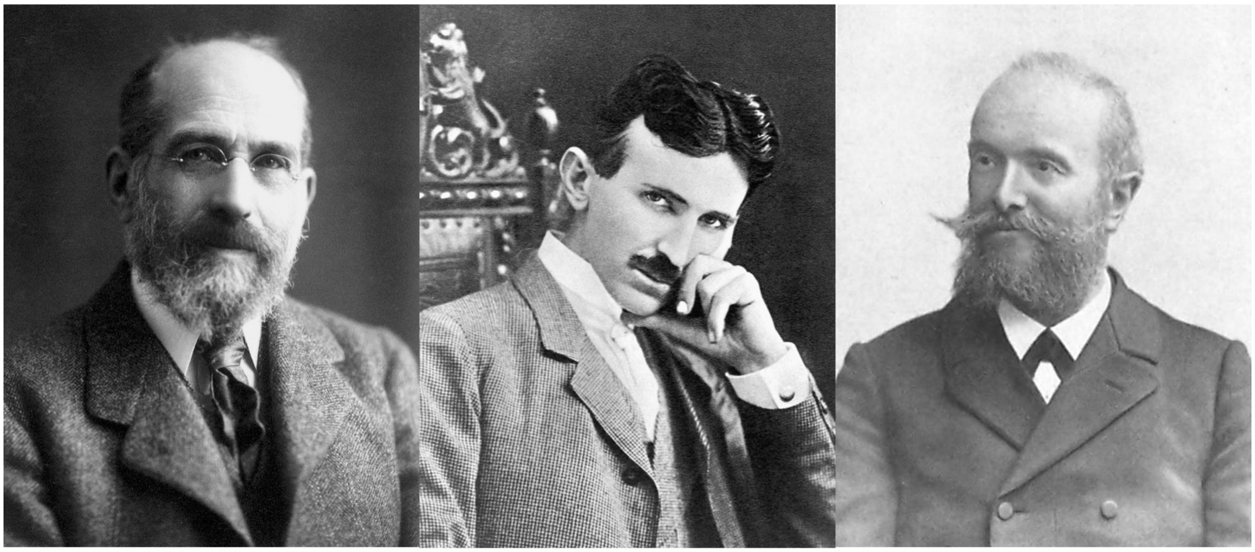


Figure 5.22: Other creators who made significant contributions to electromagnetism included Gustav Mie, Franz Ernst Neumann, Georg Ohm, Julius Plücker, Johann Christian Poggendorff, and Heinrich Rühmkorff.

Electromagnetism

Arthur Schuster (1851–1934) **Nikola Tesla (1856–1943)** **August Toepler (1836–1912)**



Wilhelm Weber (1804–1891) **Emil Wiechert (1861–1928)** **Wilhelm Wien (1864–1928)**

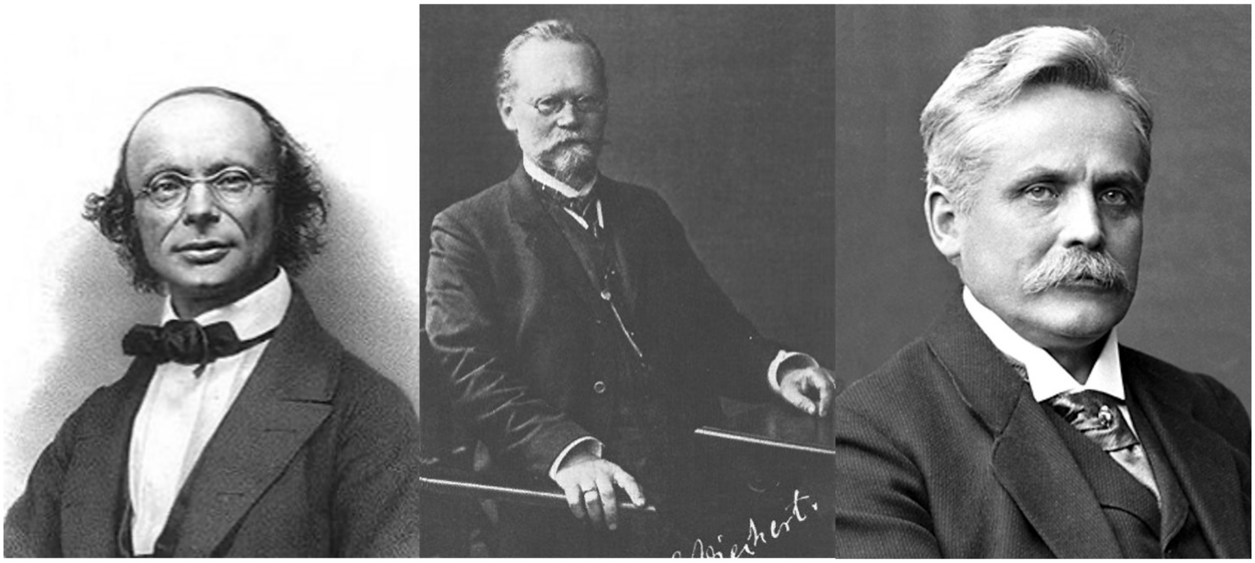


Figure 5.23: Other creators who made significant contributions to electromagnetism included Arthur Schuster, Werner von Siemens (p. 950), Nikola Tesla, August Toepler, Wilhelm Weber, Emil Wiechert, and Wilhelm Wien.

5.2.1 Electric Currents and Magnetic Fields

Carl Friedrich Gauss (German states, 1777–1855) and Wilhelm Weber (German, 1804–1891) conducted magnetic research together, building the first electromagnetic telegraph in 1833 (p. 974) and creating maps based on geomagnetic measurements. Along the way, Gauss discovered what is now known as Gauss's law, which determines how magnetic fields are created and spread out [Dunnington 1955]. (See also pp. 740, 793, 828, and 972.) The cgs (centimeter-gram-second) unit of magnetic field strength is named in Gauss's honor, and the metric SI (Système International) unit of magnetic flux is named after Weber.

Georg Ohm (German states, 1789–1854) studied the electrical properties of circuits and demonstrated that the voltage difference V across an electrical component depends on the current I through the component and the electrical resistance R of the component, in accordance with the equation $V = IR$, which is now known as Ohm's law. (See Fig. 5.18 top.) The unit of electrical resistance is named in his honor.

Andreas von Ettingshausen (Austrian, 1796–1878) designed the first machine to use electromagnetic induction to generate power, and also did research in optics.

Franz Ernst Neumann (German, 1798–1895) worked out laws for the induction of currents by magnetic fields, as well as the optical behavior of crystals.

Heinrich Lenz (Baltic German, 1804–1865) formulated what is now known as Lenz's law, which describes how a changing magnetic field induces electric currents in nearby conductors that create new magnetic fields opposing the changing field. He also discovered that the power P consumed by an electric circuit depends on the current I flowing through the circuit and the electrical resistance R of the circuit, $P = I^2R$.

Heinrich Rühmkorff (German, 1803–1877) developed improved magnetic induction coils, now called Rühmkorff coils, and used them in a variety of applications such as high-voltage generators (p. 949). He also investigated the rotation of the plane of polarized light in magnetic media, thermoelectric effects, and other aspects of electromagnetism.

Werner von Siemens (German, 1816–1892) began his career by creating more sophisticated telegraphs that could point to individual letters, and went on to produce a wide range of additional electrical innovations such as generators and transformers (pp. 950 and 975). The unit of electrical conductivity (the inverse of electrical resistance) is named in his honor [Bähr 2016; von Siemens 1895].

Gustav Kirchhoff (German, 1824–1887) discovered a number of physical laws that now have his name attached to them. Kirchhoff's various laws describe the current and voltage in electric circuits (p. 951), the emission and absorption spectra of materials as measured by spectroscopy (p. 433), and the emission and absorption of thermal radiation (p. 915).

Hendrik Lorentz (Dutch, 1853–1928) made many contributions to electromagnetism and other areas of physics, including formulating what is now called the Lorentz force, the force that electric and magnetic fields exert on a particle with a given electric charge and velocity. He won the Nobel Prize in Physics in 1902 (p. 891).

Johann Christian Poggendorff (German, 1796–1877), Wilhelm Holtz (German, 1836–1913), and August Toepler (German, 1836–1912) each built very early high-voltage generators and used those to study electrostatics. Other physicists used such high-voltage generators to power some of the earliest cathode ray tubes for producing electron beams.

5.2.2 Electromagnetic Waves

Joseph von Fraunhofer (German states, 1787–1826) made a number of important discoveries and inventions in optics. He improved prisms, invented diffraction grating, and studied the diffraction of light of different wavelengths. He used a diffraction slit and prism to develop a spectroscope, which he and others then applied to make important measurements in physics and chemistry (p. 961). He also created achromatic telescope lenses and other specialized lenses. Through all of these developments, von Fraunhofer learned and applied a great deal of knowledge about the behavior of light waves.

Christian Doppler (Austrian, 1803–1853) discovered and explained how the wavelength and frequency of waves changes depending on the velocity of the object emitting the waves, which is now commonly known as the Doppler effect. (See Fig. 5.18 middle.)

In 1856, Wilhelm Weber collaborated with Rudolf Kohlrausch (German states, 1809–1858) to combine the laws governing electric fields with those governing magnetic fields, and to use those to show that light is an electromagnetic wave with its speed c (as Weber and Kohlrausch labelled it) given by those equations. [Rudolf Kohlrausch was the father of Friedrich Kohlrausch (p. 599).] At approximately the same time, Gustav Kirchhoff independently arrived at a mathematical derivation of the speed of electromagnetic waves. Several years later, in the 1860s and 1870s, James Clerk Maxwell (Scottish, 1831–1879) also derived and published the equations for electromagnetic waves and the speed of light. In his published papers, Maxwell specifically gave credit to Weber's earlier work. It could be interesting for historians to more closely scrutinize the connections, similarities, and differences between Maxwell's work and the earlier work by Weber, Kohlrausch, and Kirchhoff.

Hermann von Helmholtz (German, 1821–1894) made a wide variety of major discoveries in biology (pp. 239, 282, 297, 311), chemistry (p. 597), and physics (p. 912) [Cahan 2018]. In electromagnetic theory, he is best remembered for the Helmholtz equation for electromagnetic waves, and also for Helmholtz electromagnetic coils for producing a very uniform magnetic field within a small volume.

Heinrich Hertz (German, 1857–1894), a student of Gustav Kirchhoff and Hermann von Helmholtz, produced, detected, and measured electromagnetic waves, specifically radio waves, making him also the true original inventor of radio transmitters and receivers. (See Fig. 5.18 bottom.) Unfortunately Hertz died very young; otherwise he would likely have played even more of a role (and been recognized far more) in the early development of radio technology. The unit of frequency (1 Hertz = 1 Hz = 1 wave/second) is named in his honor. Because Hertz died before Nobel Prizes were awarded, he was not eligible to be considered for one. However, Professor Hj. Théel, President of the Royal Swedish Academy of Sciences, paid tribute to Hertz's groundbreaking contributions in his speech for the 1902 Nobel Prize in Physics [https://www.nobelprize.org/prizes/physics/1902/ceremony-speech/]:

> This so-called electromagnetic theory of light of Maxwell's at first aroused compara-

> tively little interest. Twenty years after its first appearance however it led to a scientific discovery which demonstrated its great significance in no uncertain manner. The German physicist Heinrich Hertz then succeeded in demonstrating that the electrical vibrations—which are generated under certain conditions when an electrically charged body is discharged—are propagated through the surrounding space in the form of a wave motion, and that the wave motion spreads at the speed of light and also possesses its properties. This gave a firm experimental basis for the electromagnetic theory of light.

Building on the earlier work of Weber, Kohlrausch, Helmholtz, and Hertz on electromagnetic waves, Ernst Lecher (Austrian, 1856–1926) developed a device that used parallel wires (now called Lecher lines) to measure the wavelength of radio waves.

Nikola Tesla (Serbo-Croatian, educated in Austria, 1856–1943) showed that Hertz's radio waves could be used to transmit signals and even power (using what are now known as Tesla coils) over considerable distances. Tesla also made countless other contributions to electromagnetism and electrical engineering, especially in AC (alternating current) electricity generation, distribution, and usage (p. 954) [Cheney 1981; Cheney and Uth 1999; Tesla 1893, 1904, 1919, 1940]. The SI unit of magnetic field strength is named in his honor.

Although Albert Michelson (1852–1931) was a U.S. citizen, he was born in Prussia, was raised by German-speaking parents, and studied in Berlin and Heidelberg. He developed methods to measure the speed of light very accurately, and then used those methods to demonstrate that the speed of light was the same in all directions. That result showed that light is simply electromagnetic waves in empty space and not waves in some invisible vibrating "ether" material that fills the universe and moves in a particular direction with some velocity relative to the earth. For these experiments, Michelson won the Nobel Prize in Physics in 1907. Professor the Count K. A. H. Mörner, President of the Royal Swedish Academy of Sciences, announced the award [https://www.nobelprize.org/prizes/physics/1907/ceremony-speech/]:

> Professor Michelson. The Swedish Academy of Sciences has awarded you this year the Nobel Prize in Physics in recognition of the methods which you have discovered for insuring exactness in measurements, and also of the investigations in spectrology which you have carried out in connection therewith.
>
> Your interferometer has rendered it possible to obtain a non-material standard of length, possessed of a degree of accuracy never hitherto attained. By its means we are enabled to ensure that the prototype of the metre has remained unaltered in length, and to restore it with absolute infallibility, supposing it were to get lost.
>
> Your contributions to spectrology embrace methods for the determination of the length of waves in a more exact manner than those hitherto known.
>
> Furthermore, you have discovered the important fact that the lines in the spectra, which had been regarded as perfectly distinct, are really in most cases groups of lines. You have also afforded us the means of closely investigating this phenomenon, both in its spontaneous occurrence and when it is produced by magnetic influence, as in Zeeman's interesting experiments.

> Astronomy has also derived great advantage, and will do so yet more in the future, from your method of measurements.

Paul Drude (German, 1863–1906) used the latest ideas about electromagnetic waves and electrons to create some of the first mathematical models for the electrical and optical properties of solids.

Gustav Mie (German, 1868–1957) derived equations for the scattering of electromagnetic waves by spherical particles, which is now called Mie scattering. Mie scattering has proven useful for everything from studying the propagation of light though the atmosphere to designing modern metamaterials. He also analyzed the electrostatic forces between molecules, now called the Mie potential, and made other contributions to electromagnetic theory.

Creators from the German-speaking world also developed a wide range of practical applications of electromagnetic waves, such as:

- Lighting technology (p. 957).
- Radio communications (p. 978).
- Television communications (p. 996).
- Lasers and holography (p. 1023).
- Infrared vision and targeting (p. 1131).
- Radio-controlled robotic vehicles (p. 1198).
- Radar (p. 1217).
- Optical technologies (p. 1260).

5.2.3 Electron, Proton, and Neutron Beams

German-speaking scientists discovered, analyzed, and harnessed electron beams (cathode rays), proton beams (anode rays or canal rays), and neutron beams, thus identifying all three building blocks of the atom.

Heinrich Geissler (German, 1814–1879) invented the first high-voltage, low-pressure gas-filled glass electrical discharge tubes, which other German-speaking creators later adapted for a wide variety of applications ranging from fluorescent lights to television screens.

In the late 1850s and 1860s, Julius Plücker (German states, 1801–1868) and Johann Wilhelm Hittorf (German, 1824–1914) modified Geissler's tubes to produce cathode rays, which were later found to be electron beams, and to measure their properties.

Philipp Lenard (Austrian/German, 1862–1947) conducted a variety of novel experiments with cathode rays beginning in 1888. He demonstrated that the electrons were particles, and he experimentally measured many of their properties. For this work, he won the Nobel Prize in Physics in 1905. Professor A. Lindstedt, President of the Royal Swedish Academy of Sciences, described Lenard's experiments [https://www.nobelprize.org/prizes/physics/1905/ceremony-speech/]:

> The discovery of the cathode rays forms the first link in the chain of brilliant discoveries with which the names of Röntgen, Becquerel and Curie are connected. The discovery itself was made by Hittorf as long ago as 1869 and therefore falls in a period before that which the Nobel Foundation is able to take into account. However, the recognition which Lenard has earned himself by the further development of Hittorf's discovery (which is becoming of increasing importance) shows that he too deserves the same reward as has already come to several of his successors for work of a similar nature. [...]
>
> These were the circumstances prevailing when Lenard began his work on cathode rays in 1893. He started from a fact which had been observed by his great and prematurely deceased teacher Heinrich Hertz: that these rays were able to pass through thin metal plates which had been introduced into the discharge tube. At Hertz's suggestion he utilized this fact in an attempt to lead the rays out of the tube. He used for this a tube which was not wholly made of glass but terminated at one place in a very thin aluminium plate. As the cathode rays reached Lenard's "aluminium window", it was found that they passed through it and continued their course in the air outside the tube. This constituted a discovery which was to have the most far-reaching consequences, above all for the study of the radiation phenomena themselves. It became possible to study cathode rays under much simpler and more convenient experimental conditions than before, and also to separate observations on conditions needed for the production of the rays in the tube from questions concerning their propagation and other characteristics.
>
> Lenard found first of all that the rays coming through the aluminium window possessed the same characteristics as those previously noted in rays inside the tube, i.e. that they cause fluorescence, can be deflected by a magnet and so on. He further proved that cathode rays have certain chemical effects such as causing impressions on photographic plates, ozonizing air, making gases conducting through so-called ionisation, etc. It was also discovered that these rays pass unimpeded through empty space but that in gases

> they are subject to diffusion which increases with the density of the gas; and, moreover, that bodies in general differ in permeability, as their absorptive power bears a direct relationship to their density. Cathode rays proved to be carriers of negative electricity even in empty space and they could be deflected from their path by both magnetic and electrical fields. Finally, Lenard showed that there are various types of cathode rays, differentiated amongst other things by the fact that they are deflected by magnets, to a greater or lesser extent. He also found that the formation of one or other type of ray is determined by the degree of gas rarification in the discharge tube. [...]
>
> The research by Lenard, only a very brief report of which is given here, has been followed by a series of valuable studies by other scientists as well. Development of the theoretical basis for the theory of electrons has gone hand in hand with the experimental work. The study of electrons, their characteristics and their behaviour in relation to matter has been given a sounder basis through these researches on cathode rays and has been gradually developed into one of the foremost theories of modern physics by Lenard himself and by other workers. This theory is in fact not only important for the explanation of cathode rays and other closely related phenomena—the electron theory with its concepts on the constitution of matter has become of the most fundamental importance for the sciences of electricity and of light and for both the physicist and the chemist.

In 1890, Arthur Schuster (German, 1851–1934) measured the charge-to-mass ratio of electrons and showed that it was remarkably large, so electrons were particles with a very small mass compared to atoms. Schuster was also the first physicist to propose the existence of antimatter particles that would annihilate and produce energy if combined with particles of ordinary matter.

The geophysicist Emil Wiechert (German, 1861–1928) also demonstrated that cathode rays were particles and measured their charge-to-mass ratio.

One could make a very strong case that the fact that electrons are particles was discovered by the qualitative demonstrations of Julius Plücker and Johann Hittorf during the 1850s–1860s, or by the quantitative measurements of Lenard, Schuster, and Wiechert in the late 1880s and early 1890s. Yet traditionally, the credit for the discovery of the electron has been given to J. J. Thomson (British, 1856–1940), who conducted very similar but much more widely publicized experiments significantly later, in 1897. For that work, Thomson received the Nobel Prize in Physics in 1906.

Eugen Goldstein (German, 1850–1930) used similar tubes not only to produce and study cathode rays or electrons, but also to produce and analyze anode rays (also called canal rays), which turned out to be positively charged ions, or atomic nuclei. More specifically, Goldstein's anode rays were protons if he used hydrogen gas in his tubes. Goldstein showed that the anode rays were particles with a positive charge and a mass much larger than that of the electron.

Wilhelm Wien (German, 1864–1928) measured the mass of the anode rays produced from hydrogen gas in 1898 and specifically showed that they had the same mass as a hydrogen atom. For some of his other work (thermal radiation), Wien won the Nobel Prize in Physics in 1911 (p. 916).

Thus one could make a convincing case that the proton was discovered in 1886 by Goldstein, or at the latest was more fully demonstrated in 1898 by Wien. Yet traditionally the credit for the discovery of the proton has been given to Ernest Rutherford (New Zealand/British, 1871–1937) for a series of experiments he conducted decades later, during the period 1917–1919.

The neutron was the last of the three building blocks of the atom to be discovered, and it too was discovered by German-speaking scientists. Carl Auer von Welsbach (Austrian, 1858–1929, p. 966) produced free neutrons and observed their effects on various nuclei no later than 1910 [Auer von Welsbach 1910; Steinhauser et al. 2013]. Walther Bothe (German, 1891–1957, p. 1026) and Herbert Becker (German?, 18??–19??) rediscovered the neutron no later than 1930, when they bombarded beryllium with alpha particles from polonium and showed that in response the beryllium emitted a new type of particles that did not match the characteristics of alpha, beta, or gamma radiation [Bothe and Becker 1930]. James Chadwick repeated the Bothe-Becker experiment in 1932 and was trumpeted in the English-speaking world as the "discoverer" of the neutron while the earlier experimental discoveries of Carl Auer von Welsbach, Walther Bothe, and Herbert Becker were forgotten.

Other creators from the German-speaking world devised a wide range of practical applications of high-voltage gas discharge tubes, such as:

- Fluorescent lights (p. 957).
- Vacuum tubes (p. 978).
- Television picture tubes (p. 996).
- Photomultiplier tubes (p. 1131).
- Electron microscopes (p. 1286).
- X-ray tubes (p. 1505).
- Geiger counters (p. 1518).
- Particle beam sources (p. 1524).
- Electric rocket propulsion (p. 1954).
- Fusion reactions and neutron sources (Section D.9).

5.3 Special and General Relativity

The theory of relativity is thus named because it deals with objects that are moving differently relative to each other, as there is no absolute frame of reference to authoritatively declare what is moving and what is not. Relativistic physics was almost entirely a product of German-speaking creators.

Special relativity (Section 5.3.1) only considers the special case in which the objects move at constant velocities.

General relativity (Section 5.3.2) covers the general case in which the objects' velocities can change, or the objects can accelerate and decelerate.

5.3.1 Special Relativity

Special relativity is valid for the special case in which the objects' relative velocities remain constant, with no acceleration or deceleration. Following that initial assumption to its logical if surprising conclusions, special relativity describes the weird things that happen when something travels nearly as fast as the speed of light (relative to some other observer), including time slowing down, lengths contracting, and not being able to travel faster than light speed no matter how hard something is pushed (Fig. 5.24). These strange effects have all been confirmed in countless experiments. At the fundamental level, these effects are manifestations of the facts that space and time are interrelated, and mass and energy are interrelated.

Relativity is quite possibly unique in how much of the field came from a single person, Albert Einstein (German, 1879–1955, Fig. 5.25).[4] Indeed, Einstein and relativity are probably the most famous creator and creation from the entire German-speaking world. In addition to developing special relativity (1905) and general relativity (1915–1916), Einstein also made major contributions to statistical and thermal physics, non-relativistic quantum physics, and relativistic quantum physics, as covered in the next sections.

Shockingly, the Nobel Committee for Physics was unwilling to give Einstein an award for relativity even years later, since they considered it so counterintuitive and controversial. They did give him a Nobel Prize in 1921, but only for his work on the quantum physics of the photoelectric effect (p. 890).

Although Einstein is justifiably lauded for special relativity, at least six other scientists also made significant contributions to special relativity: Hendrik Lorentz, Woldemar Voigt, Ernst Mach, Hermann Minkowski, Walter Kaufmann, and Alfred Bucherer. Many other scientists from the German-speaking world also made contributions to general relativity. See Figs. 5.26–5.30.

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[4] For good overviews of this area, see especially: Laurie Brown et al. 1995; Isaacson 2007; Jungnickel and McCormmach 1986, 2017; Kragh 2002; Levenson 2003; Pais 1982; Thorne 1994.

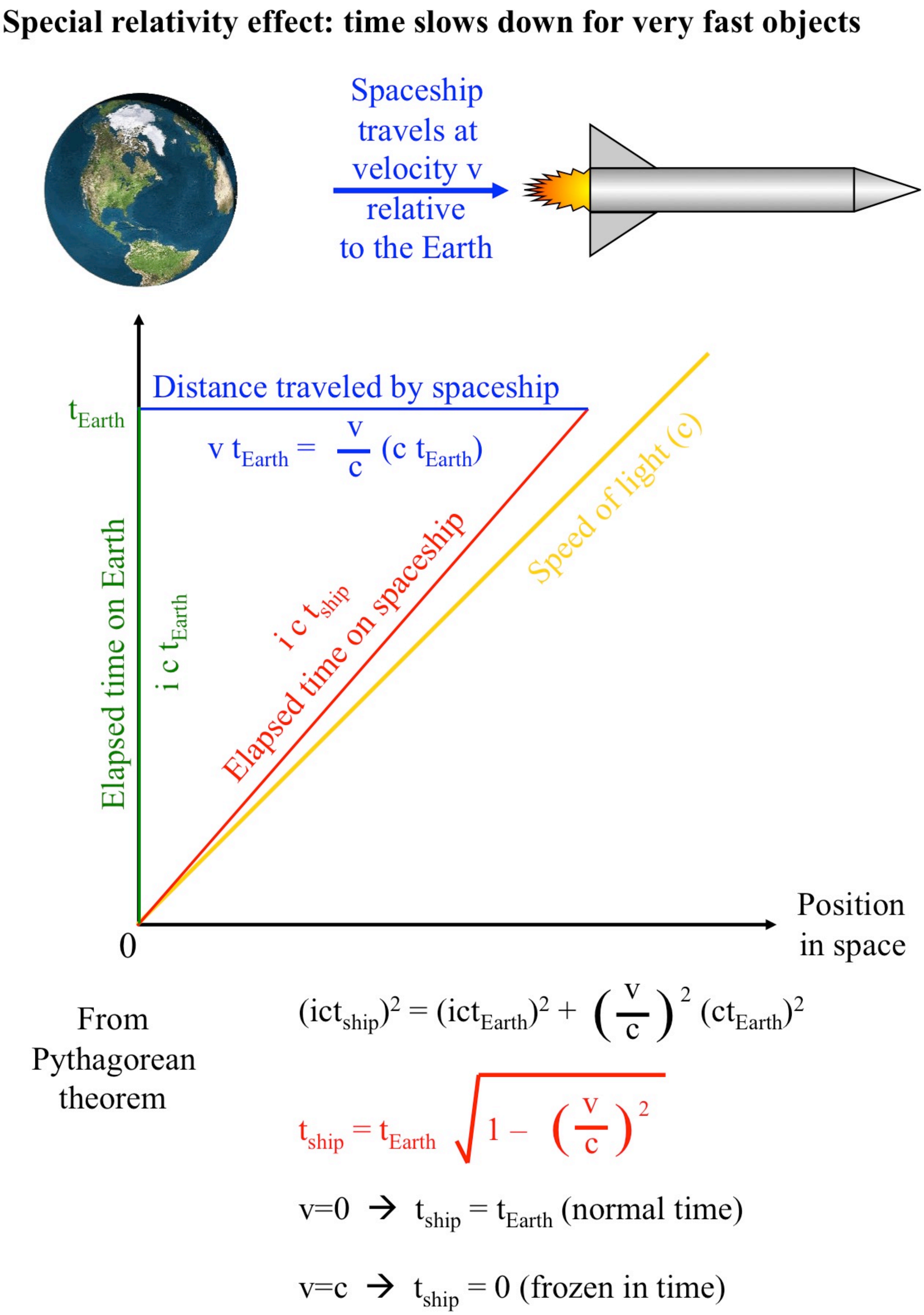
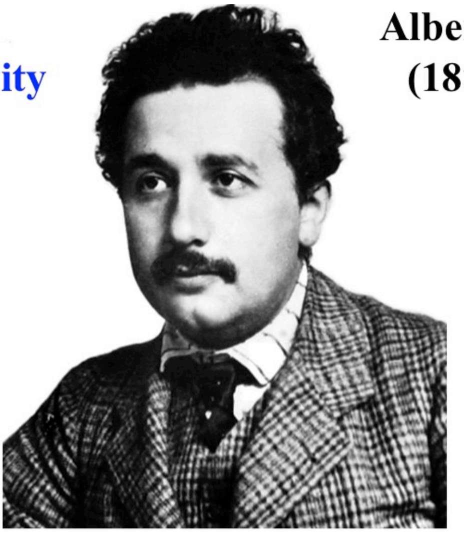


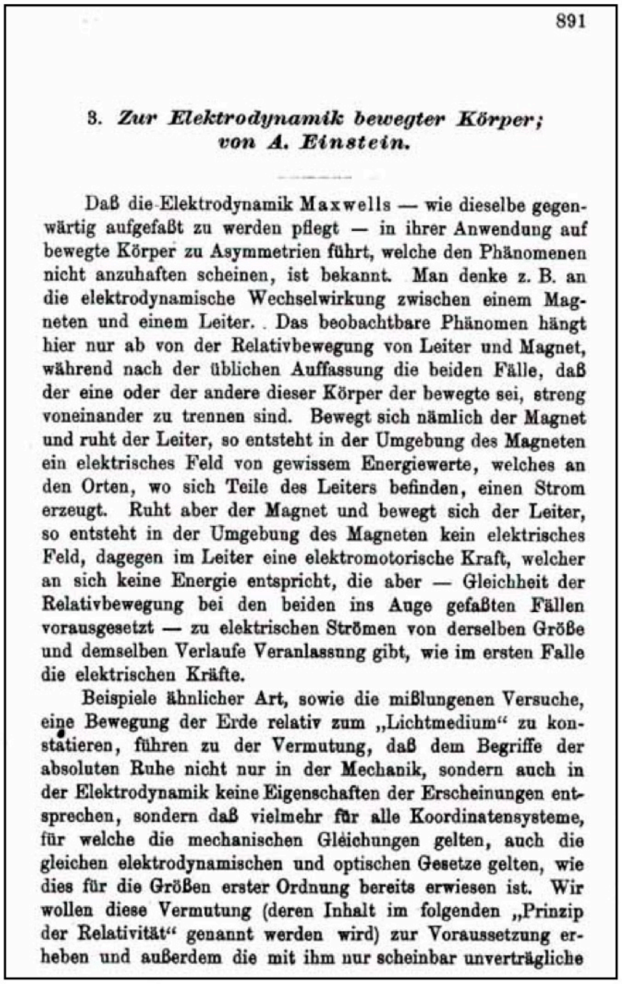
Figure 5.24: Special relativity correctly predicts that time slows down for objects moving very quickly (approaching the speed of light).

Special and general relativity



Albert Einstein (1879–1955)

Einstein's first 1905 paper on special relativity in *Annalen der Physik*



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3. ***Zur Elektrodynamik bewegter Körper;***
von A. Einstein.

Daß die Elektrodynamik **Maxwells** — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium" zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität" genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

Einstein's first 1916 paper on general relativity in *Annalen der Physik*

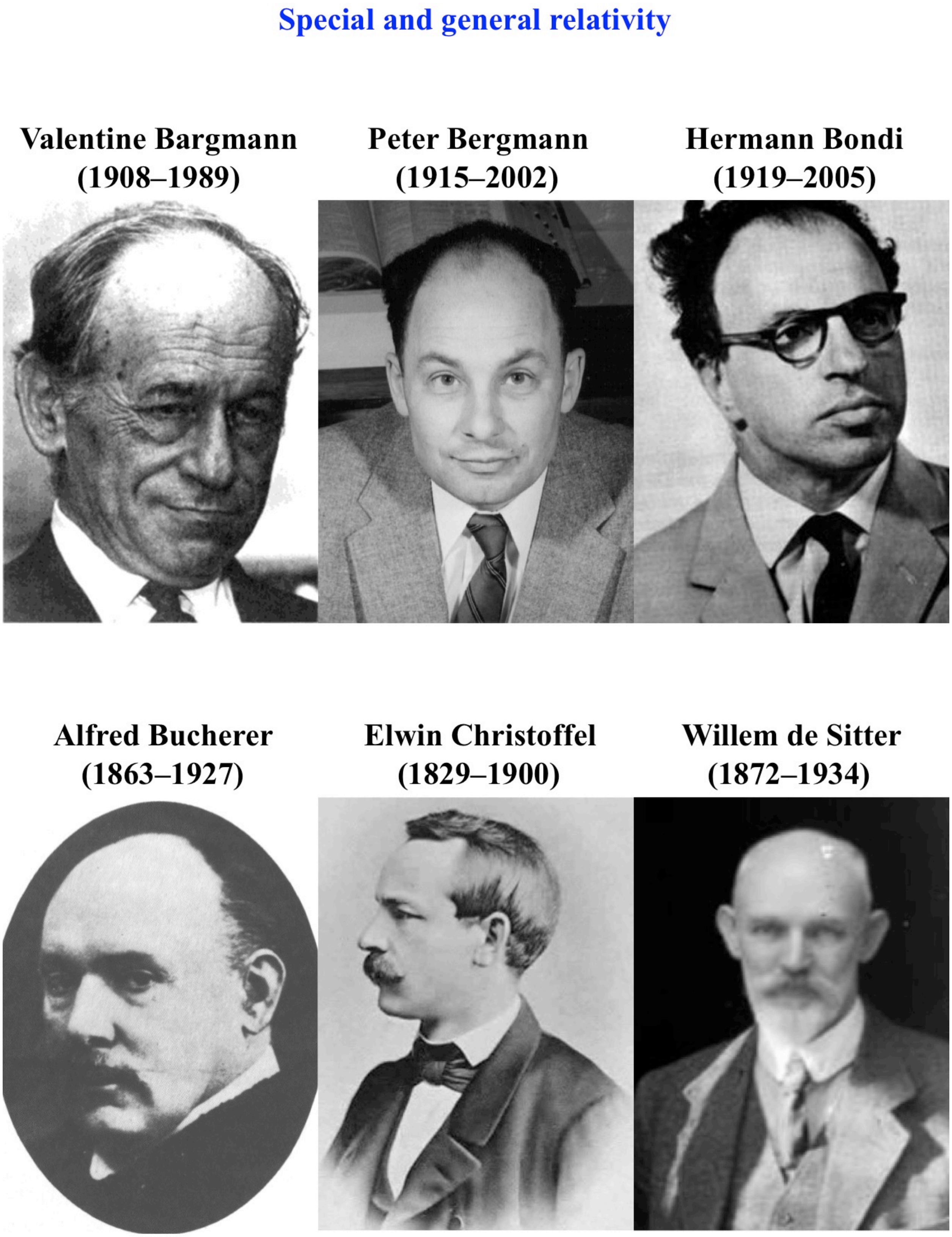
1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. ***Die Grundlage der allgemeinen Relativitätstheorie;***
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch **Minkowski** gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von **Gauss**, **Riemann** und **Christoffel** über nichteuklidische Mannigfaltigkeiten ruht und von **Ricci** und **Levi-Civita** in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers **Grossmann**, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

Figure 5.25: Albert Einstein proposed special relativity in papers he published in 1905, and general relativity in a series of papers published in 1915–1916.



Special and general relativity

Valentine Bargmann (1908–1989)

Peter Bergmann (1915–2002)

Hermann Bondi (1919–2005)

Alfred Bucherer (1863–1927)

Elwin Christoffel (1829–1900)

Willem de Sitter (1872–1934)

Figure 5.26: Other creators who made significant contributions to special and general relativity included Valentine Bargmann, Peter Bergmann, Hermann Bondi, Alfred Bucherer, Elwin Christoffel, and Willem de Sitter.

Special and general relativity

Loránd Eötvös (1848–1919) **Ludwig Flamm (1885–1964)** **Erwin Finlay-Freundlich (1885–1964)**

George Gamow (1904–1968) **Thomas Gold (1920–2004)** **Gustav Herglotz (1881–1953)**

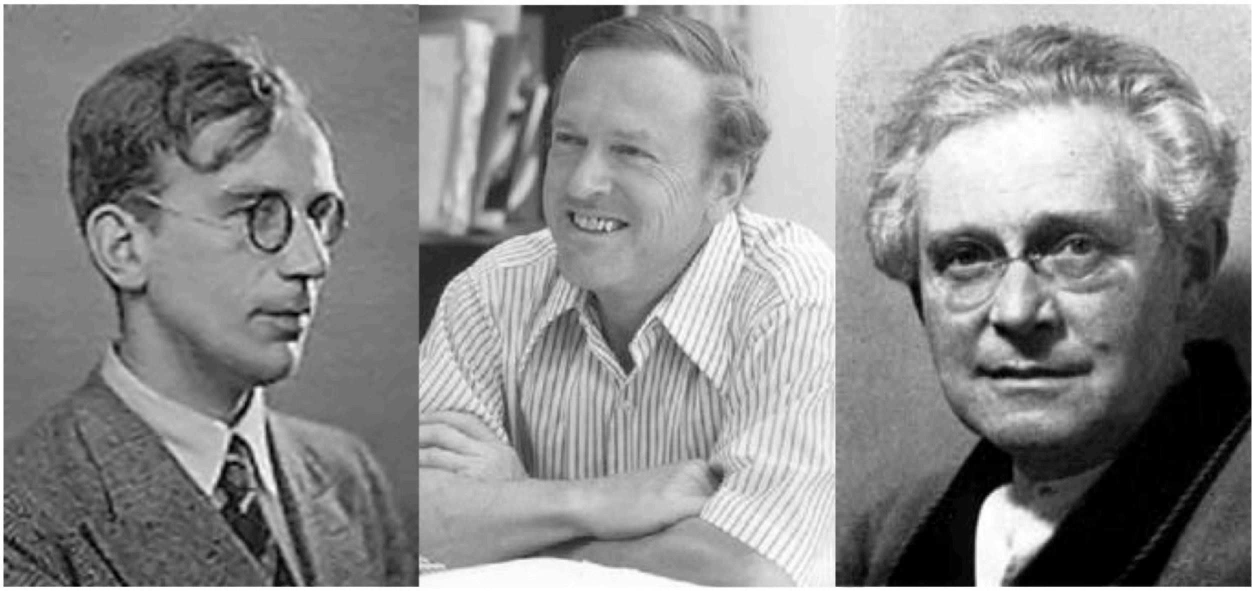


Figure 5.27: Other creators who made significant contributions to special and general relativity included Loránd Eötvös, Erwin Finlay-Freundlich, Ludwig Flamm, George Gamow, Thomas Gold, and Gustav Herglotz.

Special and general relativity

David Hilbert (1862–1943)

Leopold Infeld (1898–1968)

Theodor Kaluza (1885–1954)

Jacobus Kapteyn (1851–1922)

Walter Kaufmann (1871–1947)

Oskar Klein (1894–1977)

Figure 5.28: Other creators who made significant contributions to special and general relativity included David Hilbert, Leopold Infeld, Theodor Kaluza, Jacobus Kapteyn, Walter Kaufmann, and Oskar Klein.

Special and general relativity

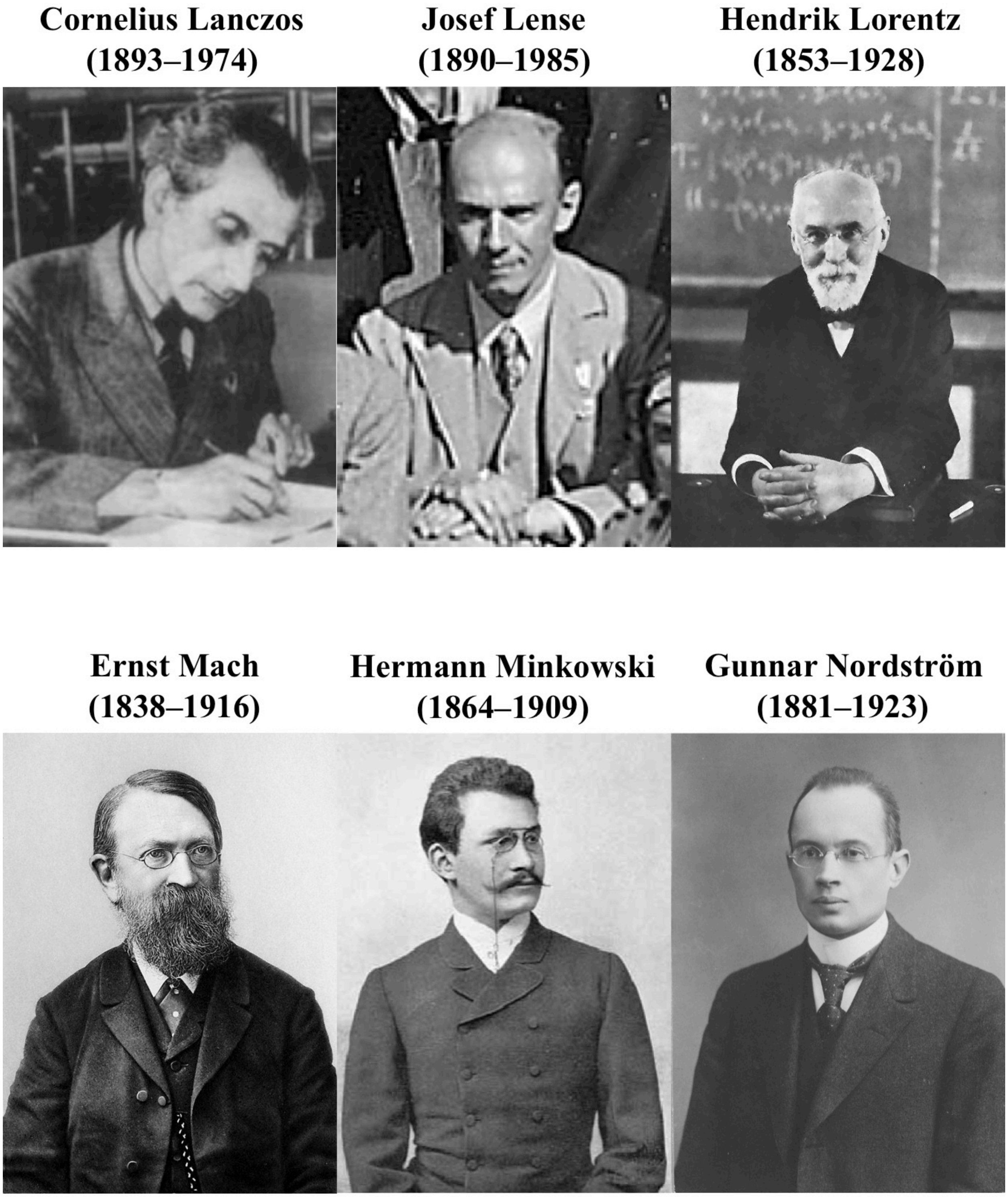

Cornelius Lanczos (1893–1974)
Josef Lense (1890–1985)
Hendrik Lorentz (1853–1928)
Ernst Mach (1838–1916)
Hermann Minkowski (1864–1909)
Gunnar Nordström (1881–1923)

Figure 5.29: Other creators who made significant contributions to special and general relativity included Cornelius Lanczos, Josef Lense, Hendrik Lorentz, Ernst Mach, Hermann Minkowski, and Gunnar Nordström.

Figure 5.30: Other creators who made significant contributions to special and general relativity included Jan Oort, Hans Reissner, Bernhard Riemann, Karl Schwarzschild, Hans Thirring, and Willem Jacob van Stockum.

Special and general relativity

Woldemar Voigt
(1850–1919)

Hermann Weyl
(1885–1955)

Carl Wilhelm Wirtz
(1876–1939)

Fritz Zwicky
(1898–1974)

Figure 5.31: Other creators who made significant contributions to special and general relativity included Woldemar Voigt, Hermann Weyl, Carl Wilhelm Wirtz, and Fritz Zwicky.

Over the period 1892–1905, Hendrik Lorentz (Dutch, 1853–1928, 1902 Nobel Prize in Physics—p. 891) developed mathematical formulas for apparent distortions of time and space for objects moving at nearly the speed of light. Those formulas for the distortions are now know as the Lorentz transformations, and they correctly describe special relativistic effects, as Einstein showed. Physicist Robert Weber described Lorentz's contributions to relativity [Weber 1988, pp. 12–13]:

> In 1892 Lorentz put forward the theory of electrons which profoundly influenced the development of theoretical physics. In 1895 he published his mathematical investigation of the effect on the shape of a body produced by its moving with speed v through the ether. [...] Ten years later this result was shown to follow from the theory of relativity.
>
> One deduction from Lorentz's electron theory of matter was that the mass of an electron increased with its velocity. Later experiments with beta rays from radioactive elements confirmed quantitatively his prediction, and once again Lorentz anticipated a finding of the theory of relativity. [...]
>
> In 1904 Lorentz made his greatest contribution to theoretical physics when he showed that James Clerk Maxwell's electromagnetic equations were not invariant with respect to velocity when transformed from one reference frame to another by the hitherto universally accepted Newtonian transformation formulae. These related the time and position coordinates of an event in one reference frame to those assigned to the same event viewed in another frame. Lorentz devised alternative transformation formulae which made Maxwell's equations invariant. Einstein, refusing to believe that there could be one set of such formulae (Newton's) for mechanical relationships and another (Lorentz's) for electrical, accepted Lorentz's transformation formulae as universally applicable. The special or restricted theory of relativity followed from that acceptance.

Actually, Woldemar Voigt (German, 1850–1919) correctly calculated the Lorentz transformations of space and time even earlier, in 1887, although he apparently did not fully consider their physical meaning or effects as in special relativity. Historians of science Christa Jungnickel and Russell McCormmach included a brief mention of Voigt's achievement in their history of early German physics [Jungnickel and McCormmach 1986, Vol. 2, p. 273]:

> In 1915, in honor of the tenth anniversary of the theory of relativity, the editors of the *Physikalische Zeitschrift* reprinted a paper of Voigt's from 1887 on the Doppler principle. This "very early precursor" of relativity theory contained what became known as the Lorentz transformations, which Voigt had derived from a study of the elastic light-ether. Physicists liked to recall this independent discovery, a curiosity that pointed up Voigt's remove from the developments that "modern" physics came to be identified with.
>
> Voigt had reservations about Einstein's relativity principle as a natural law[...]

Ernst Mach (Austrian, 1838–1916) intensively studied the physics of objects approaching or moving faster than the speed of sound waves. (Hence the Mach number of an object is the ratio of its speed to the speed of sound.) However, many of his results carry over to consideration of what would happen if objects approached or moved faster than the speed of light waves. Mach's philosophical approach to space and time also influenced Einstein's development of relativity, as described by historian Volker Berghahn [Berghahn 2005, p. 161]:

> Among the first to do so was Ernst Mach in Vienna who, in light of recent developments, proposed a total separation of metaphysics from the sciences. In his book *Die Mechanik in ihrer Entwicklung* (1883) he even went so far as to portray time and space as metaphysical concepts that should be thrown overboard. Nature, he wrote, did not know such confines. The body's temporal and spatial position was determined only in relation to other objects. Influenced by Mach, Einstein took the final step on this journey[...]

After Einstein worked out the physics and effects of special relativity, in 1907 Hermann Minkowski (German, 1864–1909) showed that those effects could be interpreted as the geometric behavior of four dimensions in which the three spatial dimensions are real numbers and the fourth or time dimension is an imaginary number (or equivalently, spatial dimensions are imaginary numbers and time is a real number). Physicist Abraham Pais summarized Minkowski's contributions [Pais 1982, pp. 151–152]:

> In 1902, Minkowski, at one time Einstein's teacher in Zürich, had moved to the University of Goettingen. There, on November 5, 1907, he gave a colloquium about relativity in which he identified Lorentz transformations with pseudorotations for which
>
> $$x_1^2 + x_2^2 + x_3^2 + x_4^2 \text{ is invariant,} \qquad x_4 = ict$$
>
> where x_1, x_2, x_3 denote the spatial variables. [...] Soon thereafter Minkowski published a detailed paper in which for the first time the Maxwell-Lorentz equations are presented in their modern tensor form, the equations of point mechanics are given a similar treatment, and the inadequacy of the Newtonian gravitation theory from the relativistic point of view is discussed. Terms such as *spacelike vector*, *timelike vector*, *light cone*, and *world line* stem from this paper.
>
> Thus began the enormous formal simplification of special relativity. Initially, Einstein was not impressed and regarded the transcriptions of his theory into tensor form as 'überflüssige Gelehrsamkeit,' (superfluous learnedness). However, in 1912 he adopted tensor methods and in 1916 acknowledged his indebtedness to Minkowski for having greatly facilitated the transition from special to general relativity.

Walter Kaufmann (German, 1871–1947) experimentally demonstrated that the mass of electrons increases with their velocity, as predicted by special relativity. He actually made his first measurements in 1901, before Einstein's first paper on relativity. Immediately after Einstein published his theory, Kaufmann made more accurate measurements of the electron mass increase in 1905. Alfred Bucherer (German, 1863–1927) made even more precise measurements in 1908, helping to distinguish between Einstein's version of special relativity and competing theories of electron mass increases.

To sum up the history of special relativity, Einstein justifiably earned the greatest credit for special relativity, through his discoveries about the physical origins and physical implications of space and time changing with velocity and his 1905 publications that elegantly tied all of that together. Yet if Einstein had never existed, these ideas were percolating within the German-speaking physics community, and it seems likely that Lorentz, Voigt, Minkowski, or others from that community would have arrived at the complete theory of special relativity within a few years after 1905.

5.3.2 General Relativity

General relativity covers the general case in which objects may be accelerating or decelerating. The forces inside an accelerating object are indistinguishable from the forces inside a gravitational field, so general relativity describes the weird things that happen when something gets close to very strong gravitational fields, such as time and space being warped (Fig. 5.32). Important effects that are correctly predicted by general relativity include the gravitational fields of stars, black holes, and wormholes; gravitational red-shifting of light; gravitational bending of light; precession of Mercury's perihelion as it orbits the sun; gravitational waves; and the overall structure and history of the universe.

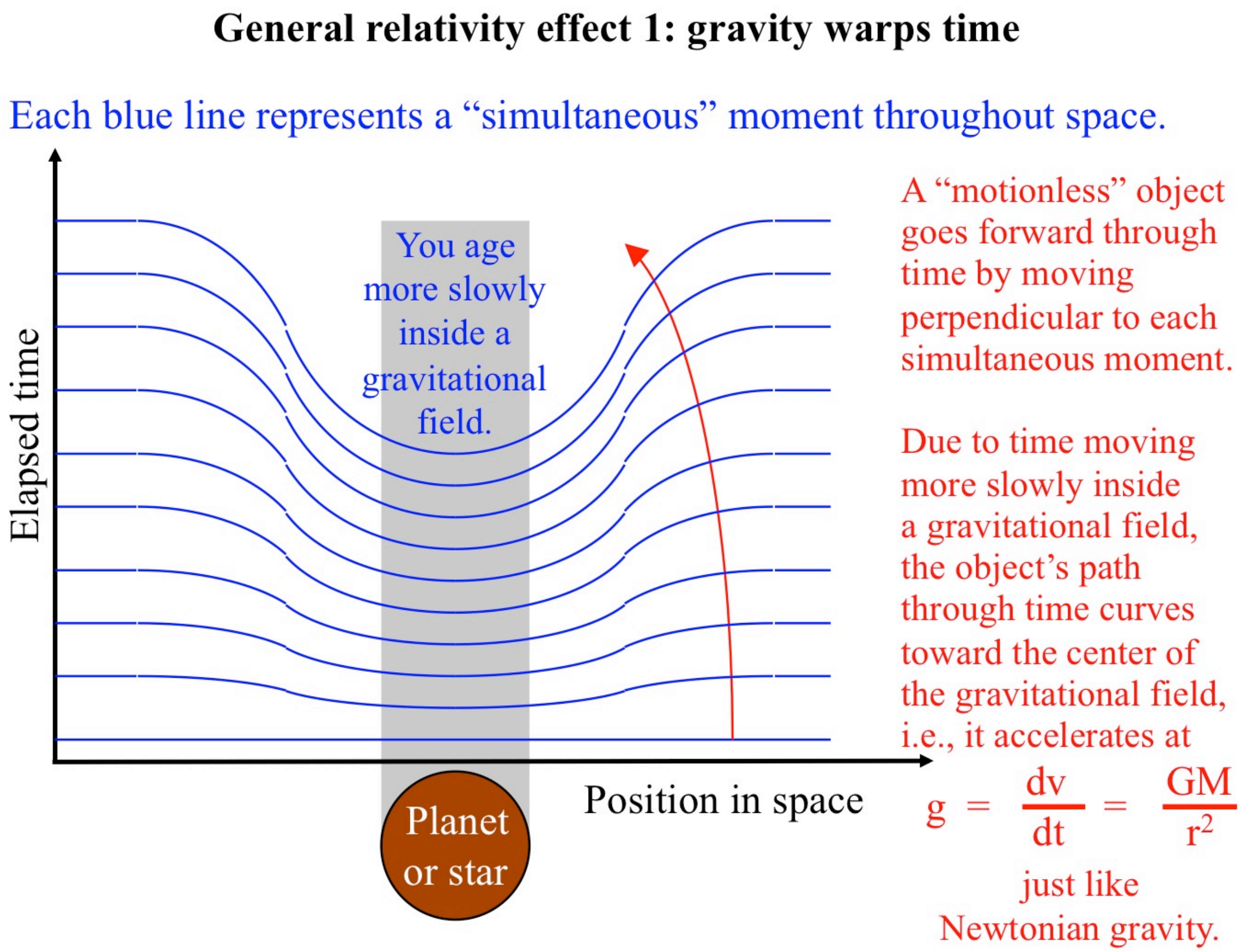
While Einstein was the dominant figure in special relativity, it is even more evident that he was the primary discoverer of general relativity. Kip Thorne, a Nobel-Prize-winning expert on general relativity, pointed out how extraordinarily farsighted and exceptional Einstein's work was [Thorne 1994, p. 119]:

> In fact, without Einstein the general relativistic laws of gravity might not have been discovered until several decades later.

While's Einstein's theory of relativity was never recognized by the Nobel Committee for Physics, the reaction from other scientists and from the public was overwhelming, as summarized by historians of science Jean Medawar and David Pyke [Medawar and Pyke 2000, p. 33]:

> Einstein was already famous, for his special theory of relativity produced in 1905 and his general theory published in 1917. However, they were still theories and not everyone was convinced. Then in 1919 an expedition, under the British physicist Sir Arthur Eddington, went to tropical Africa to photograph a total eclipse of the sun. This confirmed Einstein's prediction, made in 1917, by showing that light was bent by gravity. Almost universal acceptance followed and Einstein was hailed as a genius.
>
> In London, the discovery was announced by J. J. Thomson, President of the Royal Society, as 'one of the greatest achievements in the history of human thought'. Introducing the findings based on the expedition's photographs, Thomson continued: 'It is not the discovery of an outlying island but of a whole continent of new ideas. It is the greatest discovery in connection with gravity since Newton enunciated his principles.'
>
> Einstein became world-famous not only among scientists but also to the public. He was modest and of a tentative demeanour but that did not dampen the interest in everything he said and did. [...] He was honoured and fêted everywhere as the embodiment of science and the cleverest man in the world. No scientist had then, nor has since, been so admired or so famous.

Despite Einstein's critical role in the development of general relativity, a number of other German-speaking physicists and mathematicians also made important contributions to the theory, before, during, and after Einstein's work.



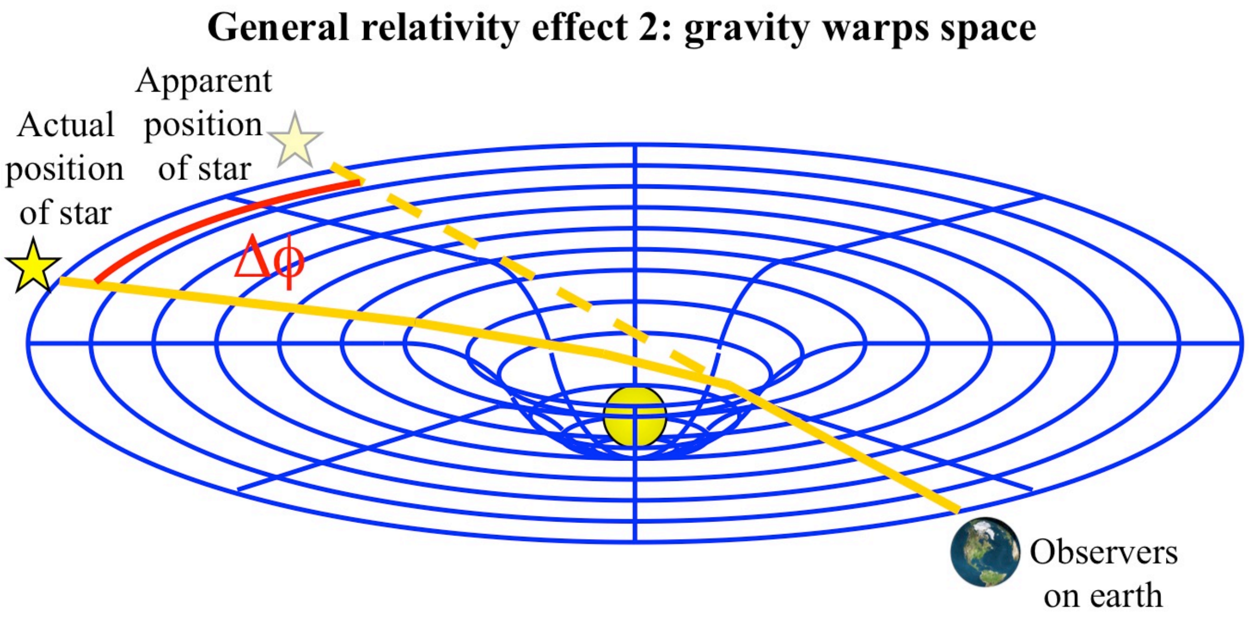


Figure 5.32: General relativity correctly predicts that gravitational fields warp both time and space, creating several measurable effects.

Just as Ernst Mach's ideas about space and time influenced Einstein's development of special relativity, Mach's ideas about inertia and acceleration also influenced Einstein's development of general relativity.

Likewise, Einstein incorporated Hermann Minkowski's ideas about the geometry of spatial and temporal dimensions, and his tensors for describing those mathematically, into the theory of general relativity.

Bernhard Riemann (German, 1826–1866) was the mathematician who originally developed most of the tensors and other mathematical methods of describing warped dimensions in general that Einstein later applied to describe warped space and time in particular.

Shortly after Riemann's death, Elwin Christoffel (German, 1829–1900) extended Riemann's work by adding some new tensors, now known as Christoffel symbols, to describe additional details of warped dimensions. Einstein ultimately incorporated the Christoffel symbols into general relativity, along with Riemann's tensors.

After Einstein's first papers on general relativity, the mathematician David Hilbert (German, 1862–1943) immersed himself in the new theory and independently published papers on the tensor mathematics of general relativity in parallel with Einstein's further papers on the topic. Gustav Herglotz (Austrian/German, 1881–1953) also published some independent and very early analyses of the tensor methods Einstein was using for general relativity.

As soon as Einstein's first equations for general relativity were available, Einstein, as well as Josef Lense (Austrian, 1890–1985) and Hans Thirring (Austrian, 1888–1976), found that in addition to the distortions of space and time caused by a massive object, if that object is rotating, it will also introduce "twisting" distortions into space and time. The twisting of space and time around massive rotating objects is called the Lense-Thirring effect or sometimes the Einstein-Lense-Thirring effect. Cornelius Lanczos (Hungarian, 1893–1974) and Willem Jacob van Stockum (Dutch, 1910–1944) later found that the spacetime twisting around massive rotating objects could be so extreme under certain circumstances that it might allow travel backward in time for someone circling in the right direction.

Loránd Eötvös (Austro-Hungarian, 1848–1919) conducted early experiments demonstrating the equivalence between gravity and acceleration, or the equivalence between gravitational mass and inertial mass. He also developed extremely sensitive methods of measuring gravitational gradients or variations along the earth's surface. The cgs unit for gravitational gradients is named in his honor, and Einstein cited Loránd Eötvös's experimental results when he published his theory of general relativity.

Immediately after Einstein published his first papers on general relativity in 1915, Karl Schwarzschild (German, 1873–1916) used those to solve the equations of general relativity for the gravitational field of a spherical, non-rotating mass. Einstein was impressed by his solution, and it is still widely used to describe the gravitational field of objects ranging from planets to black holes. The Schwarzschild radius, which appears in Schwarzschild's general mathematical solution, is the size to which a given mass must be compressed to form a black hole. Equivalently, the Schwarzschild radius is the distance from the center of the black hole to the point of no return (also called the event horizon) for objects near the black hole, where the gravitational field becomes so strong that not even light can escape from falling toward the center. If Schwarzschild had not died almost immediately after publishing his result, he might have gone on to make many more contributions to general relativity. Physicist Abraham Pais summarized Schwarzschild's contributions [Pais 1982, p. 255]:

> [O]n January 16, 1916, Einstein read a paper before the Prussian Academy on behalf of Karl Schwarzschild, who was in the German army at the Russian front at that time. The paper contained the exact solution of the static isotropic gravitational field of a mass point, the first instance of a rigorous solution of Einstein's full gravitational field equations. On February 24, 1916, Einstein read another paper by Schwarzschild, this one giving the solution for a mass point in the gravitational field of an incompressible fluid sphere. It is there that the Schwarzschild radius is introduced for the first time. On June 29, 1916, Einstein addressed the Prussian Academy to commemorate Schwarzschild, who had died on May 11 after a short illness contracted at the Russian front. He spoke of Schwarzschild's great talents and contributions both as an experimentalist and a theorist. He also spoke of Schwarzschild's achievements as director (since 1909) of the astrophysical observatory in Potsdam. He concluded by expressing his conviction that Schwarzschild's contributions would continue to play a stimulating role in science.

The same year (1916) that Schwarzschild published his solution for uncharged nonrotating black holes, Hans Reissner (German, 1874–1967) published the solution for charged nonrotating black holes. Gunnar Nordström (Finnish but very closely coupled to the German physics community, 1881–1923) and Hermann Weyl (German, 1885–1955) did further work on this solution.

Likewise, Ludwig Flamm (Austrian, 1885–1964) also responded to Einstein's first papers on general relativity by considering gravitational field solutions for specific cases in 1916. In particular, Flamm considered possible solutions for what would now be regarded as wormholes, or tunnels of warped space and time connecting two different parts of the universe. Hermann Weyl, Einstein, and Nathan Rosen (one of Einstein's close collaborators) later did further mathematical analysis of these wormhole solutions (which were ultimately dubbed Einstein-Rosen bridges).

The astronomer Erwin Finlay-Freundlich (German, 1885–1964) planned some of the first experimental tests of general relativity, including red-shifting of light from the sun and bending of starlight around the sun. Other scientists later carried out those tests and ultimately proved that general relativity was correct.

Gunnar Nordström, Theodor Kaluza (German, 1885–1954), and Oskar Klein (Swedish but very closely coupled to the German physics community, 1894–1977) considered how to extend Einstein's theory of general relativity to include extra dimensions and other forces such as electromagnetism.

Willem de Sitter (Dutch, 1872–1934) collaborated with Einstein to apply general relativity to describe various possible scenarios for the structure and history of the universe, and they both agreed that the equations of general relativity appeared to predict an expanding (or possibly contracting) universe. Historian Thomas Levenson wrote about the first interactions of de Sitter and Einstein regarding the theoretical discovery that the universe could be expanding [Levenson 2003, p. 135]:

> In February 1917 Willem De Sitter, professor of astronomy at the University of Leyden in the Netherlands, responded to Einstein's theory almost as soon as it appeared by

> proposing a model of an expanding universe. Einstein looked for some flaw in De Sitter's work that could rule out so unsettling a notion, but he soon gave up and admitted that there was nothing formally wrong with the idea.

In a series of 1918–1924 publications (Fig. 5.33), Carl Wilhelm Wirtz (German, 1876–1939) measured the distances and the red-shifting of light from other galaxies. The amount of red shift or Doppler shift indicated the galaxies' velocities relative to the Earth. With that data, he experimentally demonstrated that the universe was indeed expanding, and that more distant galaxies were moving away from us faster than galaxies closer to us, in agreement with de Sitter's and Einstein's predictions [Wirtz 1918, 1922a, 1922b, 1924, 1936]. Wirtz's first results in this area occurred more than a decade before Edwin Hubble's (American, 1889–1953) first 1929 paper that also showed evidence of the expanding universe. For example, in October 1921 Wirtz wrote [Wirtz 1922a]:

> Alle diese statistischen Erscheinungen lagern sich über den auffälligsten und Hauptvorgang, der sich als ein Auseinandertreiben des Systems den Spiralnebel relativ zu unserm Standpunkt beschreiben läßt. Dann bedeutet z.B. die Abhängigkeit von der galaktischen Breite, daß die Nebel bei den Polen sich rascher von uns entfernen als die Nebel der niedrigeren Breiten, und die Abhängigkeit von der Größenklasse zeigt an, daß die uns nächsten oder auch die massenstarken Spiralnebel eine geringere Auswärtsbewegung besitzen als die fernen oder etwa die massenschwachen Nebel. Daß der Zielpunkt aus den Radialbewegungen der Spiralnebel nichts zu tun hat mit dem Sonnenapex, ist bekannt.

> All of these statistical data result from the most remarkable and main process, which can be described as a driving apart of the system of the spiral galaxies relative to our point of view. Then for example the dependence on the galactic latitude means that the galaxies at the poles move away from us faster than the galaxies of the lower latitudes, and the dependence on the distance indicates that the spiral galaxies closest to us or perhaps the more massive galaxies have a smaller outward movement than the distant or the less massive galaxies. It is known that the target point from the radial movements of the spiral galaxies has nothing to do with the solar apex.

Several years after Wirtz's discovery and publications, Edwin Hubble aggressively promoted himself in public as the discoverer of the expanding universe, and Wirtz's accomplishments have unfortunately been nearly forgotten by history [Kragh and Smith 2003; Seitter and Duerbeck 1999; van den Bergh 2011]. Astronomer Sidney van den Bergh described the situation [van den Bergh 2011]:

> In his 1922 paper Wirtz concludes that either the nearest or the most massive galaxies have the lowest redshifts. From the more extensive observational material available in 1924 Wirtz found that the radial velocities of spiral nebulae grow quite significantly with increasing distance. He was aware of the fact that the General Theory of Relativity predicted that redshifts should increase with increasing distance. Wirtz published his results in the Astronomische Nachrichten, the leading German astronomy journal. (Hubble received an A in his high-school German course [...] and he also read German text books on corporate law [...] so he would have had no trouble reading Wirtz's papers.) [...]
>
> The myth that Hubble discovered the velocity-distance relation seems to have originated with Humason (1931) (who was at that time acting as Hubble's observing assistant).

Thus not only did Hubble's first papers on the expanding universe come more than a decade after Wirtz's first papers on that topic, but there are good reasons to believe that Hubble read the *Astronomische Nachrichten* journal containing Wirtz's papers, repeated Wirtz's astronomical observations, and tried to claim the discovery as his own while not mentioning Wirtz. If that is what happened, then Hubble was actually guilty of gross scientific misconduct. Books of scientific history should be rewritten to give proper credit to Wirtz, not Hubble.

George Gamow (Russian but educated and worked in Germany, lived 1904–1968) built on the earlier work of Einstein, de Sitter, Wirtz, and others regarding the history of the universe. Gamow considered the implications that the universe has been expanding outward ever since a "Big Bang" billions of years ago. Gamow made specific predictions about what evidence such a Big Bang would have produced (such as the production of certain amounts of nuclei and of electromagnetic "echoes" or background radiation) that were later discovered in experiments to be correct.

Following Einstein, de Sitter, and Wirtz, other theoretical physicists also took up the idea of an expanding universe: Alexander Friedman (Russian but published in German, 1888–1925) in 1924, Georges Lemaître (Belgian, 1894–1966) beginning in 1927, and Howard Robertson (American but trained in Germany, 1903–1961) and Arthur Walker (British, 1909–2001) in the 1930s.

In addition to his other predictions, in 1917 Einstein also predicted the properties and physical implications of what he called a "cosmological constant," but what is now called "dark energy," a diffuse field throughout the universe that acts to oppose the attraction of gravity [Pais 1982]. The first experimental evidence of dark energy was detected over 80 years later, in 1998, and much more evidence has been discovered since then (Fig. 4.61).

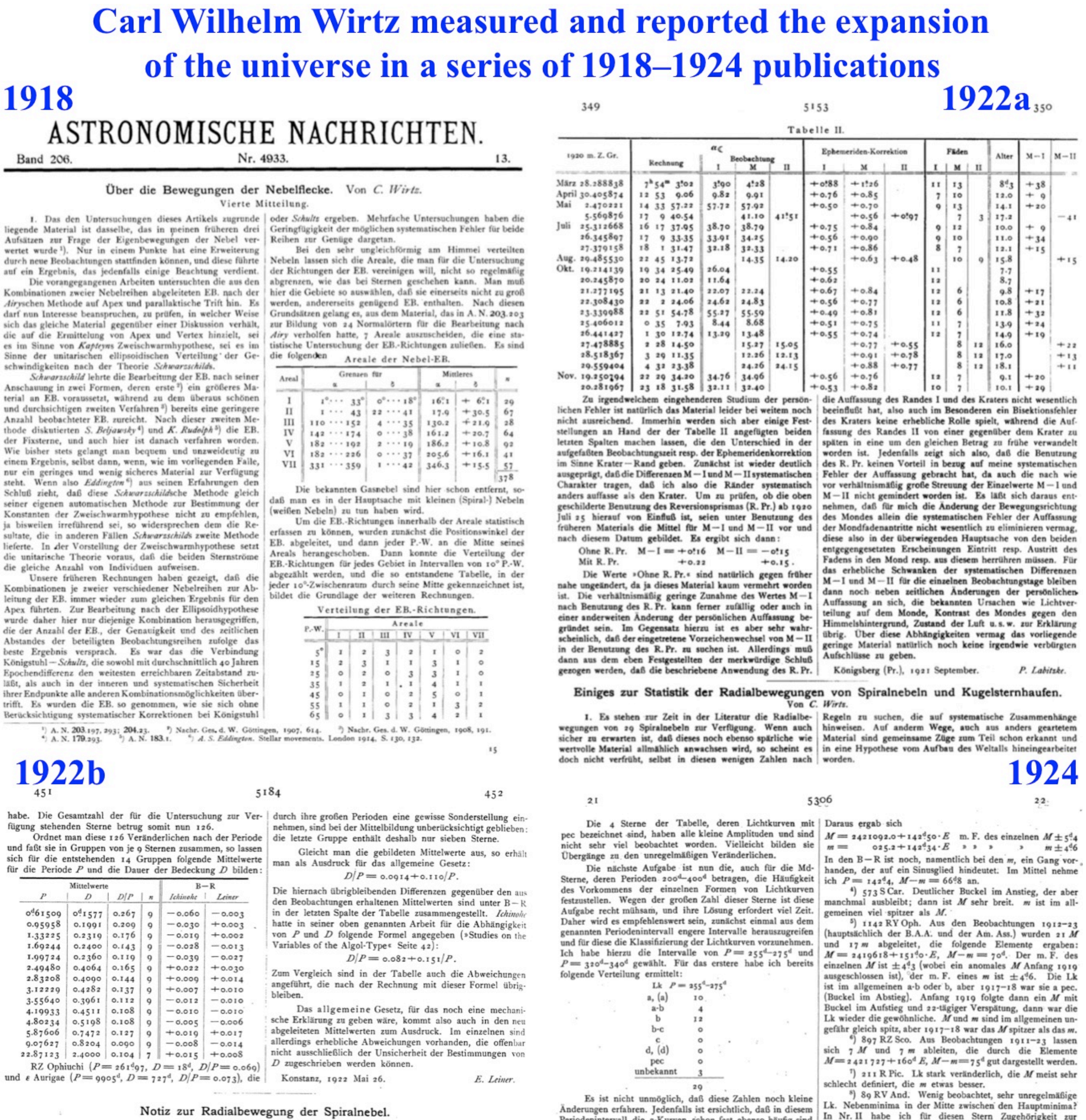
Jacobus Kapteyn (Dutch, 1851–1922), Fritz Zwicky (Swiss, 1898–1974), and Jan Oort (Dutch, 1900–1992) predicted dark matter, mysterious material that adds to the gravitational attraction of the universe but does not appear to be made out of known types of particles, decades before its existence was proven experimentally [John Johnson, Jr., 2019; Stöckli and Müller 2008]. Large amounts of evidence for the existence of dark matter were finally found in the 1970s and 1980s (Fig. 4.60).

Both dark energy and dark matter have had a decisive effect on the history and current state of our entire universe.

Hermann Bondi (Austrian, 1919–2005) and Thomas Gold (Austrian, 1920–2004) used general relativity to analyze a wide range of scenarios such as gravity waves, black holes, and the structure and history of the universe.

In the final decades of Einstein's life, Valentine Bargmann (German, 1908–1989) and Peter Bergmann (German, 1915–2002) collaborated with him on a number of possible extensions and applications of general relativity. Leopold Infeld (Austrian, 1898–1968) also collaborated with Einstein on how to calculate the motions of a large number of objects interacting with each other due to gravity.

For additional information on German-speaking contributions to astrophysics, see Section 4.6.



ASTRONOMISCHE NACHRICHTEN.

Band 206. Nr. 4933. 13.

Über die Bewegungen der Nebelflecke. Von *C. Wirtz.*

Vierte Mitteilung.

1. Das den Untersuchungen dieses Artikels zugrunde liegende Material ist dasselbe, das in meinen früheren drei Aufsätzen zur Frage der Eigenbewegungen der Nebel verwertet wurde¹). Nur in einem Punkte hat eine Erweiterung durch neue Beobachtungen stattfinden können, und diese führte auf ein Ergebnis, das jedenfalls einige Beachtung verdient.

Die vorangegangenen Arbeiten untersuchten die aus den Kombinationen zweier Nebelreihen abgeleiteten EB. nach der *Airy*schen Methode auf Apex und parallaktische Trift hin. Es darf nun Interesse beanspruchen, zu prüfen, in welcher Weise sich das gleiche Material gegenüber einer Diskussion verhält, die auf die Ermittelung von Apex und Vertex hinzielt, sei es im Sinne von *Kapteyns* Zweischwarmhypothese, sei es im Sinne der unitarischen ellipsoidischen Verteilung der Geschwindigkeiten nach der Theorie *Schwarzschilds*.

Schwarzschild lehrte die Bearbeitung der EB. nach seiner Anschauung in zwei Formen, deren erste[2]) ein größeres Material an EB. voraussetzt, während zu dem überaus schönen und durchsichtigen zweiten Verfahren[3]) bereits eine geringere Anzahl beobachteter EB. zureicht. Nach dieser zweiten Methode diskutierten *S. Beljawsky*[4]) und *K. Rudolph*[5]) die EB. der Fixsterne, und auch hier ist danach verfahren worden. Wie bisher stets gelangt man bequem und unzweideutig zu einem Ergebnis, selbst dann, wenn, wie im vorliegenden Falle, nur ein geringes und wenig sicheres Material zur Verfügung steht. Wenn also *Eddington*[6]) aus seinen Erfahrungen den Schluß zieht, daß diese *Schwarzschild*sche Methode gleich seiner eigenen automatischen Methode zur Bestimmung der Konstanten der Zweischwarmhypothese nicht zu empfehlen, ja bisweilen irreführend sei, so widersprechen dem die Resultate, die in anderen Fällen *Schwarzschilds* zweite Methode lieferte. In der Vorstellung der Zweischwarmhypothese setzt die unitarische Theorie voraus, daß die beiden Sternströme die gleiche Anzahl von Individuen aufweisen.

Unsere früheren Rechnungen haben gezeigt, daß die Kombinationen je zweier verschiedener Nebelreihen zur Ableitung der EB. immer wieder zum gleichen Ergebnis für den Apex führten. Zur Bearbeitung nach der Ellipsoidhypothese wurde daher hier nur diejenige Kombination herausgegriffen, die der Anzahl der EB., der Genauigkeit und des zeitlichen Abstandes der beteiligten Beobachtungsreihen zufolge das beste Ergebnis versprach. Es war das die Verbindung Königstuhl—*Schultz*, die sowohl mit durchschnittlich 40 Jahren Epochendifferenz den weitesten erreichbaren Zeitabstand zuläßt, als auch in der inneren und systematischen Sicherheit ihrer Endpunkte alle anderen Kombinationsmöglichkeiten übertrifft. Es wurden die EB. so genommen, wie sie sich ohne Berücksichtigung systematischer Korrektionen bei Königstuhl oder *Schultz* ergeben. Mehrfache Untersuchungen haben die Geringfügigkeit der möglichen systematischen Fehler für beide Reihen zur Genüge dargetan.

Bei den sehr ungleichförmig am Himmel verteilten Nebeln lassen sich die Areale, die man für die Untersuchung der Richtungen der EB. vereinigen will, nicht so regelmäßig abgrenzen, wie das bei Sternen geschehen kann. Man muß hier die Gebiete so auswählen, daß sie einerseits nicht zu groß werden, andererseits genügend EB. enthalten. Nach diesen Grundsätzen gelang es, aus dem Material, das in A. N. 203.203 zur Bildung von 24 Normalörtern für die Bearbeitung nach *Airy* verholfen hatte, 7 Areale auszuscheiden, die eine statistische Untersuchung der EB.-Richtungen zuließen. Es sind die folgenden

Areale der Nebel-EB.

Areal	Grenzen für α	δ	Mittleres α	δ	n
I	1°···33°	0°···18°	16°.1	+6°.1	29
II	1···43	22···41	17.9	+30.5	67
III	110···152	4···35	130.2	+21.9	28
IV	142···174	0···38	161.2	+20.7	64
V	182···192	2···19	186.2	+10.8	92
VI	182···226	0···37	205.6	+16.1	41
VII	331···359	1···42	346.3	+15.5	57
					378

Die bekannten Gasnebel sind hier schon entfernt, sodaß man es in der Hauptsache mit kleinen (Spiral-) Nebeln (weißen Nebeln) zu tun haben wird.

Um die EB.-Richtungen innerhalb der Areale statistisch erfassen zu können, wurden zunächst die Positionswinkel der EB. abgeleitet, und dann jeder P.-W. an die Mitte seines Areals herangeschoben. Dann konnte die Verteilung der EB.-Richtungen für jedes Gebiet in Intervallen von 10° P.-W. abgezählt werden, und die so entstandene Tabelle, in der jeder 10°-Zwischenraum durch seine Mitte gekennzeichnet ist, bildet die Grundlage der weiteren Rechnungen.

Verteilung der EB.-Richtungen.

P.-W.	Areale I	II	III	IV	V	VI	VII
5°	1	2	3	2	1	0	2
15	2	3	1	1	3	1	0
25	0	2	0	3	3	1	0
35	1	2	1	1	4	1	1
45	0	1	0	2	5	0	1
55	1	1	0	2	1	3	2
65	0	1	3	3	4	2	1

1) A. N. 203.197, 293; 204.23. 2) Nachr. Ges. d. W. Göttingen, 1907, 614. 3) Nachr. Ges. d. W. Göttingen, 1908, 191.
4) A. N. 179.293. 5) A. N. 183.1. 6) *A. S. Eddington*. Stellar movements. London 1914, S. 130, 132.

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Tabelle II.

1920 m. Z. Gr.	α☾ Rechnung	Beobachtung I	M	II	Ephemeriden-Korrektion I	M	II	Fäden I	M	II	Alter	M−I	M−II
März 28.288838	$7^h54^m3^s.02$	$3^s.90$	$4^s.28$		$+0^s.88$	$+1^s.26$		11	13		$8^d.3$	+38	
April 30.405874	12 53 9.06	9.82	9.91		+0.76	+0.85		7	10		12.0	+9	
Mai 2.470221	14 33 57.22	57.72	57.92		+0.50	+0.70		9	13		14.1	+20	
5.569876	17 9 40.54		41.10	$41^s.51$		+0.56	$+0^s.97$		7	3	17.2		−41
Juli 25.312668	16 17 37.95	38.70	38.79		+0.75	+0.84		9	12		10.0	+9	
26.345897	17 9 33.35	33.91	34.25		+0.56	+0.90		9	10		11.0	+34	
27.379158	18 1 31.47	32.18	32.33		+0.71	+0.86		8	7		12.1	+15	
Aug. 29.485530	22 45 13.72		14.35	14.20		+0.63	+0.48		10	9	15.8		+15
Okt. 19.214139	19 34 25.49	26.04			+0.55			11			7.7		
20.245870	20 24 11.02	11.64			+0.62			12			8.7		
21.277195	21 13 21.40	22.07	22.24		+0.67	+0.84		12	6		9.8	+17	
22.308430	22 2 24.06	24.62	24.83		+0.56	+0.77		12	6		10.8	+21	
23.339988	22 51 54.78	55.27	55.59		+0.49	+0.81		12	6		11.8	+32	
25.406012	0 35 7.93	8.44	8.68		+0.51	+0.75		11	7		13.9	+24	
26.441427	1 30 12.74	13.29	13.48		+0.55	+0.74		12	7		14.9	+19	
27.478885	2 28 14.50		15.27	15.05		+0.77	+0.55		8	12	16.0		+22
28.518367	3 29 11.35		12.26	12.13		+0.91	+0.78		8	12	17.0		+13
29.559404	4 32 23.38		24.26	24.15		+0.88	+0.77		8	12	18.1		+11
Nov. 19.250794	22 29 34.20	34.76	34.96		+0.56	+0.76		12	7		9.1	+20	
20.281967	23 18 31.58	32.11	32.40		+0.53	+0.82		10	7		10.1	+29	

Zu irgendwelchem eingehenderen Studium der persönlichen Fehler ist natürlich das Material leider bei weitem noch nicht ausreichend. Immerhin werden sich aber einige Feststellungen an Hand der der Tabelle II angefügten beiden letzten Spalten machen lassen, die den Unterschied in der aufgefaßten Beobachtungszeit resp. der Ephemeridenkorrektion im Sinne Krater—Rand geben. Zunächst ist wieder deutlich ausgeprägt, daß die Differenzen M—I und M—II systematischen Charakter tragen, daß ich also die Ränder systematisch anders auffasse als den Krater. Um zu prüfen, ob die oben geschilderte Benutzung des Reversionsprismas (R. Pr.) ab 1920 Juli 25 hierauf von Einfluß ist, seien unter Benutzung des früheren Materials die Mittel für M—I und M—II vor und nach diesem Datum gebildet. Es ergibt sich dann:

Ohne R. Pr. $M-I = +0^s.16$ $M-II = -0^s.15$
Mit R. Pr. $+0.22$ $+0.15$.

Die Werte »Ohne R. Pr.« sind natürlich gegen früher nahe ungeändert, da ja dieses Material kaum vermehrt worden ist. Die verhältnismäßig geringe Zunahme des Wertes M—I nach Benutzung des R. Pr. kann ferner zufällig oder auch in einer anderweiten Änderung der persönlichen Auffassung begründet sein. Im Gegensatz hierzu ist es aber sehr wahrscheinlich, daß der eingetretene Vorzeichenwechsel von M—II in der Benutzung des R. Pr. zu suchen ist. Allerdings muß dann aus dem eben Festgestellten der merkwürdige Schluß gezogen werden, daß die beschriebene Anwendung des R. Pr. die Auffassung des Randes I und des Kraters nicht wesentlich beeinflußt hat, also auch im Besonderen ein Bisektionsfehler des Kraters keine erhebliche Rolle spielt, während die Auffassung des Randes II von einer gegenüber dem Krater zu späten in eine um den gleichen Betrag zu frühe verwandelt worden ist. Jedenfalls zeigt sich also, daß die Benutzung des R. Pr. keinen Vorteil in bezug auf meine systematischen Fehler der Auffassung gebracht hat, da auch die nach wie vor verhältnismäßig große Streuung der Einzelwerte M—I und M—II nicht gemindert worden ist. Es läßt sich daraus entnehmen, daß für mich die Änderung der Bewegungsrichtung des Mondes allein die systematischen Fehler der Auffassung der Mondfadenantritte nicht wesentlich zu eliminieren vermag, diese also in der überwiegenden Hauptsache von den beiden entgegengesetzten Erscheinungen Eintritt resp. Austritt des Fadens in den Mond resp. aus diesem herrühren müssen. Für das erhebliche Schwanken der systematischen Differenzen M—I und M—II für die einzelnen Beobachtungstage bleiben dann noch neben zeitlichen Änderungen der persönlichen Auffassung an sich, die bekannten Ursachen wie Lichtverteilung auf dem Monde, Kontrast des Mondes gegen den Himmelshintergrund, Zustand der Luft u. s. w. zur Erklärung übrig. Über diese Abhängigkeiten vermag das vorliegende geringe Material natürlich noch keine irgendwie verbürgten Aufschlüsse zu geben.

Königsberg (Pr.), 1921 September. *P. Labitzke.*

Einiges zur Statistik der Radialbewegungen von Spiralnebeln und Kugelsternhaufen.

Von *C. Wirtz.*

1. Es stehen zur Zeit in der Literatur die Radialbewegungen von 29 Spiralnebeln zur Verfügung. Wenn auch sicher zu erwarten ist, daß dieses noch ebenso spärliche wie wertvolle Material allmählich anwachsen wird, so scheint es doch nicht verfrüht, selbst in diesen wenigen Zahlen nach Regeln zu suchen, die auf systematische Zusammenhänge hinweisen. Auf anderm Wege, auch aus anders geartetem Material sind gemeinsame Züge zum Teil schon erkannt und in eine Hypothese vom Aufbau des Weltalls hineingearbeitet worden.

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habe. Die Gesamtzahl der für die Untersuchung zur Verfügung stehenden Sterne betrug somit nun 126.

Ordnet man diese 126 Veränderlichen nach der Periode und faßt sie in Gruppen von je 9 Sternen zusammen, so lassen sich für die entstehenden 14 Gruppen folgende Mittelwerte für die Periode P und die Dauer der Bedeckung D bilden:

Mittelwerte P	D	D/P	n	B—R *Ichinohe*	*Leiner*
$0^d.61509$	$0^d.1577$	0.267	9	−0.060	−0.003
0.95958	0.1991	0.209	9	−0.030	+0.003
1.33225	0.2319	0.176	9	−0.019	+0.002
1.69244	0.2400	0.143	9	−0.028	−0.013
1.99724	0.2360	0.119	9	−0.039	−0.027
2.49480	0.4064	0.165	9	+0.022	+0.030
2.83208	0.4090	0.144	9	+0.009	+0.014
3.12229	0.4282	0.137	9	+0.007	+0.010
3.55640	0.3961	0.112	9	−0.012	−0.010
4.19933	0.4511	0.108	9	−0.010	−0.010
4.80234	0.5198	0.108	9	−0.005	−0.006
5.87606	0.7472	0.127	9	+0.019	+0.017
9.07627	0.8204	0.090	9	−0.008	−0.014
22.87123	2.4000	0.104	7	+0.015	+0.008

RZ Ophiuchi ($P = 261^d.97$, $D = 18^d$, $D/P = 0.069$) und ε Aurigae ($P = 9905^d$, $D = 727^d$, $D/P = 0.073$), die durch ihre großen Perioden eine gewisse Sonderstellung einnehmen, sind bei der Mittelbildung unberücksichtigt geblieben: die letzte Gruppe enthält deshalb nur sieben Sterne.

Gleicht man die gebildeten Mittelwerte aus, so erhält man als Ausdruck für das allgemeine Gesetz:

$$D/P = 0.0914 + 0.110/P.$$

Die hiernach übrigbleibenden Differenzen gegenüber den aus den Beobachtungen erhaltenen Mittelwerten sind unter B—R in der letzten Spalte der Tabelle zusammengestellt. *Ichinohe* hatte in seiner oben genannten Arbeit für die Abhängigkeit von P und D folgende Formel angegeben (»Studies on the Variables of the Algol-Type« Seite 42):

$$D/P = 0.082 + 0.151/P.$$

Zum Vergleich sind in der Tabelle auch die Abweichungen angeführt, die nach der Rechnung mit dieser Formel übrigbleiben.

Das allgemeine Gesetz, für das noch eine mechanische Erklärung zu geben wäre, kommt also auch in den neu abgeleiteten Mittelwerten zum Ausdruck. Im einzelnen sind allerdings erhebliche Abweichungen vorhanden, die offenbar nicht ausschließlich der Unsicherheit der Bestimmungen von D zugeschrieben werden können.

Konstanz, 1922 Mai 26. *E. Leiner.*

Notiz zur Radialbewegung der Spiralnebel.

Es ist bemerkt worden, daß die Radialgeschwindigkeit der Spiralnebel um so größer wird, je näher die Spiralebenen zur Sehrichtung liegen, daß sie sich also mit der Kante voran bewegen (*Newcomb-Engelmann*, Pop. Astron., 6. Aufl., 1921, S. 713). Das in AN 5153, S. 351 verwendete Material zeigt, auf diese interessante Erscheinung hin nachgesehen, folgendes Verhalten. Man ordnet sowohl die absoluten Radialgeschwindigkeiten als auch die absoluten nach Anbringung des systematischen Anteils X, Y, Z, K übrigbleibenden Reste (B—R), d. h. die speziellen Radialbewegungen der 29 Nebel, nach dem Verhältnis A der großen zur kleinen Achse:

A	v absol.	B—R absol.	n
1.3	694 km	416 km	13
2.7	438	181	4
4.0	629	354	6
5.0	533	67	3
9.3	893	234	3
			29

In den absoluten v erscheint eine sehr lose Verknüpfung in dem Sinne, daß die v wachsen mit wachsendem Achsenverhältnis, d. i. mit abnehmender Neigung gegen die Gesichtslinie. Den Rang der Bindung gibt der Korrelationskoeffizient aus den 29 einzelnen Wertepaaren wieder durch $r = +0.14$, m. F. $= \pm 0.18$, wohl noch undeutlicher, als der Anblick der gruppenweisen Mittelbildung erwarten läßt. Ganz verschwunden ist dieser Zusammenhang, nach Berücksichtigung der systematischen Bewegungskomponenten, in der Reihe (B—R).

Dagegen scheint sich ein Einfluß des Windungssinnes der Spiralen auszuprägen. Der zugänglichen Literatur und veröffentlichten Abbildungen konnte für 15 Spiralen der Windungssinn (ob rechts oder links) entnommen werden; für 11 läßt sich darüber nicht entscheiden, weil die Ebene der Spiralen nahe in die Gesichtslinie fällt oder weil die Windungen zu verwaschen sind, und für drei weitere Nebel fanden sich keine Angaben.

Bildet man die Mittelwerte der speziellen Radialbewegungen (B—R), so erhält man

für 8 linksgewundene Spiralen + 3 km
für 7 rechtsgewundene Spiralen −253 km

und dieser Unterschied bleibt in Sinn und Ausmaß bestehen, mag man die absoluten beobachteten v oder die beobachteten v mit Vorzeichen nehmen. Das sieht so aus, als ob in Linkswindung gesehene Spiralen sich rascher von unserem Standpunkte im Weltall entfernen als rechtsgewundene. Nicht weniger wahrscheinlich dürfte es sein, daß die bei den Spiralnebeln beobachtete Rotverschiebung nicht nur auf einen Dopplereffekt zurückgeführt zu werden braucht.

Kiel, 1922 April. *C. Wirtz.*

Inhalt zu Nr. 5184. *C. Wirtz.* Helligkeit und Rotation des Uranus. 437. — *H. Michnik.* Konstruktion einer siderischen Sonnenuhr. 441. — *E. Leiner.* Über das *Chandler*sche Gesetz zwischen Periode und Dauer der Verfinsterung bei Algolsternen. 449. — *C. Wirtz.* Notiz zur Radialbewegung der Spiralnebel. 451.

Geschlossen 1922 Sept 26. Herausgeber: H. Kobold. Druck von C. Schaidt. Expedition: Kiel, Moltkestr. 80. Postscheck-Konto Nr. 6238 Hamburg 11.

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Die 4 Sterne der Tabelle, deren Lichtkurven mit pec bezeichnet sind, haben alle kleine Amplituden und sind nicht sehr viel beobachtet worden. Vielleicht bilden sie Übergänge zu den unregelmäßigen Veränderlichen.

Die nächste Aufgabe ist nun die, auch für die Md-Sterne, deren Perioden 200^d–400^d betragen, die Häufigkeit des Vorkommens der einzelnen Formen von Lichtkurven festzustellen. Wegen der großen Zahl dieser Sterne ist diese Aufgabe recht mühsam, und ihre Lösung erfordert viel Zeit. Daher wird es empfehlenswert sein, zunächst einmal aus dem genannten Periodenintervall engere Intervalle herauszugreifen und für diese die Klassifizierung der Lichtkurven vorzunehmen. Ich habe hierzu die Intervalle von $P = 255^d$–275^d und $P = 320^d$–340^d gewählt. Für das erstere habe ich bereits folgende Verteilung ermittelt:

Lk	$P = 255^d$–275^d
a, (a)	10
a-b	4
b	12
b-c	0
c	0
d, (d)	0
pec	0
unbekannt	3
	29

Es ist nicht unmöglich, daß diese Zahlen noch kleine Änderungen erfahren. Jedenfalls ist ersichtlich, daß in diesem Periodenintervall die a-Kurven schon fast ebenso häufig sind wie die b-Kurven, während sie bei den Md-Sternen mit $P \leqq 200^d$ überhaupt nicht vorkommen.

Anhang. Anmerkungen zu der Tabelle.

1) 1408 Z Aql. Aus den Beobachtungen 1913–23 des Harvard-Obs. und der Am. Ass. ließen sich 11 M und 8 m ablesen, woraus ich neue Elemente abgeleitet habe, um das bisher unsichere $M-m$ genauer zu bestimmen. Es ergab sich $M = 2421871 + 129^d.5\,E$, $M-m = 61^d.3$; m. F. eines $M \pm 4^d.1$; m. F. eines $m \pm 8^d.0$.

2) 1667 Z Aqr. Nach den photographischen Harvard-Beobachtungen scheinen An- und Abstieg der Lk sehr steil, die M und m dagegen meist sehr flach. Manchmal entstehen Algol-ähnliche Lichtkurven. Die Lk ist jedenfalls sehr veränderlich.

3) 204 X Cam. Aus verschiedenen Beobachtungsreihen konnten für 1911–23 20 M und 20 m ermittelt werden. Daraus ergab sich

$M = 2421092.0 + 142^d.50 \cdot E$ m. F. des einzelnen $M \pm 5^d.4$
$m = 1025.2 + 142^d.34 \cdot E$ » » » » $m \pm 4^d.6$

In den B—R ist noch, namentlich bei den m, ein Gang vorhanden, der auf ein Sinusglied hindeutet. Im Mittel nehme ich $P = 142^d.4$, $M-m = 66^d.8$ an.

4) 573 S Car. Deutlicher Buckel im Anstieg, der aber manchmal ausbleibt; dann ist M sehr breit. m ist im allgemeinen viel spitzer als M.

5) 1142 RY Oph. Aus den Beobachtungen 1912–23 (hauptsächlich der B.A.A. und der Am. Ass.) wurden 21 M und 17 m abgeleitet, die folgende Elemente ergaben: $M = 2419618 + 151^d.0 \cdot E$, $M-m = 70^d$. Der m. F. des einzelnen M ist $\pm 4^d.3$ (wobei ein anomales M Anfang 1919 ausgeschlossen ist), der m. F. eines m ist $\pm 4^d.6$. Die Lk ist im allgemeinen a-b oder b, aber 1917–18 war sie a pec. (Buckel im Abstieg). Anfang 1919 folgte dann ein M mit Buckel im Aufstieg und 22-tägiger Verspätung, dann war die Lk wieder die gewöhnliche. M und m sind im allgemeinen ungefähr gleich spitz, aber 1917–18 war das M spitzer als das m.

6) 897 RZ Sco. Aus Beobachtungen 1911–23 lassen sich 7 M und 7 m ableiten, die durch die Elemente $M = 2421727 + 160^d\,E$, $M-m = 75^d$ gut dargestellt werden.

7) 211 R Pic. Lk stark veränderlich, die M meist sehr schlecht definiert, die m etwas besser.

8) 89 RV And. Wenig beobachtet, sehr unregelmäßige Lk. Nebenminima in der Mitte zwischen den Hauptminima? In Nr. II habe ich für diesen Stern Zugehörigkeit zur RV Tauri-Klasse vermutet.

9) 1345 RT Cyg. Aus 23 M und 21 m, die 1912–23 beobachtet sind, ergab sich $M = 2419454 + 191^d.6 \cdot E$, $M-m = 91^d$. M. F. eines $M \pm 8^d.7$, m. F. eines $m \pm 5^d.6$. Bei dem Anstieg Ende 1912 hatte die Kurve einen Buckel, sonst war sie stets glatt. 1912–23 war die Lk entschieden nicht so unsymmetrisch, wie in der G. u. L. angegeben.

10) 1141 W Lyr. Die Lk hat im Aufstieg meist einen deutlichen Buckel. Die im Text der G. u. L. behauptete Ähnlichkeit mit U Geminorum besteht nicht; die dort erwähnten langsamen Helligkeitsanstiege sind von 1911–23 nur ein- oder höchstens zweimal vorgekommen.

11) 247 T Pic. Aus Beobachtungen 1918–23 des Observatoriums zu Johannesburg und der Am. Ass. habe ich 6 M und 3 m abgeleitet, aus denen sich ergab $M = 2421834 + 200^d \cdot E$, $M-m = 101^d$. Diese Elemente stellen die Beobachtungen gut dar.

Potsdam, Astrophysikalisches Observatorium, 1924 März. *H. Ludendorff.*

De Sitters Kosmologie und die Radialbewegungen der Spiralnebel. Von *C. Wirtz.*

Die Welt *de Sitters* ist eine sphärische Raum-Zeit-Welt, ein vierdimensionales Kontinuum aus Raum und imaginärer Zeit, das die Oberfläche einer Kugel in fünf Dimensionen bildet. *De Sitters* Weltraum ist masseleer, alle Masse fortgefegt an eine der Beobachtung nicht zugängliche Stelle des Raumes, in einen Massenhorizont oder in einen Ring peripherischer Materie, notwendig, um die Leere innerhalb aufrecht zu erhalten. *Einsteins* ein Höchstmaß an Materie enthaltende und *de Sitters* Welt bilden die beiden Grenzfälle, zwischen die die wirkliche Welt sich einordnet. *W. de Sitter*, MN 78.3, 1918; *A. S. Eddington*, Math. theory of relativity. Cambridge 1923. Chapt. III, V; vgl. ferner die anschauliche graphische Darstellung der *de Sitter*schen Welt bei *H. Weyl*, Naturwiss. 12 (1924), p. 201.

In *de Sitters* Welt, System B, tritt nun ein Phänomen ein, das der astronomischen Beobachtung zugänglich ist. Mit wachsendem Abstand vom Koordinatenursprung verlaufen die natürlichen Erscheinungen immer langsamer, immer lang-

Figure 5.33: Carl Wilhelm Wirtz measured and reported the expansion of the universe in a series of 1918–1924 publications [Wirtz 1918, 1922a, 1922b, 1924].

5.4 Non-Relativistic Quantum Physics

Like an Impressionist painting, matter looks clearly delineated and well behaved when seen macroscopically from a distance, but blurry and confusing when viewed microscopically at the level of individual atoms. (Non-relativistic) quantum physics describes the strange behavior of very small things. (Section 5.6 discusses relativistic quantum physics, the even stranger behavior when relativity and quantum physics are combined.)

As shown in Fig. 5.34, there are two fundamental ideas in quantum physics:

- What we normally think of as waves can act like particles; for example, electromagnetic waves can act like discrete particles called photons.

- Conversely, at the microscopic scale, particles of matter can act like blurry waves instead of discrete chunks of solid stuff.

Weird quantum effects of particles acting like waves (and vice versa) generally only happen with things the size of atoms or smaller, because the interrelationship between wave and particle behavior involves a very small physical constant (Planck's constant $h \approx 6.626 \times 10^{-34}$ Joule-seconds). Nevertheless, those quantum phenomena can have profound effects on the behavior of subatomic particles, atoms, and molecules, and therefore on any reactions (chemical or nuclear) in which they are involved, or devices (transistors, lasers, etc.) of which they are a part.

Like relativity, quantum physics was almost entirely a product of the German-speaking world (Figs. 5.35–5.39).[5] Perhaps the most significant contributions to quantum physics from outside the German-speaking world were those of the French physicist Louis de Broglie (1892–1987), who proposed the mathematical relationship between particle momentum and quantum wavelength, and the Danish physicist Niels Bohr (1885–1962), who proposed a simple quantum model of the atom and was closely connected with the German-speaking scientific world throughout his career. In fact, historians are generally in such agreement that quantum physics was primarily a product of the German-speaking world that they have spent decades debating what factors may have promoted that development [Carson et al. 2011].

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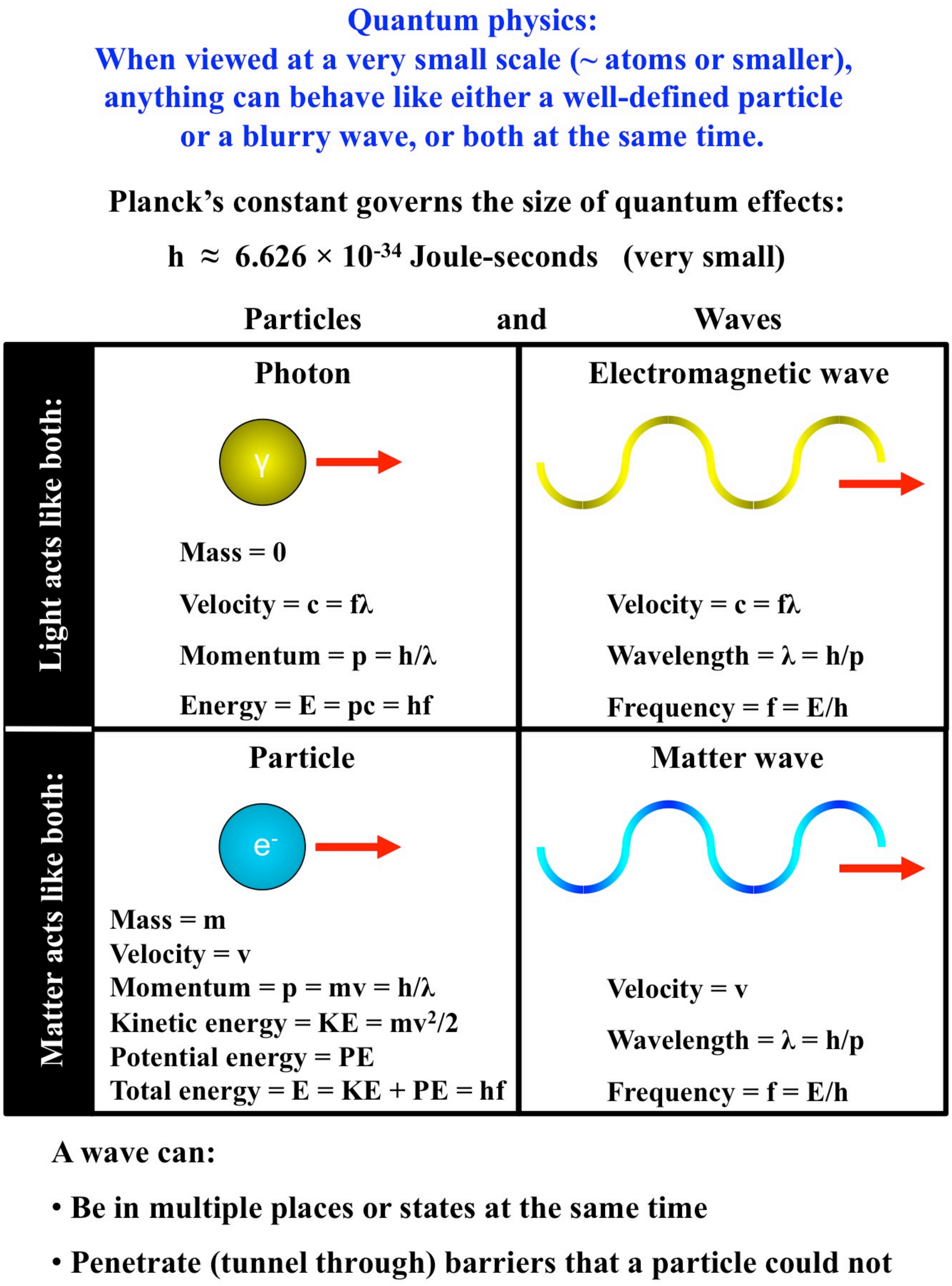
[5] For good overviews of this area, see especially: Laurie Brown et al. 1995; Gamow 1966; Jones 2008; Jungnickel and McCormmach 1986, 2017; Kragh 2002; L'Annunziata 2016; von Meÿenn 1997; Weber 1988.



Quantum physics:
When viewed at a very small scale (~ atoms or smaller), anything can behave like either a well-defined particle or a blurry wave, or both at the same time.

Planck's constant governs the size of quantum effects:

$h \approx 6.626 \times 10^{-34}$ Joule-seconds (very small)

	Particles and	**Waves**
Light acts like both:	**Photon** Mass = 0 Velocity = c = fλ Momentum = p = h/λ Energy = E = pc = hf	**Electromagnetic wave** Velocity = c = fλ Wavelength = λ = h/p Frequency = f = E/h
Matter acts like both:	**Particle** Mass = m Velocity = v Momentum = p = mv = h/λ Kinetic energy = KE = $mv^2/2$ Potential energy = PE Total energy = E = KE + PE = hf	**Matter wave** Velocity = v Wavelength = λ = h/p Frequency = f = E/h

A wave can:

- **Be in multiple places or states at the same time**
- **Penetrate (tunnel through) barriers that a particle could not**

Figure 5.34: The central concept of quantum physics is that when the world is viewed at a very small scale (typically at the size of atoms or smaller), anything can behave like either a well-defined particle or a blurry wave, or both at the same time.

Quantum physics

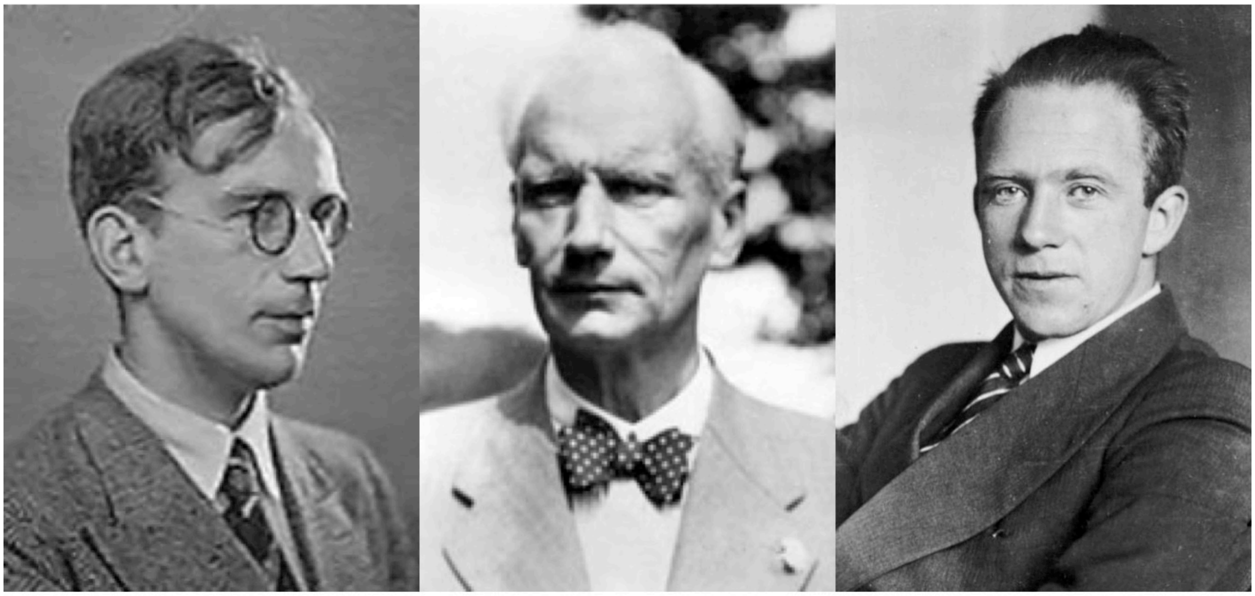
Johann Balmer (1825–1898) **Niels Bohr (1885–1962)** **Max Born (1882–1970)**

Paul Ehrenfest (1880–1933) **Albert Einstein (1879–1955)** **James Franck (1882–1964)**

Figure 5.35: Some creators who made significant contributions to quantum physics included Johann Balmer, Niels Bohr (Danish but closely tied to the German scientific community), Max Born, Paul Ehrenfest, Albert Einstein, and James Franck.

Quantum physics

George Gamow (1904–1968) **Walther Gerlach (1889–1979)** **Werner Heisenberg (1901–1976)**

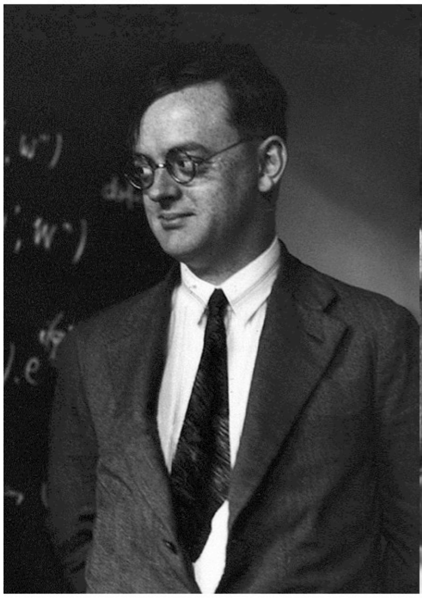


Grete Hermann (1901–1984) **Gustav Hertz (1887–1975)** **Friedrich Hund (1896–1997)**

Figure 5.36: Other creators who made significant contributions to quantum physics included George Gamow, Walther Gerlach, Werner Heisenberg, Grete Hermann, Gustav Hertz, and Friedrich Hund.

Quantum physics

Pascual Jordan
(1902–1980)



Hendrik Kramers
(1894–1952)

Ralph Kronig
(1904–1995)

Werner Kuhn
(1899–1963)

Alfred Landé
(1888–1976)

Hendrik Lorentz
(1853–1928)

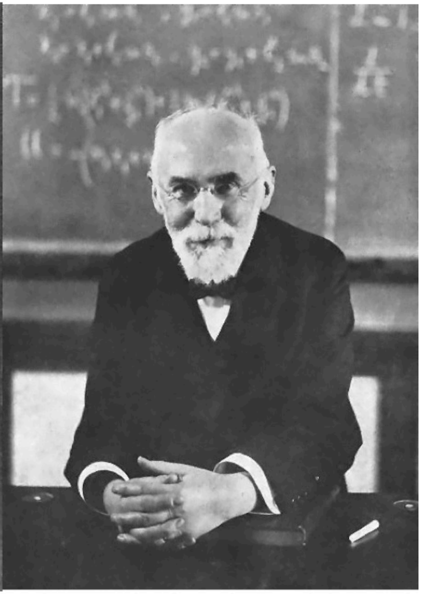
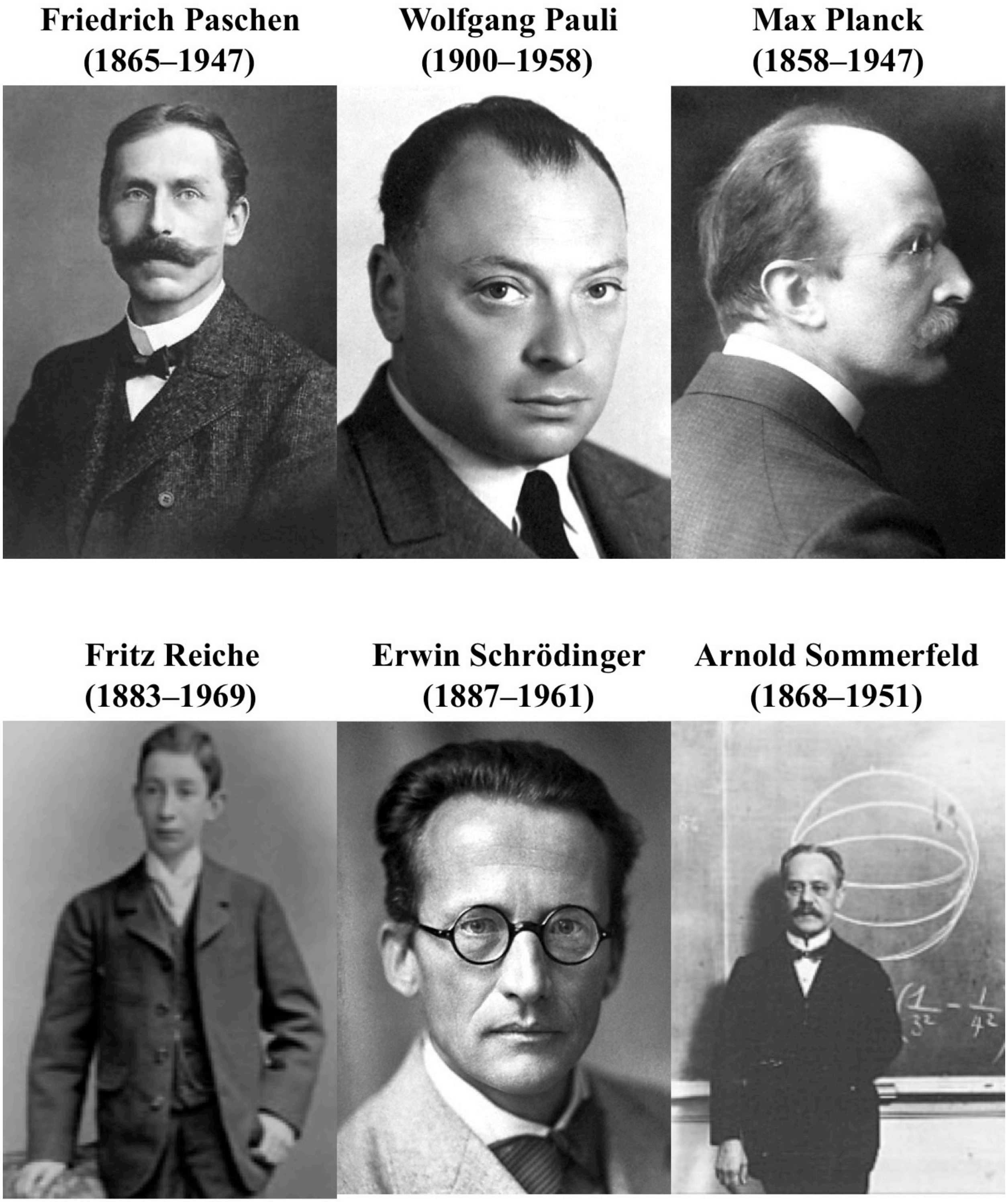


Figure 5.37: Other creators who made significant contributions to quantum physics included Pascual Jordan, Hendrik Kramers, Ralph Kronig, Werner Kuhn, Alfred Landé, and Hendrik Lorentz.

Quantum physics



Friedrich Paschen (1865–1947)

Wolfgang Pauli (1900–1958)

Max Planck (1858–1947)

Fritz Reiche (1883–1969)

Erwin Schrödinger (1887–1961)

Arnold Sommerfeld (1868–1951)

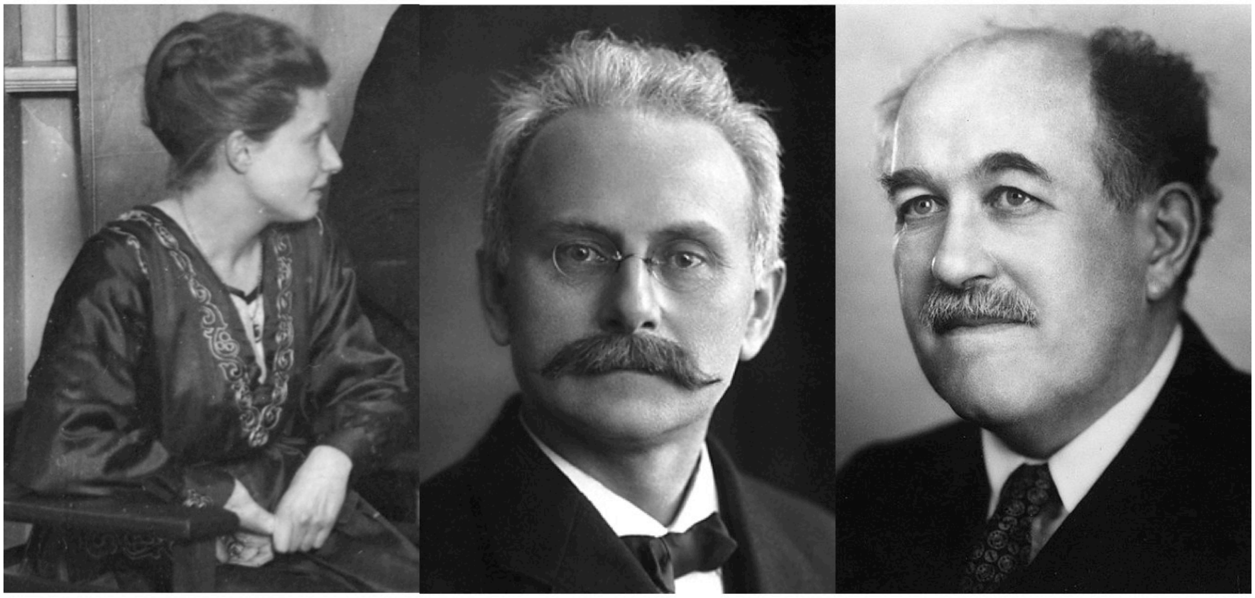
Figure 5.38: Other creators who made significant contributions to quantum physics included Friedrich Paschen, Wolfgang Pauli, Max Planck, Fritz Reiche, Erwin Schrödinger, and Arnold Sommerfeld.

Quantum physics

Hertha Sponer (1895–1968)

Johannes Stark (1874–1957)

Otto Stern (1888–1969)



Willy Thomas (?–?)

Gregor Wentzel (1898–1978)

Pieter Zeeman (1865–1943)

Figure 5.39: Other creators who made significant contributions to quantum physics included Hertha Sponer, Johannes Stark, Otto Stern, Willy Thomas, Gregor Wentzel, and Pieter Zeeman.

5.4.1 Early Steps Toward Quantum Theory

Arguably the first significant work on quantum theory was by Johann Balmer (Swiss, 1825–1898). In 1885, he developed a mathematical formula that correctly described the spacing between different wavelengths of light that could be emitted or absorbed by hydrogen atoms. Many years later, other scientists would show that the spacings Balmer described occurred because quantum physics only allowed certain electron orbits and energy levels in atoms, and therefore certain energies or wavelengths of light that could be emitted or absorbed by electrons transitioning between those atomic energy levels. In 1908, Friedrich Paschen (German, 1865–1947) also demonstrated that the spectral lines continue beyond visible wavelengths well into the infrared spectrum [Jungnickel and McCormmach 1986].

In 1900, Max Planck (German, 1858–1947) made a seminal discovery in quantum physics [Brandon Brown 2015; Planck 1950]. He showed that the spectrum of light and other electromagnetic radiation emitted by a hot object (a "black body" that glows because of its heat) could be explained if the electromagnetic radiation was acting not just as waves, but also as particles (later dubbed "photons"). Planck found that the energy E of the particles was proportional to the frequency f of the waves, where the two quantities were related by a new constant $h \approx 6.626 \times 10^{-34}$ Joule-seconds that came to be known as Planck's constant ($E = hf$). Later scientists would realize that Planck's constant governed a wide variety of quantum effects. Planck won the Nobel Prize in Physics in 1918 for his pioneering work. Dr. Å. G. Ekstrand, President of the Royal Swedish Academy of Sciences, announced the award [https://www.nobelprize.org/prizes/physics/1918/ceremony-speech/]:

> Professor Planck. The Swedish Academy of Sciences has awarded you the Nobel Prize for 1918 in recognition of your epoch-making investigations into the quantum theory. This theory, which was originally connected with black-body radiation, has now demonstrated its validity for other fields and relationships of Nature, and the constant number, named after you, is a proportionality factor which describes a common, but until now unknown, property of matter.

Albert Einstein (German, 1879–1955) expanded on Planck's work regarding how light behaves like quantum particles, or photons [Isaacson 2007; Pais 1982]. Specifically, Einstein showed that the particle nature of light could explain the photoelectric effect, in which there is a clear difference between particles of light that do or do not have enough energy to knock electrons loose in a substance. For helping to further establish and expand the growing field of quantum physics (but not for his contributions to statistical physics or his development of special and general relativity!), Einstein received the Nobel Prize in Physics in 1921. Professor S. Arrhenius, Chairman of the Nobel Committee for Physics, explained [https://www.nobelprize.org/prizes/physics/1921/ceremony-speech/]:

> There is probably no physicist living today whose name has become so widely known as that of Albert Einstein. Most discussion centres on his theory of relativity. This pertains essentially to epistemology and has therefore been the subject of lively debate in philosophical circles. It will be no secret that the famous philosopher Bergson in Paris has challenged this theory, while other philosophers have acclaimed it wholeheartedly. The theory in question also has astrophysical implications which are being rigorously examined at the present time.
>
> Throughout the first decade of this century the so-called Brownian movement stimulated the keenest interest. In 1905 Einstein founded a kinetic theory to account for this

> movement by means of which he derived the chief properties of suspensions, i.e. liquids with solid particles suspended in them. This theory, based on classical mechanics, helps to explain the behaviour of what are known as colloidal solutions, a behaviour which has been studied by Svedberg, Perrin, Zsigmondy and countless other scientists within the context of what has grown into a large branch of science, colloid chemistry.
>
> A third group of studies, for which in particular Einstein has received the Nobel Prize, falls within the domain of the quantum theory founded by Planck in 1900. This theory asserts that radiant energy consists of individual particles, termed "quanta", approximately in the same way as matter is made up of particles, i.e. atoms. This remarkable theory, for which Planck received the Nobel Prize for Physics in 1918, suffered from a variety of drawbacks and about the middle of the first decade of this century it reached a kind of impasse. Then Einstein came forward with his work on specific heat and the photoelectric effect. This latter had been discovered by the famous physicist Hertz in 1887. He found that an electrical spark passing between two spheres does so more readily if its path is illuminated with the light from another electrical discharge. A more exhaustive study of this interesting phenomenon was carried out by Hallwachs who showed that under certain conditions a negatively charged body, e.g. a metal plate, illuminated with light of a particular colour—ultraviolet has the strongest effect—loses its negative charge and ultimately assumes a positive charge. In 1899 Lenard demonstrated the cause to be the emission of electrons at a certain velocity from the negatively charged body. The most extraordinary aspect of this effect was that the electron emission velocity is independent of the intensity of the illuminating light, which is proportional only to the number of electrons, whereas the velocity increases with the frequency of the light. Lenard stressed that this phenomenon was not in good agreement with the then prevailing concepts. [...]
>
> Einstein's law of the photo-electrical effect has been extremely rigorously tested by the American Millikan and his pupils and passed the test brilliantly. Owing to these studies by Einstein the quantum theory has been perfected to a high degree and an extensive literature grew up in this field whereby the extraordinary value of this theory was proved. Einstein's law has become the basis of quantitative photo-chemistry in the same way as Faraday's law is the basis of electro-chemistry.

While some physicists were exploring various aspects of the wave/particle duality of light, other physicists were investigating aspects of what ultimately proved to be the wave/particle duality of electrons, as revealed by how the electrons orbiting in atoms emitted and absorbed light. Building on the earlier work by Johann Balmer about the behavior of normal atoms, they studied how atoms responded to strong magnetic or electric fields.

Pieter Zeeman (Dutch, 1865–1943) demonstrated and Hendrik Lorentz (Dutch, 1853–1928) explained how applied magnetic fields shift the energy levels of electrons orbiting in atoms, and therefore the wavelengths of light that they absorb and emit [Jungnickel and McCormmach 1986]. For this work, they both won the Nobel Prize in Physics in 1902. Professor Hj. Théel, President of the Royal Swedish Academy of Sciences, remarked upon the importance of their discovery [https://www.nobelprize.org/prizes/physics/1902/ceremony-speech/]:

> The greatest credit for the further development of the electromagnetic theory of light

> is due to Professor Lorentz, whose theoretical work on this subject has borne the richest fruit. While Maxwell's theory is free from any assumptions of an atomistic nature, Lorentz starts from the hypothesis that in matter extremely small particles, called electrons, are the carriers of certain specific charges. These electrons move freely in so-called conductors and thus produce an electrical current, whereas in non-conductors their movement is apparent through electrical resistance. Starting from this simple hypothesis, Lorentz has been able not only to explain everything that the older theory explained but, in addition, to overcome some of its greatest shortcomings.
>
> [...] Guided by the electromagnetic theory of light, Zeeman took up Faraday's last experiment, and, after many unsuccessful attempts, finally succeeded in demonstrating that the radiation from a source of light changes its nature under the influence of magnetic forces in such a way that the different spectral lines of which it consisted were resolved into several components. The consequences of this discovery give a magnificent example of the importance of theory to experimental research. Not only was Professor Lorentz, with the aid of his electron theory, able to explain satisfactorily the phenomena discovered by Professor Zeeman, but certain details which had hitherto escaped Professor Zeeman's attention could also be foreseen, and were afterwards confirmed by him. He showed, in fact, that the spectral lines which were split under the influence of magnetism consisted of polarized light, or in other words that the light vibrations are orientated in one particular way under the influence of the magnetic force, and in a way which varies according to the direction of the beam of light in relation to this force.
>
> For the physicist this discovery—the Zeeman effect—represents one of the most important experimental advances that recent decades have to show. For, through the demonstration that light is affected by magnetism in accordance with the same laws as vibrating electrically charged particles, clearly not only has the strongest support been given to the electromagnetic theory of light, but the consequences of Zeeman's discovery promise to yield the most interesting contributions to our knowledge of the constitution of spectra and of the molecular structure of matter. For these reasons the Swedish Royal Academy of Sciences has come to the conclusion that the discovery outlined here is of such great importance for the understanding of the connection between the forces of Nature and for the development of physical science that its recognition by the award of the Nobel Prize for Physics is justified. The Academy also bore in mind the great part which Professor Lorentz has played in the following up of this discovery through his masterly theory of electrons, which is moreover of the greatest significance as a guiding principle in various other realms.

Alfred Landé (German, 1888–1976) later showed that the Zeeman effect was influenced by both the spin and orbital angular momentum of electrons in atoms. A factor in the relevant equations is still known as the Landé g-factor.

Likewise, Johannes Stark (German, 1874–1957) discovered how applied electric fields shift the energy levels of electrons orbiting in atoms, and hence the wavelengths of light that they absorb and emit [Jungnickel and McCormmach 1986]. The specific effects were somewhat different than those induced by magnetic fields, so they provided important new information about the quantum behavior of electrons in atoms. For these experiments, Stark won the Nobel Prize in Physics in 1919. Dr. Å.G. Ekstrand, President of the Royal Swedish Academy of Sciences, announced the award [https://www.nobelprize.org/prizes/physics/1919/ceremony-speech/]:

> Professor Stark. Our Academy of Sciences has awarded you the Nobel Prize in Physics for 1919 in recognition of your epoch-making research into the so-called Doppler effect in canal rays, which has given us an insight into the reality of the internal structure of atoms and molecules. The Nobel Prize relates also to your discovery of the splitting of spectral lines in electric fields—a discovery which is of the greatest scientific importance.

In 1914, James Franck (German, 1882–1964) and Gustav Hertz (German, 1887–1975) carried out an important experiment that became known as the Franck-Hertz experiment [L'Annunziata 2016; Weber 1988]. By colliding electrons of various energies with atoms, they demonstrated that electron orbits in atoms only have certain allowed energy levels, as had already been independently suggested by optical experiments. Both Franck and Hertz went on to make many other important contributions to physics, especially later in nuclear weapons programs (Franck in the United States, Hertz first in Germany and then in the Soviet Union—see Chapter 8). For their famous experiment together, though, they won the Nobel Prize in Physics in 1925. Professor C.W. Oseen, a member of the Nobel Committee for Physics, praised their work [https://www.nobelprize.org/prizes/physics/1925/ceremony-speech/]:

> Franck and Hertz have opened up a new chapter in physics, viz., the theory of collisions of electrons on the one hand, and of atoms, ions, molecules or groups of molecules on the other. This should not be interpreted as meaning that Franck and Hertz were the first to ask what happens when an electron collides with an atom or a molecule, or that they were the originators of the general method which paved the way for their discoveries and which consists of the study of the passage of a stream of electrons through a gas. The pioneer in this field is Lenard. But Franck and Hertz have developed and refined Lenard's method so that it has become a tool for studying the structure of atoms, ions, molecules and groups of molecules. By means of this method and not least through the work of Franck and Hertz themselves, a great deal of material has been obtained concerning collisions between electrons and matter of different types. Although this material is important, even more important at the present time is the general finding that Bohr's hypotheses concerning the different states of the atom and the connexion between these states and radiation, have been shown to agree completely with reality.

As already noted, the Danish physicist Niels Bohr used some of these results to propose one of the first quantum models of how electrons orbit in the atom, and how they can emit or absorb photons of electromagnetic energy by changing from one orbit to another. For that work, he won the Nobel Prize in Physics in 1922 [https://www.nobelprize.org/prizes/physics/1922/ceremony-speech/]. Bohr interacted very closely with the greater German-speaking scientific community throughout his long career, hosting visiting German-speaking scientists in Denmark and visiting German-speaking scientists in their home countries and in the U.S. nuclear laboratories that later employed many of them [Jungnickel and McCormmach 1986; Rhodes 1986].

Bohr's atomic models were expanded and extended by Arnold Sommerfeld (German, 1868–1951) [Eckert 2013]. Sommerfeld patiently worked out the theoretical foundations for much of quantum physics, applying it to everything from individual atoms to metallic solids. As a result, his name is still attached to many key formulas and theories, such as the Sommerfeld model of electrons in metals, the Sommerfeld fine structure constant, the Sommerfeld identity, the Sommerfeld approximation, and many others. He was also famed as a teacher and mentor, authoring physics books that were used worldwide and training a vast number of students in his own lab, many of whom went on to make major discoveries themselves. Historian Michael Eckert summed up Sommerfeld's enormous impact [Eckert 2013, p. XI]:

> Who was Arnold Sommerfeld? Along with Max Planck (1858–1947), Albert Einstein (1879–1955), and Niels Bohr (1885–1962), he belongs among the founders of theoretical physics, which developed into an independent discipline during his lifetime (1868–1951). Among his best known achievements is the elaboration of the Bohr atomic theory established a century ago. Even among physicists of the twenty-first century, the "Bohr-Sommerfeld Atom" and the "Sommerfeld fine-structure constant" remain current concepts. Older physicists associate Sommerfeld's name with the first "school" of modern theoretical physics, and with the work known as the "Bible of atomic physics," *Atomic Structure and Spectral Lines.* This legendary textbook was spread throughout the world in many editions and translations, and initiated generations of physics students into the field of nuclear physics. Additionally, Sommerfeld's *Lectures on Theoretical Physics*, published in six volumes, and reissued long after his death in ever new editions, conveys a sense of the charismatic teacher's personality. At the University of Munich, where he taught and pursued research from 1906 for over three decades, the tradition of the Sommerfeld school continues at the "Arnold Sommerfeld Center for Theoretical Physics." [...] A hundred years ago, the Munich "nursery of theoretical physics" (as Sommerfeld liked to describe his institute) was a haven for the new quantum physics. Sommerfeld's students included Nobel Prize winners Peter Debye (1884–1966), Max von Laue (1879–1960), Wolfgang Pauli (1900–1958), Werner Heisenberg (1901–1976), Linus Pauling (1901–1994) and Hans Bethe (1906–2005). With his 81 nominations, Sommerfeld himself holds the sad record of having been proposed for the Nobel Prize more often than any other physicists . . . without ever receiving the coveted distinction.

5.4.2 Final Development of Quantum Theory

Building on the work of Sommerfeld and other early physicists, much of the overarching framework of what became the final version of quantum theory was provided (at least in large part) by Erwin Schrödinger (Austrian, 1887–1961) [Moore 1989] and Werner Heisenberg (German, 1901–1976) [Cassidy 1992, 2009]. The names of these two physicists remain recognized even by the modern general public:

- "Schrödinger's cat" is a thought experiment involving a cat that is both alive and dead at the same time as the result of an unobserved quantum experiment, in order to emphasize the strangeness of the concept that smeared-out quantum waves can be in two different places or in two different states at the same time.

- The "Heisenberg uncertainty principle" describes how trying to make one aspect of a quantum wave (such as its position) less blurry and more accurately measured inevitably causes other aspects of the wave (such as its momentum) to become even more blurry and less accurately measured.

In the mid-1920s, Schrödinger and Heisenberg independently derived two theories of quantum physics that were fully equivalent to each other, yet expressed in very different mathematical terms.

Schrödinger used wave equations to calculate the smoothly varying back-and-forth wiggling motion of matter waves in space and time. Heisenberg preferred to calculate with matrices of numbers, where each number essentially represented how many humps a matter wave had. Ultimately both mathematical approaches gave the same answer, although Schrödinger's approach made it somewhat easier to solve some problems, and Heisenberg's approach made it somewhat easier to solve other problems.

Since the Nobel Committee for Physics had not awarded a prize in 1932, in 1933 it chose to simultaneously award Heisenberg with the 1932 Nobel Prize and Schrödinger with the 1933 Nobel Prize in Physics. Professor H. Pleijel, Chairman of the Nobel Committee for Physics, described how their discoveries fit together [https://www.nobelprize.org/prizes/physics/1933/ceremony-speech/]:

> Since the electrons were the seat of outgoing waves, Schrödinger thought that it should be possible to find a wave equation for the motions executed by the electrons which would define these waves in the same way as the wave equation which determined the propagation of light. From the solution of this wave equation one should be able to select those oscillations which were feasible for the motions within the atoms. He was successful, too, in determining the wave equation for a series of different motions of the electron, and it turned out that these equations gave finite solutions only when the energy of the system had specific discrete values, determined by Planck's constant. In Bohr's theory these discrete energy values of the electron paths were only hypothetical, but in Schrödinger's, on the contrary, they appeared as completely determined by the form of the wave equation. Schrödinger himself, and others after him, have applied his wave theory to various optical problems including the interpretation of the phenomena accompanying the impact between light rays and electrons, investigations into the behaviour of atoms in electric and magnetic fields, the diffraction of light rays, etc. In every direction, values and formulae have been obtained using Schrödinger's theory, which have been in closer agreement with experience than the older theories were. Schrödinger's wave equation has provided a convenient and simple method for handling problems to do with light spectra, and has become an indispensible tool for the present-day physicist.
>
> Somewhat before the appearance of Schrödinger's theory Heisenberg brought out his famous quantum mechanics. Heisenberg started off from quite different standpoints and viewed his problem, from the very beginning, from so broad an angle that it took care of systems of electrons, atoms, and molecules. According to Heisenberg one must start from such physical quantities as permit of direct observation, and the task consists of finding the laws which link these quantities together. The quantities first of all to be considered are the frequencies and intensities of the lines in the spectra of atoms and molecules. Heisenberg now considered the combination of all the oscillations of such a spectrum as one system, for the mathematical handling of which, he set out certain symbolical rules of calculation. It had formerly been determined already that certain kinds of motions within the atom must be viewed as independent from one another to a certain degree, in the same way that a specific difference is made in classical mechanics between parallel motion and rotational motion. It should be mentioned in this connection that in order to explain the properties of a spectrum it had been necessary to assume self-rotation of the positive nuclei and the electrons. These different kinds of motion for atoms and molecules produce different systems in Heisenberg's quantum mechanics. As

> the fundamental factor of Heisenberg's theory can be put forward the rule set out by him with reference to the relationship between the position coordinate and the velocity of an electron, by which rule Planck's constant is introduced into the quantum-mechanics calculations as a determining factor.
>
> Although Heisenberg's and Schrödinger's theories had different starting points and were developed by the use of different processes of thought, they produced the same results for problems treated by both theories.

What is often overlooked is that Heisenberg did not develop the matrix version of quantum physics alone, but rather with other physicists. One of those was Max Born (German, 1882–1970), Heisenberg's mentor at Göttingen [Greenspan 2005]. Born also made a hugely important contribution to Schrödinger's wave version of quantum physics, by showing that the waves represent the probability of where the corresponding particle could be found. Born made numerous other important contributions to theoretical physics, many of which now bear his name (Born approximation, Born equation, Born series, Born-Haber cycle, Born-Infeld theory, Born-Landé equation, Born-Oppenheimer approximation, Born-von Kármán boundary condition, etc.). Over the course of Born's career, he mentored many students and young scientists. In addition to Heisenberg, they included Max Delbrück, Walter Elsasser, Enrico Fermi, Siegfried Flügge, Maria Goeppert-Mayer, Friedrich Hund, Pascual Jordan, Lothar Nordheim, J. Robert Oppenheimer, and Victor Weisskopf. For his contributions to quantum physics, Max Born won the Nobel Prize in Physics in 1954. Professor I. Waller, a member of the Nobel Committee for Physics, explained the importance of Born's innovations [https://www.nobelprize.org/prizes/physics/1954/ceremony-speech/]:

> Research into the laws valid for the movement of the electrons around the nucleus in the centre of the atom has been a central problem for physics during this century. Niels Bohr made a start on the solution to the problem in 1913. But his theory was of a provisional nature. Professor Max Born took an active part in striving to improve it, as did the many followers who gathered round him in Göttingen. During the twenties of this century, Göttingen, together with Copenhagen and Munich, was a place of pilgrimage for researchers in the field of atomic theory. When the young Heisenberg, formerly a pupil of Sommerfeld in Munich and of Bohr in Copenhagen, published his epoch-making preliminary work on the exact laws for atomic phenomena in 1925, he was Born's assistant in Göttingen. His work was immediately continued by Born, who gave logical mathematical form to the Heisenberg theory. Owing to this progress, Born, in collaboration with his pupil Jordan and later with Heisenberg also, was able to expand the latter's original results into a comprehensive theory for atomic phenomena. This theory was called quantum mechanics.
>
> The following year Born got a new result of fundamental significance. Schrödinger had just then found a new formulation for quantum mechanics. Schrödinger's work expanded the earlier ideas of De Broglie which imply that atomic phenomena are connected with a wave undulation. However, Schrödinger had not solved the problem of how it is possible to make statements about the positions and velocities of particles if one knows the wave corresponding to the particle.
>
> Born provided the solution to the problem. He found that the waves determine the probability of the measuring results. For this reason, according to Born, quantum mechanics

> gives only a statistical description. This can be illustrated by a simple example. When you shoot at a target it is possible in principle—according to the older conception—to aim the shot from the start so that it is certain to hit the target in the middle. Quantum mechanics teaches us to the contrary—that in principle we cannot predict where a single shot will hit the target. But we can achieve this much, that from a large number of shots the average point of impact will lie in the middle of the target. In contradiction to the deterministic predictions of the older mechanics, quantum mechanics accordingly poses laws which are of a statistical character, and as regards single phenomena will only determine the probabilities that one or another of various possibilities will occur. For material bodies of ordinary dimensions the uncertainty of the predictions of quantum mechanics is practically of no significance. But in atomic phenomena, on the other hand, it is fundamental. Such a radical break with older ideas could not of course prevail without opposition. But Born's conception is now generally accepted by physicists, with a few exceptions.
>
> In addition to these achievements, which have been rewarded with the Nobel Prize, Born has made fundamental contributions to many fields of physics. In the first place he dedicated his interest to the theory of crystals and has been one of the great pioneers in that field.

Pascual Jordan (German, 1902–1980) played a major role in the development of both nonrelativistic quantum physics and relativistic quantum physics (Section 5.6) [Jones 2008]. Working directly with Heisenberg and Born, he helped to develop the matrix version of quantum theory. He then went on to publish a string of important papers on quantum theory, both alone and in collaboration with various other physicists. The modern *Encyclopedia Britannica* still includes a brief note testifying to his importance [EB 2010, Jordan, Pascual]:

> German physicist who in the late 1920s founded (with Max Born and Werner Heisenberg) quantum mechanics and (with Wolfgang Pauli and Eugene Wigner) quantum electrodynamics.

Nevertheless, other than a few similarly brief mentions or footnotes in modern books, Jordan's important contributions to the development of quantum physics have been largely forgotten by history, perhaps because of his associations with the German government during World War II. Modern historians should examine Jordan's many scientific accomplishments in much more detail than they generally have.

Paul Ehrenfest (Austrian, 1880–1933) made several important contributions to quantum theory [Jones 2008]. His most famous discovery became known as the Ehrenfest theorem. It described mathematically how, even though quantum waves are very blurry, averages of the waves have the same values as classical mechanics would predict for well-defined particles.

Otto Stern (German, 1888–1969) and Walther Gerlach (German, 1889–1979) demonstrated that the angular momentum of atoms was quantized, or could only have certain values, due to quantum effects [L'Annunziata 2016; Weber 1988]. Their experiment was one of the earliest insights into how quantum physics constrains the behavior of rotating things (angular momentum or spin). For this work, which has since become known as the Stern-Gerlach experiment, Stern won the Nobel Prize in Physics in 1943. Professor E. Hulthén, a member of the Nobel Committee for Physics, described the experiment [https://www.nobelprize.org/prizes/physics/1943/ceremony-speech/]:

> The experiment was carried out in Frankfurt in 1920 by Otto Stern and Walter Gerlach, and was arranged as follows: In a small electrically heated furnace, was bored a tiny hole, through which the vapour flowed into a high vacuum so as to form thereby an extremely thin beam of vapour. The molecules in this so-called atomic or molecular beam all fly forwards in the same direction without any appreciable collisions with one another, and they were registered by means of a detector, the design of which there is unfortunately no time to describe here. On its way between the furnace and the detector the beam is affected by a non-homogeneous magnetic field, so that the atoms—if they really are magnetic—become unlinked in one direction or another, according to the position which their magnetic axles may assume in relation to the field. The classical conception was that the thin and clear-cut beam would consequently expand into a diffuse beam, but in actual fact the opposite proved to be the case. The two experimenters found that the beam divided up into a number of relatively still sharply defined beams, each corresponding to one of the just mentioned discrete positional directions of the atoms in relation to the field. This confirmed the space-quantization hypothesis. Moreover, the experiment rendered it possible to estimate the magnetic factors of the electron, which proved to be in close accord with the universal magnetic unit, the so-called "Bohr's magneton".
>
> When Stern had, so to speak, become his own master, having been appointed Head of the Physical Laboratory at Hamburg in 1923, he was able to devote all his energies to perfecting the molecular beam method. Among many other problems investigated there was a particular one which excited considerable interest.
>
> It had already been realized when studying the fine structure of the spectral lines that the actual nucleus of the atom, like the electron, possesses a rotation of its own, a so-called "spin". Owing to the minute size of the nuclear magnet, estimated to be a couple of thousand times smaller than that of the electron, the spectroscopists could only determine its size by devious ways—and that too only very approximately. The immense interest attaching in this connection to a determination of the magnetic factors of the hydrogen nucleus, the so-called proton, was due to the fact that the proton, together with the recently discovered neutron, forms the basic constituent of all the elements of matter; and if these two kinds of particles were to be regarded, like the electron, as true elementary particles, indivisible and uncompounded, then as far as the proton is concerned, its magnetic factor would be as many times smaller than the electron's as its mass is greater than the electron's, implying that the magnetic factor of the proton must be, in round figures, 1,850 times smaller than the electron's. Naturally then, it aroused great interest when, in 1933, Stern and his colleagues made this determination according to the molecular beam method, it being found that the proton factor was about 2½ times greater than had theoretically been anticipated.

Wolfgang Pauli (Austrian, 1900–1958) explained mathematically how angular momentum or spin works in quantum systems, constructing what are now known as Pauli spin matrices [L'Annunziata 2016; Weber 1988]. Moreover, he proved that identical particles with half-integer spin values that are in the same atom or other quantum system do not want to do the exact same thing as each other, which became known as the Pauli exclusion principle. For example, in an atom, each electron finds a way to orbit or spin somewhat differently than every other electron. The same is also true among the protons in the atomic nucleus, and likewise among the neutrons in the nucleus. Pauli won the

Nobel Prize in Physics in 1945. Professor I. Waller, a member of the Nobel Committee for Physics, praised Pauli's discoveries [https://www.nobelprize.org/prizes/physics/1945/ceremony-speech/]/:

> At this stage of the development of atomic theory, Wolfgang Pauli made a decisive contribution through his discovery in 1925 of a new law of Nature, the exclusion principle or Pauli principle. [...]
>
> The principle, first discovered for electrons, has proved to be valid for the nuclei of hydrogen, called protons, and also for the neutrons which are formed in many nuclear reactions. The neutrons are particles which have no charge but have approximately the same masses as the protons. According to present views any atomic nucleus consists of protons and neutrons. The Pauli principle is therefore essential for the description of the properties of atomic nuclei.
>
> Pauli occupies a leading position in present theoretical physics. He has made many other important contributions to different branches of his science, among them several to nuclear physics.

Friedrich Hund (German, 1896–1997) worked out specifically how the electrons in an atom are arranged in accordance with the Pauli exclusion principle [Laurie Brown et al. 1995]. The patterns he found, now called Hund's rules, are still widely used in atomic physics and chemistry.

Other aspects of quantum theory were named after their originators [Laurie Brown et al. 1995]. Gregor Wentzel (German, 1898–1978), Hendrik Kramers (Dutch, 1894–1952), and Léon Brillouin (French, 1889–1969) independently and roughly simultaneously in 1926 proposed what is now known as the Wentzel-Kramers-Brillouin (WKB) approximation for estimating the size of a quantum matter wave under conditions that are too complicated to find exact mathematical solutions. George Gamow (1904–1968) was Russian but studied and worked in Germany before moving to the United States. In Göttingen in 1928, Gamow used the WKB approximation to calculate the rate at which alpha particles can quantum-mechanically tunnel out of the nucleus, introducing a factor still known as the Gamow factor.

Similarly, Willy Thomas (German?, ??–??), Fritz Reiche (German, 1883–1969), and Werner Kuhn (Swiss, 1899–1963) developed the Thomas-Reiche-Kuhn (TRK) sum rule for calculating transitions rates between different energy levels in atoms or other quantum systems [Laurie Brown et al. 1995]. The WKB and TRK methods of calculating quantum effects remain widely used to this day.

Ralph Kronig (German, 1904–1995) made a number of contributions to quantum theory, including early ideas about electron spin, the Kronig-Penney model of electron behavior in crystals, the Kramers-Kronig relations for optical and electronic properties, and other effects [Laurie Brown et al. 1995].

At least two German-speaking women made important contributions to quantum physics that have been largely overlooked by conventional histories, and there are significant parallels in their careers. Hertha Sponer (German, 1895–1968) received her Ph.D. in physics from the University of Göttingen in 1920 and spent her career doing experimental research on quantum effects (including molecular physics and spectroscopy), first in Germany and then in the United States. In 1946 she married James Franck [https://www.deutsche-biographie.de/sfz123855.html]. Grete Hermann (German, 1901–1984) received her Ph.D. in physics from the University of Göttingen in 1926 and spent her career exploring some of the theoretical and philosophical implications of quantum physics, including whether or not the apparent wave-like nature of matter could be explained away as classical particles simply obeying undiscovered "hidden variables" [https://arxiv.org/abs/0812.3986]. Both Sponer and Hermann left Germany during the Third Reich; Sponor did not return to live in Germany until late in life, whereas Hermann returned soon after the war. Sponer and Hermann, and any other women who played important roles in the development of quantum physics, deserve much more attention than they have received.

Within the German-speaking world, the development of non-relativistic quantum physics had a great impact on many other fields, such as:

Cellular respiration (p. 145).

Vision (p. 281).

Photosynthesis (p. 405).

Inorganic chemistry (p. 427).

Organic chemistry (p. 456).

Physical chemistry (p. 594).

Film Photography (p. 624).

Astrophysics (p. 804).

Statistical/thermal physics (p. 901).

Relativistic quantum physics (p. 923).

Lighting technology (p. 957).

Lasers and holography (p. 1023).

Solid state physics/microelectronics (p. 1034).

Infrared vision (p. 1131).

Electron microscopes (p. 1286).

Nuclear diagnostics/therapeutics (p. 1505).

Radiation detectors (p. 1518).

Models of the atomic nucleus (p. 1530).

Nuclear fission reactions (p. 1537).

Nuclear fusion reactions (p. 1542).

5.5 Statistical and Thermal Physics

Statistical and thermal physics deals with the collective behavior of enormous numbers of particles, such as those that make up solids, liquids, gases, plasmas, and even light or other electromagnetic radiation. Heat or thermal energy is a random jittering of those particles; the higher the temperature, the more the particles dance around. Even though one cannot predict the random motions of any individual particle, the laws of statistical and thermal physics can accurately predict the average behavior of a whole population of particles.

Because statistical and thermal physics deals with collections of microscopic particles, it overlaps with quantum physics, which governs the behavior of particles at the microscopic scale (Section 5.4). Many of the same scientists and discoveries were important for both areas. Yet whereas simple quantum physics only calculates the behavior of one or a few particles, statistical physics employs additional mathematical methods to extend those calculations to huge numbers of particles.

Statistical and thermal physics also describes how such a collection of particles will respond to and carry heat energy in a system such as a refrigerator, an engine, an ice crystal, or a blast furnace. Thus this topic has large degrees of overlap with physical chemistry (Section 3.6), solid state physics (Section 6.5), engineering thermodynamics (Section 7.3), aerodynamics (Section 9.2), and other areas.

According to quantum physics, particles can behave like spinning tops, and the allowed angular momentum of their spin comes in units of $\hbar = h/(2\pi)$, where h is Planck's constant (p. 883). Moreover, some particles have a spin value that is an integer multiple of $\hbar$ (e.g. photons that carry the electromagnetic force and particles that carry the nuclear force have "spin 1," or $1\hbar$), and other particles have a spin value that is a half-integer multiple of $\hbar$ (e.g. electrons, protons, and neutrons have "spin 1/2," or $\hbar/2$). According to statistical and thermal physics, these two categories of particles behave very differently when they are around other particles of the exact same type:

- Integer-spin particles (such as photons) are called "bosons" because they obey Bose-Einstein statistics, which basically means that they are conformists and love to be doing the same thing as each other, unless they have so much thermal energy that they randomly move in many different ways. Since light and other electromagnetic radiation can be viewed as either waves or particles (photons), the boson nature of light is especially important for "black-body radiation," or radiation emitted by something that is so hot that it glows. See Fig. 5.40 for information on how the energy density and spectral distribution of black-body radiation change with the temperature.

- Half-integer-spin particles (such as electrons) are called "fermions" because they obey Fermi-Dirac statistics, which essentially means that they are individualists, with each particle in a system insisting on doing at least one thing differently than any other identical particle in that system (the Pauli exclusion principle). That difference might be having a different energy, different spin direction (e.g., up vs. down), or different magnitude or direction for the angular momentum of the particle's orbit. If a population of fermions has very little thermal energy, they fill up all the lowest available energy states, like sports fans arriving in a stadium with open seating. If a population of fermions has significant thermal energy, some of them randomly jump up to higher energy states, leaving their formerly occupied lower energy states empty (like sports fans who are so excited that they run up and down the levels of the stadium). Figure 5.41 illustrates the characteristics of fermions such as electrons.

As some of the names in the introduction of this section suggest, there were some important contributions to statistical and thermal physics from outside the German-speaking world. The most notable outside contributions came from Satyendra Bose (Indian, 1894–1974), Sadi Carnot (French, 1796–1832), Subrahmanyan Chandrasekhar (Indian, 1910–1995), Paul Dirac (English, 1902–1984), Enrico Fermi (Italian, 1901–1954), James Joule (English, 1818–1889), Lord Kelvin (Scottish, 1824–1907), and James Clerk Maxwell (Scottish, 1831–1879). With the exception of Bose, Chandrasekhar, Dirac, and Fermi, those outside contributions occurred before the German-speaking scientific world had really ramped up by the late nineteenth century.

After that time, a large number of German-speaking physicists dominated the field, as shown in Figs. 5.42–5.47.[6]

For simplicity, the German-speaking creators in this section are divided into the following categories of research:

5.5.1. Thermodynamic properties

5.5.2. Bosons

5.5.3. Fermions

5.5.4. Cryogenics

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[6] For coverage of different aspects of this area, see especially: Laurie Brown et al. 1995; Gamow 1966; Jones 2008; Jungnickel and McCormmach 1986, 2017; Kragh 2002; L'Annunziata 2016; von Meÿenn 1997; Ingo Müller 2007; Teichmann et al. 2008; Weber 1988.

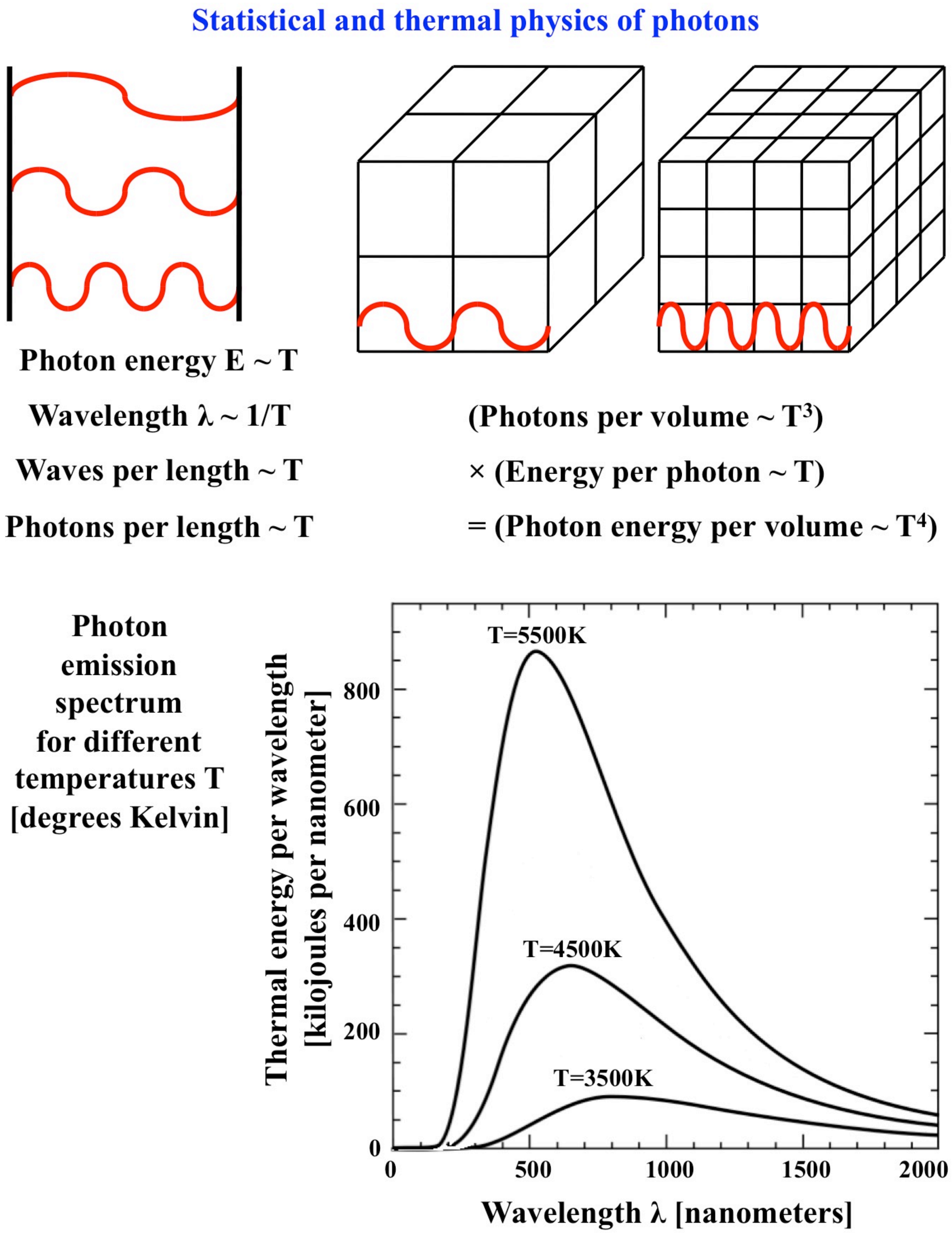
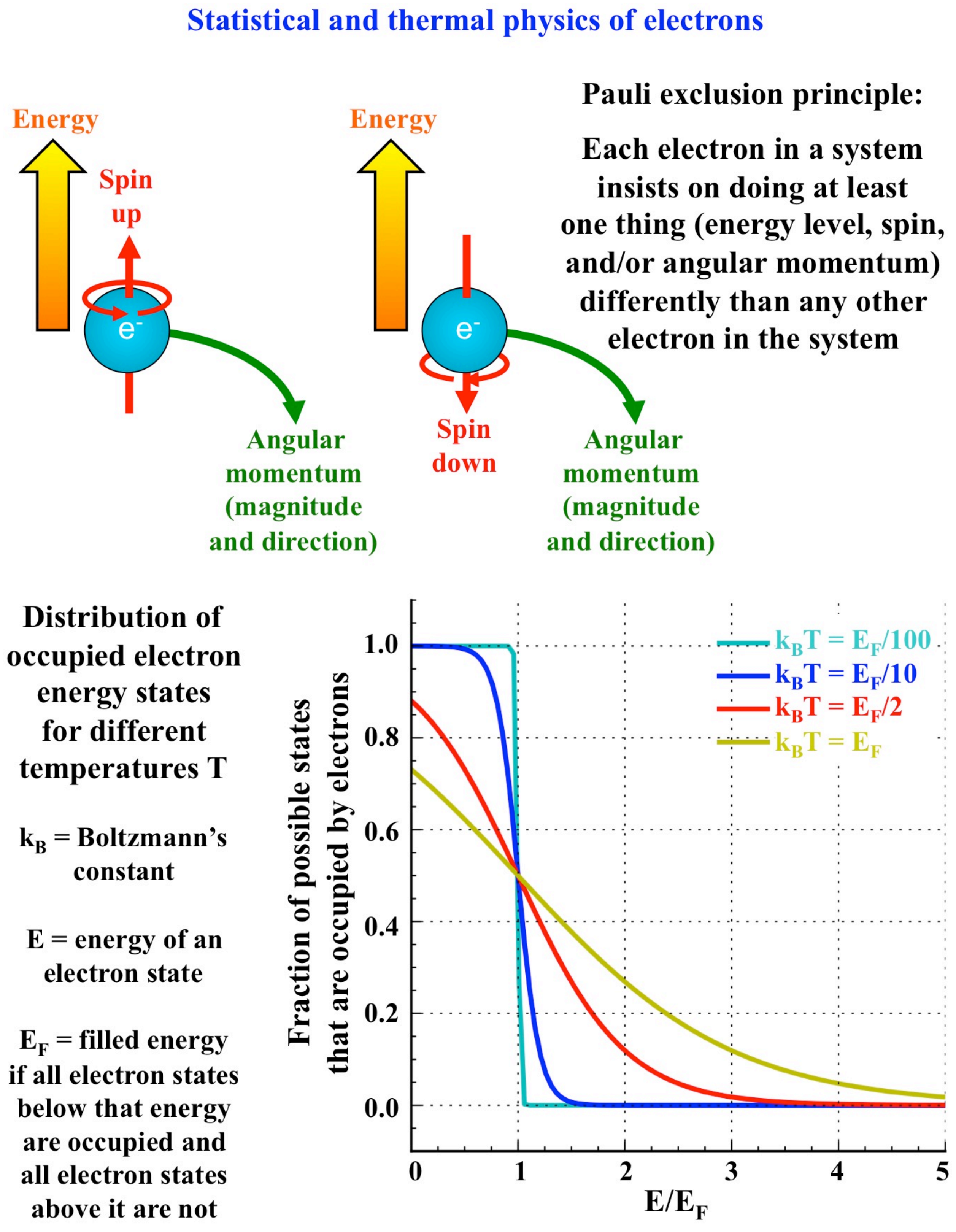


Figure 5.40: Some important discoveries in statistical and thermal physics are that the energy density of photons (electromagnetic radiation such as light) rapidly increases with temperature T (as T^4), and that a hot object emits a spectrum of photons with a predominant wavelength that becomes shorter as the temperature increases.



Statistical and thermal physics of electrons

Pauli exclusion principle:

Each electron in a system insists on doing at least one thing (energy level, spin, and/or angular momentum) differently than any other electron in the system

Distribution of occupied electron energy states for different temperatures T

k_B = Boltzmann's constant

E = energy of an electron state

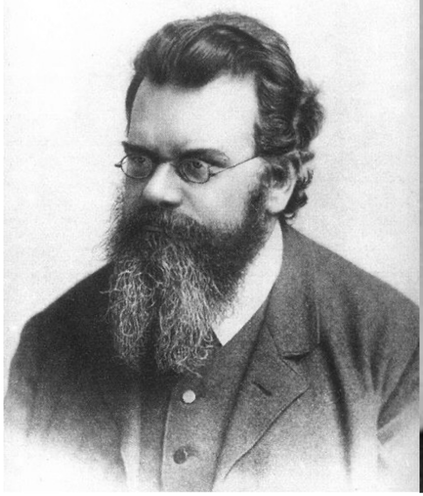
E_F = filled energy if all electron states below that energy are occupied and all electron states above it are not

Figure 5.41: Other important discoveries in statistical and thermal physics are that each electron in a system does not want to do exactly the same thing as any other electron in the system. Thus like sports fans filling a stadium with open seating, the first electrons occupy the states with the lowest energy levels, and succeeding electrons occupy additional states with higher and higher energies.

Statistical and thermal physics

Richard Becker (1887–1955)

Ludwig Boltzmann (1844–1906)



Rudolf Clausius (1822–1888)

Peter Debye (1884–1966)

Paul Ehrenfest (1880–1933)

Tatjana Ehrenfest-Afanassjewa (1876–1964)

Albert Einstein (1879–1955)

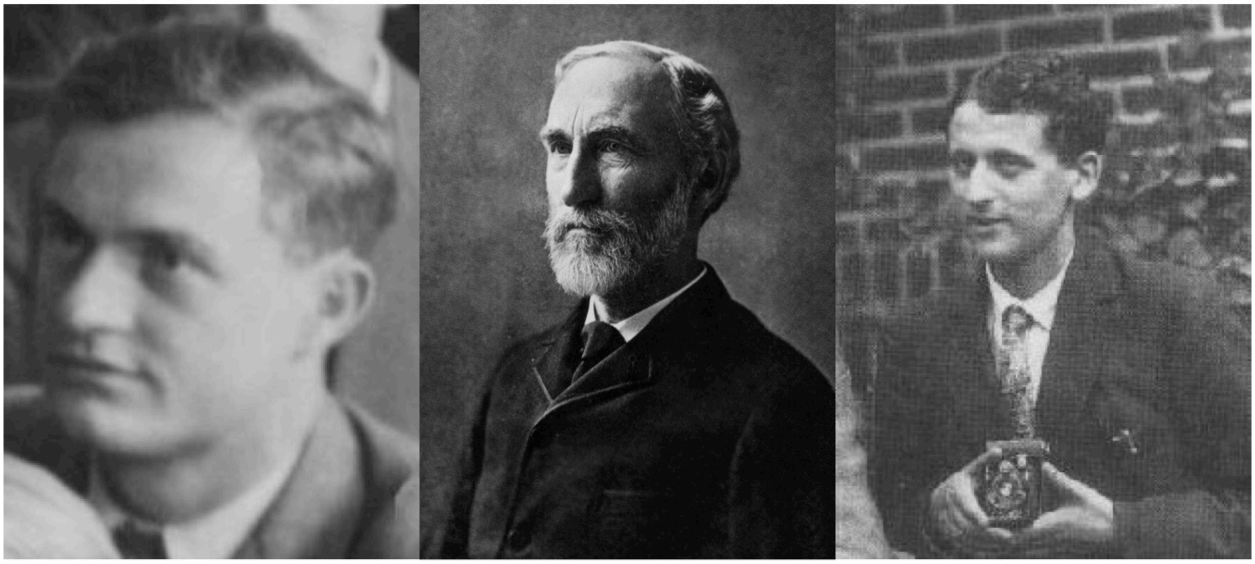
Figure 5.42: Some creators who made significant contributions to statistical and thermal physics included Richard Becker, Ludwig Boltzmann, Rudolf Clausius, Peter Debye, Paul Ehrenfest, Tatjana Ehrenfest-Afanassjewa, and Albert Einstein.

Statistical and thermal physics

Markus Fierz (1912–2006)

Josiah Gibbs (1839–1903)

Samuel Goudsmit (1902–1978)



Hermann von Helmholtz (1821–1894)

Friedrich Hund (1896–1997)

Pascual Jordan (1902–1980)

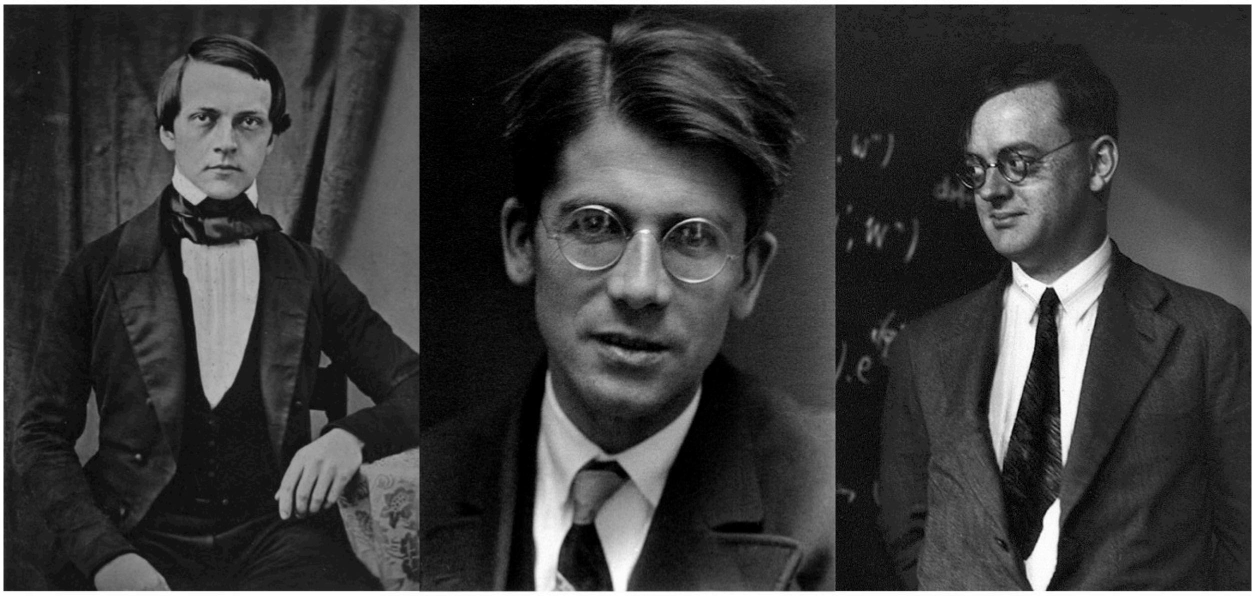


Figure 5.43: Other creators who made significant contributions to statistical and thermal physics included Markus Fierz, Josiah Gibbs, Samuel Goudsmit, Hermann von Helmholtz, Friedrich Hund, and Pascual Jordan.

Statistical and thermal physics

Heike Kammerlingh Onnes (1853–1926)

Gustav Kirchhoff (1824–1887)

Ralph Kronig (1904–1995)

Ferdinand Kurlbaum (1857–1927)

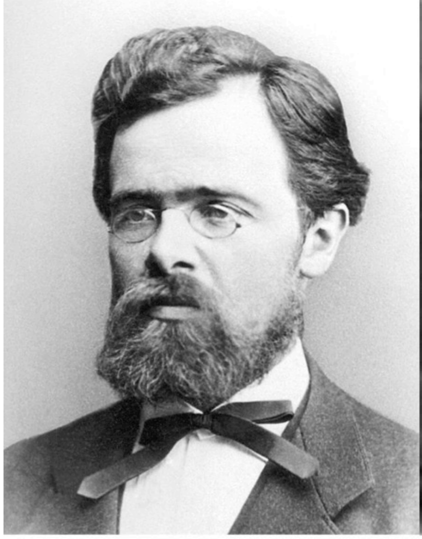
Nicholas Kurti (1908–1998)

Max von Laue (1879–1960)

Figure 5.44: Other creators who made significant contributions to statistical and thermal physics included Heike Kammerlingh Onnes, Gustav Kirchhoff, Ralph Kronig, Ferdinand Kurlbaum, Nicholas Kurti, and Max von Laue.

Statistical and thermal physics

Carl von Linde
(1842–1934)



Fritz London
(1900–1954)

Heinz London
(1907–1970)

Otto Lummer
(1860–1925)

Julius von Mayer
(1814–1878)

Fritz Walther Meissner
(1882–1974)

Figure 5.45: Other creators who made significant contributions to statistical and thermal physics included Carl von Linde, Fritz London, Heinz London, Otto Lummer, Julius von Mayer, and Fritz Walther Meissner.

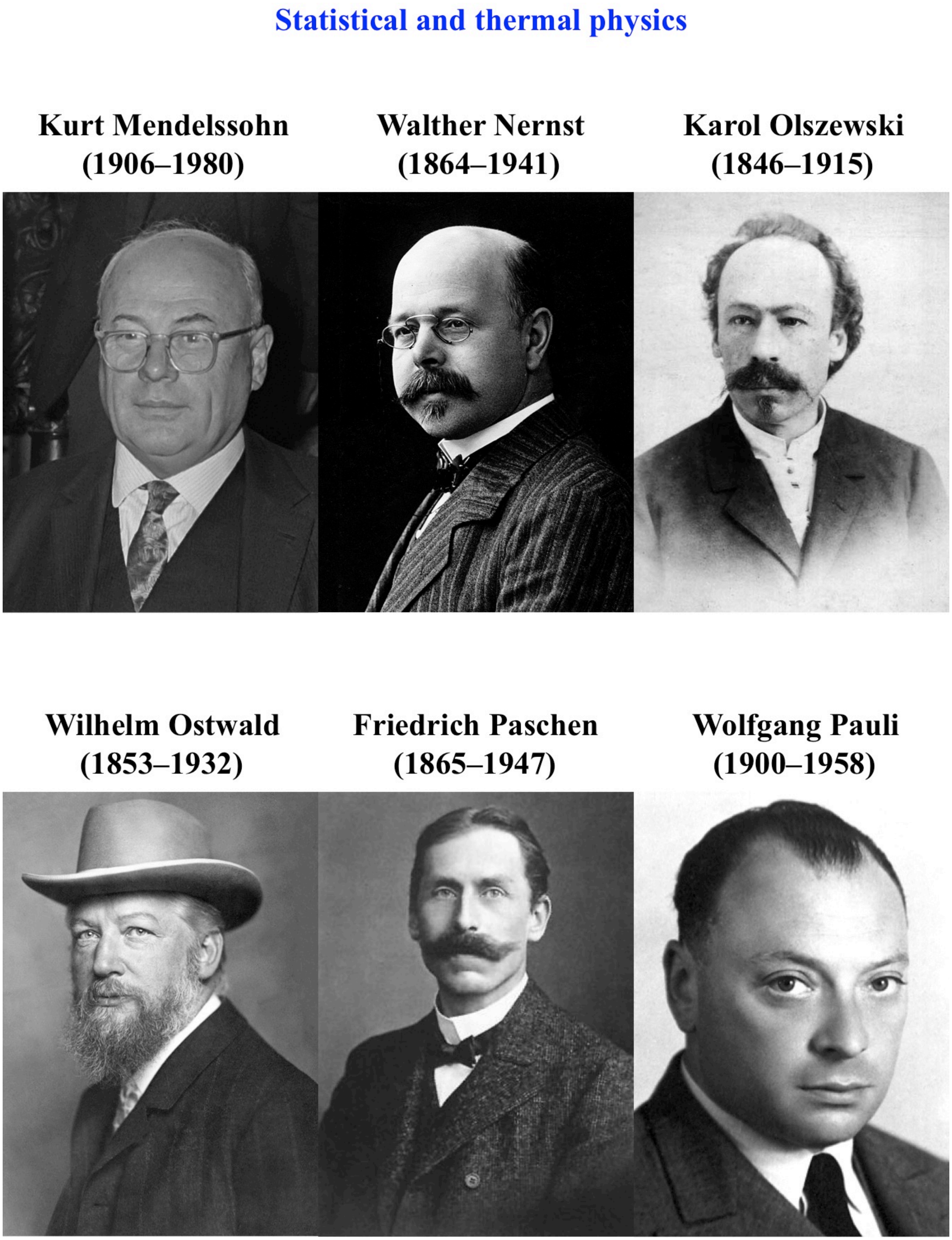


Figure 5.46: Other creators who made significant contributions to statistical and thermal physics included Kurt Mendelssohn, Walther Nernst, Karol Olszewski, Wilhelm Ostwald, Friedrich Paschen, and Wolfgang Pauli.

Statistical and thermal physics

Raoul Pictet (1846–1929) **Max Planck (1858–1947)** **Ernst Pringsheim (1859–1917)**

Heinrich Rubens (1865–1922) **Franz Simon (1893–1956)** **Arnold Sommerfeld (1868–1951)**

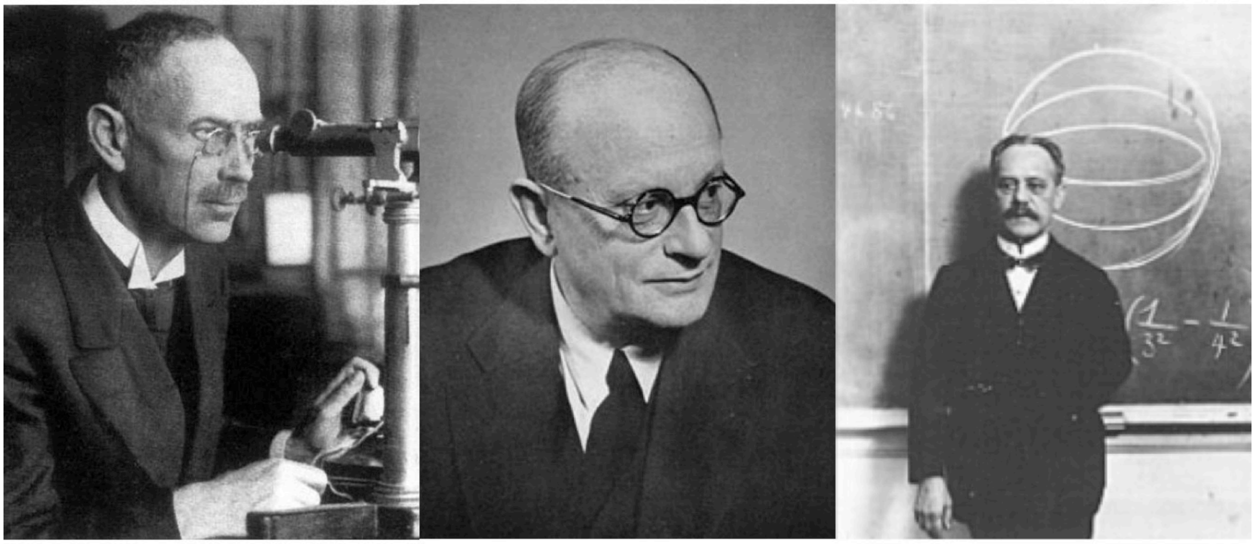


Figure 5.47: Other creators who made significant contributions to statistical and thermal physics included Raoul Pictet, Max Planck, Ernst Pringsheim, Heinrich Rubens, Franz Simon, and Arnold Sommerfeld.

Figure 5.48: Other creators who made significant contributions to statistical and thermal physics included Josef Stefan, Leo Szilard, George Uhlenbeck, Johannes van der Waals, Wilhelm Wien, and Zygmunt Wróblewski.

5.5.1 Thermodynamic Properties

Julius von Mayer (German, 1814–1878) expressed the first law of thermodynamics, the law of conservation of energy (including heat energy and work), in 1841. (James Joule independently rediscovered that law, published it in 1843, and historically has received most of the publicity for it.) He was also the first to find equations for the specific heat of an ideal gas, or the relationship between the amount of heat energy absorbed by a substance and the corresponding temperature rise for that substance.

Hermann von Helmholtz (German, 1821–1894) made a wide variety of major discoveries in biology (pp. 239, 282, 297, 311), chemistry (p. 597), and physics (p. 859) [Cahan 2018]. In 1847, he published a more detailed treatment of the first law of thermodynamics, *Über die Erhaltung der Kraft* (*On the Conservation of Energy*), and also studied the thermodynamics of fluids.

In 1850, Rudolf Clausius (German, 1822–1888) was the first to clearly articulate the second law of thermodynamics, that entropy cannot decrease, or equivalently that heat flows from regions of higher temperature to regions of lower temperature.

Johannes van der Waals (Dutch, 1837–1923) developed detailed thermodynamic equations relating the pressure, density, and temperature of gases and liquids. He won the Nobel Prize in Physics in 1910. Professor O. Montelius, President of the Royal Swedish Academy of Sciences, described his accomplishments [https://www.nobelprize.org/prizes/physics/1910/ceremony-speech/]:

> On the basis of this law of what are known as "corresponding states" for various gases and liquids Van der Waals was able to provide a complete description of the physical state of gases and, more important, of liquids under varying external conditions. He showed how certain regularities can be explained which had earlier been found by empirical means, and he devised a number of new, previously unknown laws for the behaviour of liquids.
>
> It appeared, however, that not all liquids conformed precisely to the simple laws formulated by Van der Waals. A protracted controversy arose around these discrepancies which were ultimately found to be attributable to the molecules in these liquids not all being of the same character; the older Van der Waals laws apply only to liquids of uniform composition. Van der Waals then extended his studies to mixtures of two or more types of molecules and here too he managed to find the laws and these, of course, are more complex than those which apply to substances composed of molecules of a single type. Van der Waals is still occupied with working out the details of this great investigation. [...]
>
> Yet Van der Waals' studies have been of the greatest importance not only for pure research. Modern refrigeration engineering, which is nowadays such a potent factor in our economy and industry, bases its vital methods mainly on Van der Waals' theoretical studies.

Josiah Gibbs (American but educated in Germany, 1839–1903) derived equations for the thermodynamic properties of chemical mixtures, and also showed how to calculate the behavior of substances as collections of large numbers of particles.

Ludwig Boltzmann (Austrian, 1844–1906) developed an extensive framework of statistical physics equations for describing the thermodynamic behavior of large numbers of particles in solids, liquids, or gases [Boltzmann 1964]. As part of that work, he gave a precise mathematical definition of entropy for the second law of thermodynamics.

Wilhelm Ostwald (German, 1853–1932) also developed statistical physics methods that were applicable to thermodynamic processes in both chemistry and physics. Ostwald's work won the Nobel Prize in Chemistry in 1909. Dr. H. Hildebrand, President of the Royal Academy of Sciences, praised Ostwald's discoveries [https://www.nobelprize.org/prizes/chemistry/1909/ceremony-speech/]:

> The Royal Academy of Sciences has resolved to award the former professor at Leipzig University and Geheimrat, Wilhelm Ostwald, the Nobel Prize for Chemistry 1909 in recognition of his work on catalysis and associated fundamental studies on chemical equilibria and rates of reaction. [...]
>
> The significance of this new idea is best revealed by the immensely important role—first pointed out by Ostwald—of catalytic processes in all sectors of chemistry. Catalytic processes are a commonplace occurrence, especially in organic synthesis. Key sections of industry such as e.g. sulphuric acid manufacture, the basis of practically the whole chemical industry, and the manufacture of indigo which has flourished so during the last ten years, are based on the action of catalysts. A factor of perhaps even greater weight, however, is the growing realization that the enzymes, so-called, which are extremely important for the chemical processes within living organisms, act as catalysts and hence the theory of plant and animal metabolism falls essentially in the field of catalyst chemistry. [...]
>
> Although the Nobel Prize for Chemistry is now being awarded to Professor Ostwald in recognition of his work on catalysis, he is a man to whom the chemical world is indebted also in other ways. By the spoken and the written word he, perhaps more than any other, has carried modern theories to a rapid victory and for several decennia he played a leading part in the field of general chemistry. In other ways too he has furthered chemistry by his versatile activity with numerous discoveries and refinements in both the experimental and the theoretical spheres.

Similar to Ostwald, Walther Nernst (German, 1864–1941) made important discoveries regarding the statistical physics underlying thermodynamics, physical chemistry, electrochemistry, and the physics of solids. He won the Nobel Prize in Chemistry in 1920. Professor Gerard de Geer, President of the Royal Swedish Academy of Sciences, announced the award [https://www.nobelprize.org/prizes/chemistry/1920/ceremony-speech/]:

> Herr Geheimrat Nernst. The discovery of fire, which during the classic age was still attributed to a titan, Prometheus, is both the oldest and certainly the most important of all discoveries.
>
> For long years chemists eagerly sought the suspected connection between the evolution

> of heat and the chemical affinity during the combustion of coal and in other chemical reactions.
>
> Your work has now brought this connection to light.
>
> You have used brilliant acuteness during your masterly experimental researches on specific heat and chemical equilibria.
>
> Using the heat theorem discovered by you it has now become possible on the one hand to calculate from the heat evolution during chemical reactions and the specific heats, the chemical affinity and the maximum possible output of energy during chemical reactions, and on the other hand to calculate the equilibrium in reactions not yet studied.
>
> The Academy of Sciences has decided to hand you the Nobel Prize for Chemistry as recognition of the exceptional merit of your work on Thermochemistry.

Peter Debye (Dutch, 1884–1966) studied and worked in Germany and Switzerland for many years. He developed statistical models of the behavior of molecules, chemical solutions, and crystalline solids. For his work, he was honored with the Nobel Prize in Chemistry in 1936. Professor A. Westgren, Secretary of the Nobel Committee for Chemistry, congratulated him [https://www.nobelprize.org/prizes/chemistry/1936/ceremony-speech/]:

> Professor Debye. Your rich scientific activity has been aimed in particular to research into the structure of matter. Your wealth of ideas, your penetration and your secure mastery of mathematical methods have yielded great success to your endeavours, and your results have enriched chemistry to an extraordinary degree in all kinds of ways. By your investigations on dipole moments and also on X-ray and electron interferences in gases you have widened and deepened our knowledge of molecular structure to such an extent that the Royal Academy of Sciences has awarded you the Nobel Prize for Chemistry.

Leo Szilard (Hungarian, 1898–1964) introduced several thermodynamic innovations including the Szilard engine, new ideas about Maxwell's demon, and the Einstein refrigerator.

5.5.2 Bosons

As mentioned in Section 5.4, experimental and theoretical investigations of black-body radiation led directly to the development of quantum physics. Those investigations were also a critical part of statistical and thermal physics, since black-body radiation is an example of the behavior of large numbers of bosons (photons).

Beginning in the 1850s, Gustav Kirchhoff (German, 1824–1887) conducted the first experimental and theoretical investigations of black-body radiation, and was also responsible for giving it that name. Historian of science Ingo Müller described Kirchhoff's foundational role in this area [Müller 2007, p. 199]:

> Kirchhoff conceived of a *black body*, a hypothetical body that sends out radiation of all frequencies and that should therefore—by Kirchhoff's law—also absorb all radiation, and reflect none, so that it appears black. Such black bodies came to play an important role in radiation research, although in the early days no real good black body existed to serve as a reliable object of study. Therefore Kirchhoff suggested an ingenious surrogate in the form of a cavity with blackened, e.g. soot-covered interior walls, which could be heated. Any radiation that enters the cavity by a small hole is absorbed or reflected when it hits a wall. If reflected, the light will most likely travel to another spot of the wall, being absorbed or reflected there, etc. In this way virtually no reflected light comes out through the hole so that the hole itself absorbs radiation *as if it were* a black body. The radiation emitted through the hole is called cavity radiation and it can be studied at leisure for any temperature of the walls.

In 1879, Josef Stefan (Austrian, 1835–1893) experimentally demonstrated that the power of emitted black-body radiation varies as the fourth power of the temperature, as shown at the top of Fig. 5.40. Stefan was also the doctoral advisor for Ludwig Boltzmann, who found a theoretical derivation for that relationship in 1884, so the relationship between power and temperature for thermal radiation is now known as the Stefan-Boltzmann law.

In the late nineteenth century, increasingly accurate experimental measurements of the spectrum of black-body radiation were conducted by Ferdinand Kurlbaum (German, 1857–1927), Otto Lummer (German, 1860–1925), Ernst Pringsheim (German, 1859–1917), Heinrich Rubens (German, 1865–1922), and Wilhelm Wien (German, 1864–1928). Those experiments essentially yielded the curves shown at the bottom of Fig. 5.40 for how the spectrum of black-body radiation varies with changes in the temperature of the object emitting the radiation.

Several scientists worked to develop equations to describe the measured black-body radiation spectrum, as well as physical explanations for the origins of those equations. Wilhelm Wien derived an approximate equation for that spectrum in 1896, and showed that it agreed quite well with his experiments except at very long wavelengths. Friedrich Paschen (German, 1865–1947) independently arrived at the same equation at the same time, although primarily based on experimental data and not theoretical reasons. In 1900, Max Planck (German, 1858–1947) found the exact equation for the black-body radiation spectrum at all wavelengths, and showed that it resulted from light behaving like a collection of particles, or photons.

For their discoveries regarding black-body radiation, Wien won the Nobel Prize in Physics in 1911 and Max Planck won it in 1918 [https://www.nobelprize.org/prizes/physics/1918/ceremony-speech/].

In awarding the 1911 Nobel Prize to Wien, Dr. E. W. Dahlgren, President of the Royal Swedish Academy of Sciences, emphasized the long line of German-speaking scientists who had pioneered the study of black-body radiation [https://www.nobelprize.org/prizes/physics/1911/ceremony-speech/]:

> Ever since the beginning of the last century and, in particular, since spectrum analysis reached an advanced stage of development as a result of the fundamental work by Bunsen and Kirchhoff, the problem of the laws of heat radiation has occupied the attention of physicists to an exceptionally high degree. [...]
>
> The difficulty in investigating the laws of radiation of black bodies was, firstly, that no completely black body exists in nature. In accordance with Kirchhoff's definition, such a body would reflect no light at all, nor allow light to pass. Even substances such as soot, platinum black etc. reflect part of the incident light.
>
> This difficulty was only removed in 1895, when Wien and Lummer stated the principles according to which a completely black body could be constructed, and showed that the radiation which issues from a small hole in a hollow body whose walls have the same temperature behaves in the same manner as the radiation emitted by a completely black body. The principle of this arrangement is based on the views of Kirchhoff and Boltzmann and had already been applied in part by Christiansen in 1884.
>
> With the assistance of this apparatus it now became possible to investigate black body radiation. In this manner, Lummer, together with Pringsheim and Kurlbaum, succeeded in substantiating the so-called Stefan-Boltzmann law which indicates the relationship between the quantity of heat radiated by a black body and its temperature. [...]
>
> In 1893 Wien published a theoretical paper which was destined to acquire the utmost importance in the development of radiation theory. In this paper he presented his so-called displacement law which provides a very simple relationship between the wavelength having the greatest radiation energy and the temperature of the radiating black body.
>
> The importance of Wien's displacement law extends in various directions. As we shall see, it provides one of the conditions which are required for the determination of the relationships between energy radiation, wavelength and temperature for black bodies, and thus represents one of the most important laws in the theory of heat radiation. Wien's displacement law has however acquired the greatest possible importance in other contexts as well. Lummer and Pringsheim have shown that the radiation of bodies other than black bodies obeys the displacement law, with the sole difference that the constant which forms part of the formula has a different value. [...]
>
> It was only natural that Wien who had contributed so much to the advancement of radiation theory should make an attempt to find an answer to the last remaining question also, i.e. that of the distribution of energy in radiation. In 1894 he indeed deduced a black body radiation law. This law has the virtue that, at short wavelengths, it agrees with the above-mentioned experimental investigations by Lummer and Pringsheim. [...]
>
> The problem now became to bridge the gap between these two laws each of which had been shown to be valid in a specific context. It was Planck who solved this problem; as far as we are aware, his formula provides the long sought-after connecting link between radiation energy, wavelength and black body temperature.

Physicist Robert Weber described the scientific contributions of Wien and Planck in more detail [Weber 1988, pp. 43, 58–59]:

> Wien's major work dealt with the distribution of radiant energy in the spectrum and the effect of a change in temperature on this distribution. Wien and Otto Lummer devised the first practical black-body or cavity radiator to provide the 'full radiation' needed for their experiments. [...]
>
> Wien next investigated the problem of the distribution of energy among the wavelengths in black-body radiation. Thermodynamical reasoning was not sufficient. Wien made some arbitrary assumptions (within the framework of classical physics) about the role of molecules in the emission of radiation, and arrived at the formula
>
> $$E_\lambda \quad = \quad \frac{c_1}{\lambda^{-5}\exp(-c_2/\lambda T)}\ ,$$
>
> where E_λ is the energy at wavelength λ over a unit range of wavelength, and c_1 and c_2 are constants, which he determined by curve-fitting. Wien's formula predicts intensities a little lower than experimental values for large values of λT. The search for a better formula led Max Planck to formulate the quantum theory of radiation. Satisfyingly, Planck's theory gives c_1 and c_2 in terms of fundamental physical constants, but oddly, Planck's equation differs from Wien's in form only by the addition of a (-1) in the denominator. In temperature measurements with an optical pyrometer, Wien's equation is still often used; the calculations are simpler and sufficiently accurate. [...]
>
> Beginning in about 1896 Planck became interested in finding the correct theoretical expression for the radiation from a black body. He applied Boltzmann's equation from the theory of gases (relating entropy and probability) to a set of resonators, the energy of which, he hypothesized, occurred only in *discrete multiples of* ε. From Wien's displacement law he reasoned that the entropy was a function of E/ν (energy/frequency). He was then led (1900) to the famous relation between a quantum of energy and the frequency, and to the introduction of the constant h named after him: $E = h\nu$.
>
> The resulting Planck radiation law, unlike Wien's, fitted all the experimental data [...] Einstein spotlighted attention on Planck's work when he used the concept of quanta in his explanation of the photoelectric effect, in 1905. Next the quantum concept was exploited in the Rutherford-Bohr model of the atom. The fact that it took 25 years of experimental and theoretical work to build the quantum theory is one measure of the quality of Planck's contribution.

In 1905, Albert Einstein (German, 1879–1955) provided detailed theoretical calculations to show that light was also behaving like particles or photons in the photoelectric effect. For that work, he won the Nobel Prize in Physics in 1921 (p. 890). In several papers published over the span of a couple of decades, Einstein extended his initial treatment of photons to cover a population of any identical particles of integer spin. In 1924, Einstein also helped Satyendra Bose to publish a paper that gave an alternative derivation of Planck's earlier equation. As a result, populations of integer-spin particles became known as Bose-Einstein particles, or bosons for short.[7] Historian Walter Isaacson evaluated Einstein's contributions [Isaacson 2007, pp. 98, 328–329]:

> Einstein explored this hypothesis [in 1905] by determining whether a volume of blackbody radiation, which he was now assuming consisted of discrete quanta, might in fact behave like a volume of gas, which he knew consisted of discrete particles. First, he looked at the formulas that showed how the entropy of a gas changes when its volume changes. Then he compared this to how the entropy of blackbody radiation changes as its volume changes. He found that the entropy of the radiation "varies with volume according to the same law as the entropy of an ideal gas."
>
> He did a calculation using Boltzmann's statistical formulas for entropy. The statistical mechanics that described a dilute gas of particles was mathematically the same as that for blackbody radiation. This led Einstein to declare that the radiation "behaves thermodynamically as if it consisted of mutually independent energy quanta." It also provided a way to calculate the energy of a "particle" of light at a particular frequency, which turned out to be in accord with what Planck had found. [...]
>
> Bose's [1924] paper dealt with photons, which have no mass. Einstein extended the idea by treating quantum particles *with mass* as being indistinguishable from one another for statistical purposes in certain cases. "The quanta or molecules are not treated as structures statistically independent of one another," he wrote. [...]
>
> When he applied this approach to a gas of quantum particles, Einstein discovered an amazing property: unlike a gas of classical particles, which will remain a gas unless the particles attract one another, a gas of quantum particles can condense into some kind of liquid even without a force of attraction between them.
>
> This phenomenon, now called Bose-Einstein condensation, was a brilliant and important discovery in quantum mechanics, and Einstein deserves most of the credit for it. [...]
>
> In 1995, Bose-Einstein condensation was finally achieved experimentally by Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman, who were awarded the 2001 Nobel Prize for this work.

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[7] In retrospect, it seems odd that of all the scientists who worked on this topic, it was Bose who was immortalized when this category of particles was named. His 1924 paper arrived at the same result that Max Planck had nearly a quarter century earlier, it was only published with Einstein's input and assistance, and his other papers before and after that time were undistinguished (especially when compared with those of other Indian physicists and mathematicians such as Homi Bhabha, Subrahmanyan Chandrasekhar, C. V. Raman, and Srinivasa Ramanujan). The mathematical theory describing populations of photons or similar types of particles was progressively developed by Wien, Planck, and Einstein, based on experimental data and earlier work by the other German-speaking scientists going back to Kirchhoff. Perhaps in the aftermath of World War I, when English was the predominant language worldwide and German speakers were isolated and viewed with hostility because of the war, it was easier for the English-speaking world to give name credit to Bose, who was an English-speaking member of the British Empire, than to the series of German-speaking scientists who spent nearly three-quarters of a century developing this part of physics from beginning to end.

5.5.3 Fermions

The greater German-speaking world also dominated in discovering the behavior of fermions such as electrons. The largest and most important parts of this work were conducted by Wolfgang Pauli (Austrian, 1900–1958). In 1924, he realized that each electron in a system such as an atom refused to be in exactly the same state as any other electron in that system, a rule that became known as the Pauli exclusion principle. In 1925, Pauli further realized that data from atomic measurements showed that each state could actually have up to two electrons; he therefore proposed that there was some previously unknown, binary quantum property that was different between those two electrons, so that they would still satisfy the Pauli exclusion principle.

Pauli's new binary-valued property of electrons turned out to be their spin angular momentum, which could be pointed in two distinct directions (e.g., up or down). Ralph Kronig (German, 1904–1995) first proposed the concept of electron spin to Pauli in January 1925. Later in 1925, Paul Ehrenfest (Austrian, 1880–1933) and his students George Uhlenbeck (Dutch, 1900–1988) and Samuel Goudsmit (Dutch, 1902–1978) rediscovered the concept of spin. Ehrenfest also collaborated on statistical physics research with his wife, Tatjana Ehrenfest-Afanassjewa (1876–1964), who was Ukrainian but was educated in Germany and worked in Germany and the Netherlands.

Pauli went on to prove that particles with half-integer spins (such as electrons, protons, and neutrons) behaved as fermions and followed the Pauli exclusion principle with regard to other identical particles in the same system. Moreover, he proved that particles with integer spins (such as photons and mesons) behaved as bosons and actually liked being in the same state as each other when their energies were low enough. In 1927, Pauli also developed what are now known as the Pauli spin matrices, which mathematically describe how the spin states of particles can change (for example, how an electron might change its spin from up to down). For his decisive contributions to this topic, Pauli won the Nobel Prize in Physics in 1945. Physicist Robert Weber [Weber 1988, pp. 125–126] summarized Pauli's discoveries:

> In 1924 Pauli enunciated his 'exclusion principle' with which much of the then existing knowledge of atomic structure fell into order: no two electrons in an atom can be in the same quantum state. In 1925 Pauli wrote that a new quantum theory property of the electron, which he called a 'two-valuedness not describable classically,' was indispensable to an understanding of the anomalous Zeeman effect. Goudsmit and Uhlenbeck identified this fourth quantum number with an angular momentum (spin) of the electron. The exclusion principle could then be stated: no two electrons in an atom can have the same set of four quantum numbers. In this form, Pauli's principle led to an understanding of the formation of electron shells in an atom and the periodicity of chemical properties observed when the elements are arranged in order of increasing atomic number. [...]
>
> Other research papers by Pauli dealt with the relation of quantum spin and the appropriate distribution statistics for elementary particles, paramagnetic properties of gases and of metals (leading to the quantum mechanical theory of electrons in metals), extension of wave mechanics from one to a large number of particles, explanation of the meson, and the nuclear binding force. To explain the beta-decay of radioactive nuclei, Pauli in 1931 postulated the existence of a new subatomic particle; it was named the *neutrino* by Fermi in 1932, and was detected in 1956.

As soon as Pauli published his 1924–1925 papers on the exclusion principle for electrons, Pascual Jordan (German, 1902–1980) realized that that principle could be extended to describe the behavior of very large numbers of electrons (or other particles that behaved in a similar fashion). In 1925, Jordan wrote an elegant paper that derived what is now known as the Fermi-Dirac distribution for such particles, as shown at the bottom of Fig. 5.41. He submitted the paper to Max Born for prompt publication in the widely read physics journal that Born edited, *Zeitschrift für Physik*. Then something unfortunate happened, as recounted by historian Nancy Thorndike Greenspan [Greenspan 2005, p. 135]:

> Born had one disconcerting moment after returning [in 1926]—his discovery of a paper by Pascual Jordan at the bottom of his suitcase. Just before Born's departure [in 1925], Jordan had given it to him for possible publication in the journal *Zeitschrift für Physik*, of which Born was an editor. Born had packed it, intending to read it on the trip. When he pulled it out and finally read it, he saw that Jordan had discovered the important statistical laws that Enrico Fermi had just published in the *Zeitschrift für Physik*. Shortly, Paul Dirac made the same discovery of what became known as the *Fermi-Dirac statistics*. These laws describe the statistical distribution of identical particles of spin ½ (now called *fermions*). They follow Pauli's exclusion principle: that only one such particle can occupy an energy state at a time. These laws, as applied to electrons, aided in the development of the field of electronics. Amid the serious problems that rocked his future relationship with Jordan, Born always felt guilty, even "ashamed," that he had robbed Jordan of his due.

Sadly, it does not appear that journal editor Born made any attempt to rectify or publicly clarify the situation even after the fact. Thus the sequence of events is: Pauli worked out the behavior of small numbers of fermions in 1924–1925. Jordan extended Pauli's results to cover large numbers of fermions in 1925 and submitted his discovery for publication. After perusing Pauli's publications, Enrico Fermi (Italian, 1901–1954) independently rediscovered the same results as Jordan in 1926, and Paul Dirac (English, 1902–1984) rediscovered those same results again in 1927. Yet Jordan has been nearly forgotten by history, and the names of Fermi and Dirac will be forever linked to this topic.[8]

In 1927, Friedrich Hund (German, 1896–1997) used the Pauli exclusion principle to work out the detailed order in which electrons fill progressively higher energy states in atoms that have many electrons. His rules are still widely used today in chemistry and physics.

Also in 1927, Arnold Sommerfeld (German, 1868–1951) used the Pauli exclusion principle to describe the behavior of electrons in metals. Sommerfeld's theory successfully explained the contributions of electrons to the electrical and thermal conductivities of metals, and it is now known as the Sommerfeld or Drude-Sommerfeld model of free electrons. (For Paul Drude's earlier work, see p. 861).

Some other German-speaking scientists who made important contributions to the physics of fermions included Richard Becker (German, 1887–1955) and Markus Fierz (Swiss, 1912–2006).

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[8] Jordan's virtual omission from this part of history is certainly not the fault of Fermi and Dirac. If Jordan had not existed, Fermi and Dirac would indeed have been the first discoverers of this statistical distribution of particles. Both Fermi and Dirac made a long string of revolutionary discoveries before and after that time. For unrelated work, Dirac won the Nobel Prize in Physics in 1933, and Fermi won it in 1938. Although Fermi came out of the Italian system and Dirac out of the British system, both were highly individualistic geniuses whose accomplishments appear to have been due to their self-created natures and specific circumstances far more than the particular systems in which they lived. Both Fermi and Dirac had extensive interactions with the German-speaking scientific world during their careers. Books have been written about both of them, but their lives should be scrutinized in even more detail for lessons that future scientists might learn.

5.5.4 Cryogenics

Cryogenics concerns methods of producing extremely cold temperatures, very close to absolute zero, and also covers testing the properties of materials at those low temperatures. Many scientists from the greater German-speaking world made tremendously important contributions to cryogenics.

Carl von Linde (German, 1842–1934) greatly improved earlier attempts at ammonia refrigeration to create a truly practical and efficient large refrigeration system. He used that to liquefy air and various gases on an industrial scale.

Zygmunt Wróblewski (Polish, educated in Germany, 1845–1888) and Karol Olszewski (Polish, 1846–1915) also conducted important early work on liquefying different gases and studying their properties.

Raoul Pictet (Swiss, 1846–1929) was the first to produce liquid nitrogen.

Heike Kamerlingh Onnes (Dutch, educated in Germany, 1853–1926) built upon and extended that earlier work, reaching colder and colder temperatures. Using those extremely cold temperatures, he was the first to liquefy helium, and he also discovered superconductivity. For his discoveries, he won the Nobel Prize in Physics in 1913. Th. Nordstrom, President of the Royal Swedish Academy of Sciences, explained the importance of his contributions
[https://www.nobelprize.org/prizes/physics/1913/ceremony-speech/]:

> It was for this research that Kamerlingh Onnes set up his famous laboratory at the beginning of the 1880's, and in it he designed and improved, with unusual success, the physical apparatus needed for his experiments.
>
> It is impossible to report briefly here on the many important results of this work. They embrace the thermodynamic properties at low temperatures of a series of monatomic and diatomic gases and their mixtures, and have contributed to the development of modern thermodynamics and to an elucidation of those associated phenomena which are so difficult to explain. They have also made very important contributions to our knowledge of the structure of matter and of phenomena related to it. [...]
>
> I should have to cover too much ground if I were to report here on the experimental equipment with which Kamerlingh Onnes was at last successful in liquefying helium, and on the enormous experimental difficulties which had to be overcome. I would only mention here that the liquefaction of helium represented a continuation of the long series of investigations into the properties of gases and liquids at low temperatures which Kamerlingh Onnes has carried out in so praiseworthy a manner. These investigations finally led to the determination of the so-called isotherms of helium and the knowledge gained here was the first step towards the liquefaction of helium. Kamerlingh Onnes has constructed cold baths with liquid helium which permit research to be done into the properties of substances at temperatures which lie between 4.3^o and 1.15^o from absolute zero.
>
> The attainment of these low temperatures is of the greatest importance to physics research, for at these temperatures both the properties of the substances and also the

> course followed by physical phenomena, are generally quite different from those at our normal and higher temperatures, and a knowledge of these changes is of fundamental importance in answering many of the questions of modern physics. [...]
>
> Various principles borrowed from gas thermodynamics have been transferred to the so-called theory of electrons, which is the guiding principle in physics in explaining all electrical, magnetic, optical, and many heat phenomena.
>
> The laws which have been arrived at in this way also seem to be confirmed by measurements at our normal and higher temperatures. That the situation is at very low temperatures not the same, however, has, amongst other things, been shown by Kamerlingh Onnes' experiments on resistance to electrical conduction at helium temperatures and by the determinations which Nernst and his students have carried out in relation to specific heat at liquid temperatures.

Physicist Anthony J. Leggett indicated how advanced Onnes's achievements were [Laurie Brown et al. 1995, p. 913]:

> If the subject which we now know as low-temperature physics can be said to have a birthday, that day would be 10 July 1908—the date on which Heike Kamerlingh Onnes and his team at the University of Leiden first successfully cooled the element helium (^{4}He) below 4.2 K and thereby liquefied it. For the next 15 years, the only place in the world where liquid helium existed was the Leiden laboratory (now named after Onnes).

Franz Simon (German, 1893–1956) and Nicholas Kurti (Hungarian, 1908–1998) developed refrigerators capable of cooling down to one millionth of a degree Celsius above absolute zero.

Kurt Mendelssohn (German, 1906–1980) studied the properties of liquid helium, demonstrating superfluidity, or flow without any viscosity or friction. He also further investigated the properties of superconductors.

Some other German-speaking scientists who made especially important contributions to superconductivity included Fritz Walther Meissner (German, 1882–1974), Max von Laue (German, 1879–1960), and the brothers Fritz London (German, 1900–1954) and Heinz London (German, 1907–1970). For more information on superconductivity, see p. 1112.

Many of these creators personally transferred their knowledge of advanced cryogenics out of the German-speaking world, as described by Leggett [Laurie Brown et al. 1995, p. 920]:

> By this time political events in Europe had begun to affect the course of low-temperature physics. Following the accession to power of the Nazi government in Germany, the years 1933–34 saw the exodus of many Jewish physicists, including Kurt Mendelssohn, Franz Simon, Nicholas Kurti and the London brothers, all of whom were attracted to Oxford by F A Lindemann (later Lord Cherwell) at the Clarendon Laboratory, which thereby rapidly became a major centre in experimental low-temperature physics. At the same time superconductivity at the PTR suffered a severe blow when Meissner left for Munich and von Laue was fired by the new Nazi-appointed head.

5.6 Relativistic Quantum Physics or Particle Physics

Relativistic quantum field theory (often simply called field theory, for short) combines special relativity, which describes very fast things, and (non-relativistic) quantum physics, which describes very small things. The resulting theory correctly predicts the behavior of fundamental particles, which are small and often move at high speeds, or are in tightly bound states where they rattle around at high speeds. For that reason, the topic is also often called particle physics, as it describes the behavior of particles that are collided together and new particles that are produced in large particle accelerators. Moreover, for the same reason, relativistic quantum theory is the best way to describe the effects of the fundamental physical forces: electromagnetic force, the strong and weak nuclear forces, and gravitational force (as well as real or potential interactions among those forces).

Relativistic quantum field theories describing the fundamental forces other than gravity do not need to incorporate general relativity. They are covered in Section 5.6.1.

However, relativistic quantum field theories describing gravity (often called quantum gravity for short) do need to incorporate general relativity, and therefore they are significantly more complicated. They are briefly treated in Section 5.6.2.

5.6.1 Quantum Field Theories of Fundamental Forces Other Than Gravity

Relativistic quantum theory applied to the electromagnetic force is called quantum electrodynamics (QED). As shown in Fig. 5.49, one may use QED to picture electrically charged particles such as electrons interacting with photons, the particles that make up an electromagnetic field. One of the first predictions of QED is that normal particles have antimatter versions or antiparticles, which have the opposite charge from the normal particles, or alternately have the same charge but travel backward in time relative to the normal particles. For example, the antimatter version of the negatively charged electron is called a positron, since it has a positive electric charge. A particle-antiparticle pair can be created from electromagnetic energy, or a particle-antiparticle pair can annihilate with each other and produce electromagnetic energy. QED correctly predicts electrostatic repulsion and attraction, particle-antiparticle annihilation, and a number of more complicated effects.

Relativistic quantum theory applied to the weak nuclear force describes phenomena such as the decay of neutrons (beta decay) and muons. Relativistic quantum theory applied to the strong nuclear force is called quantum chromodynamics, and is relevant to the behavior of the quarks that compose particles like protons, neutrons, and pions, as well as the collective interactions among protons, neutrons, and pions that hold the atomic nucleus together.

Relativistic quantum physics and particle physics are generally viewed as subjects that were developed largely after World War II, and largely outside the German-speaking world. The best-known luminaries in the field were mostly Americans (e.g., Richard Feynman, Murray Gell-Mann, Sheldon Glashow, Willis Lamb, Julian Schwinger, and Steven Weinberg) plus a few British (e.g., Paul Dirac and Freeman Dyson) and Japanese physicists (e.g., Sin-Itiro Tomonaga and Hideki Yukawa). Most of the early giant particle accelerators used to experimentally confirm the predictions of relativistic quantum theory were in the United States.

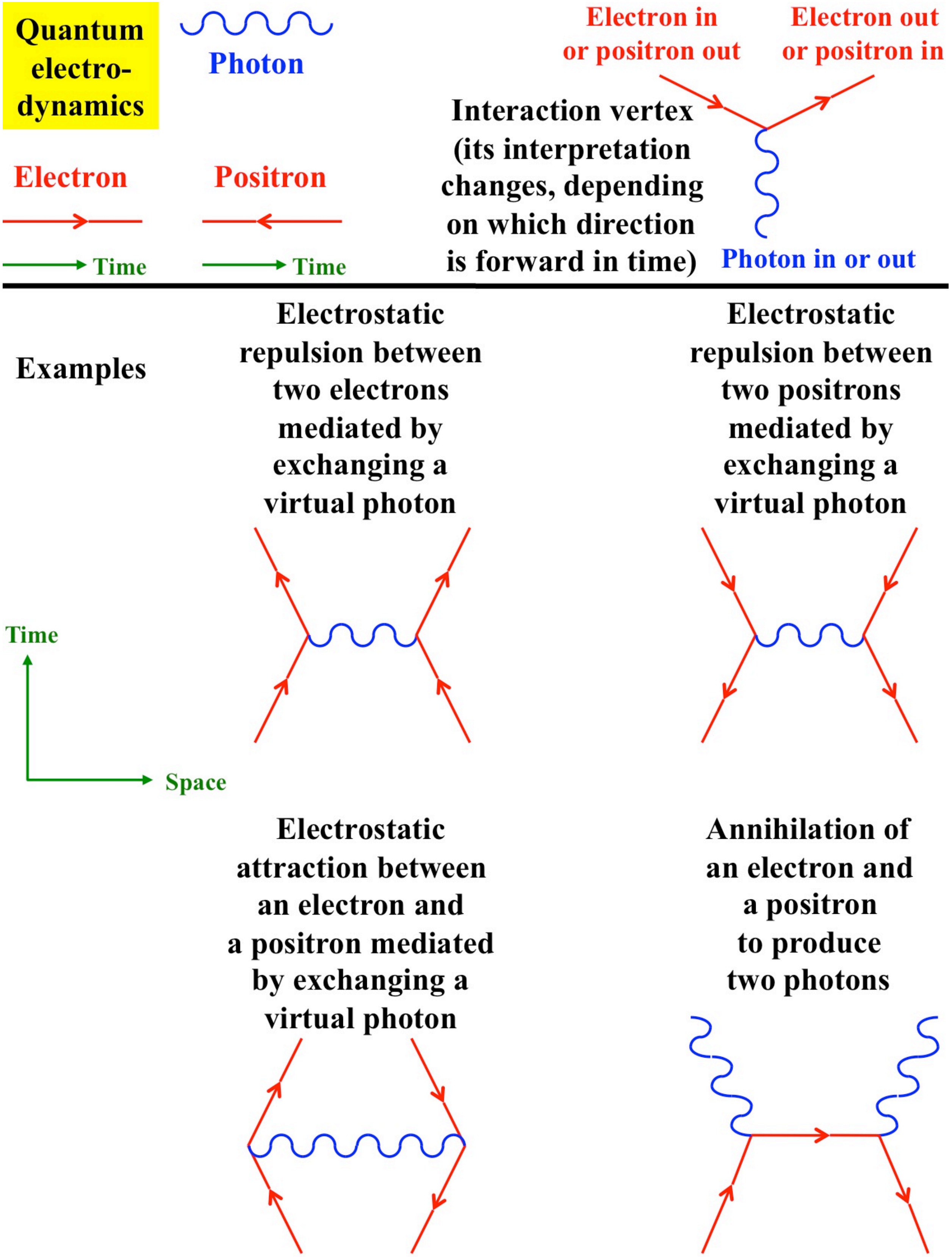

Figure 5.49: Combining special relativity, quantum physics, and electromagnetism yields quantum electrodynamics, which successfully predicted the existence of antimatter and numerous other effects.

In fact, there were a large number of German-speaking scientists who made major early contributions to relativistic quantum theory, as shown in Figs. 5.50–5.54.[9] Their research was foundational to later work outside the German-speaking world, and in some cases they made the same discoveries as non-German-speaking scientists, but earlier (and sadly with far less fame). There are several reasons why there was not even more German-speaking work on relativistic quantum theory, and why the work that was conducted is not as well known as it should be:

- The most detailed, successful work on combining relativity with non-relativistic quantum theory could not begin until non-relativistic quantum theory was fully developed, which did not occur until the end of the 1920s. Very soon thereafter, the rise of Nazism caused ~25% of scientists (including many of those working on relativistic quantum theory) to leave German-speaking Europe, disrupting their work and their interactions with other German-speaking scientists and/or spreading more of the development of relativistic quantum theory to other countries (especially the United States).

- Further development of relativistic quantum theory by scientists who remained in Germany and Austria during the Third Reich was hindered by the Nazi party's dislike for "Jewish physics" theories, the wartime focus on research with military applications, the difficulties of publishing scientific papers during the war and in the first several years after the war, and the scarcity of particle accelerators to confirm theoretical predictions. (The Third Reich appears to have possessed many particle accelerators by the end of the war, but they were devoted to military applications such as nuclear physics during the war, and most were confiscated by Allied countries after the war—see Section C.1 and pp. 3954–4022 and 4504–4510.)

- Likewise, immediate development of relativistic quantum theory by German-speaking scientists who fled to Allied countries was also retarded by the wartime focus on military research and the lack of particle accelerators not devoted to military purposes.

- Further work on relativistic quantum theory after the war in the German-speaking world was greatly impeded by the Allied procurement of most of the scientists, scientific documents, and scientific equipment from the German-speaking world at the end of the war. That chaotic dismantlement of the German-speaking scientific world also obscured many of the scientific results that it had achieved in the preceding years.

- Many of the Americans who contributed to relativistic quantum theory (Murray Gell-Mann, Julian Schwinger, Steven Weinberg, etc.) were the children of immigrants who had fled German-speaking areas of Europe due to the political turmoil of World War I, its aftermath, and the rise of Nazism.

- There are few books that cover the history of relativistic quantum physics, and most of those that do exist were generally written for American and British audiences, without devoting sufficient attention to German-speaking contributions in this field.

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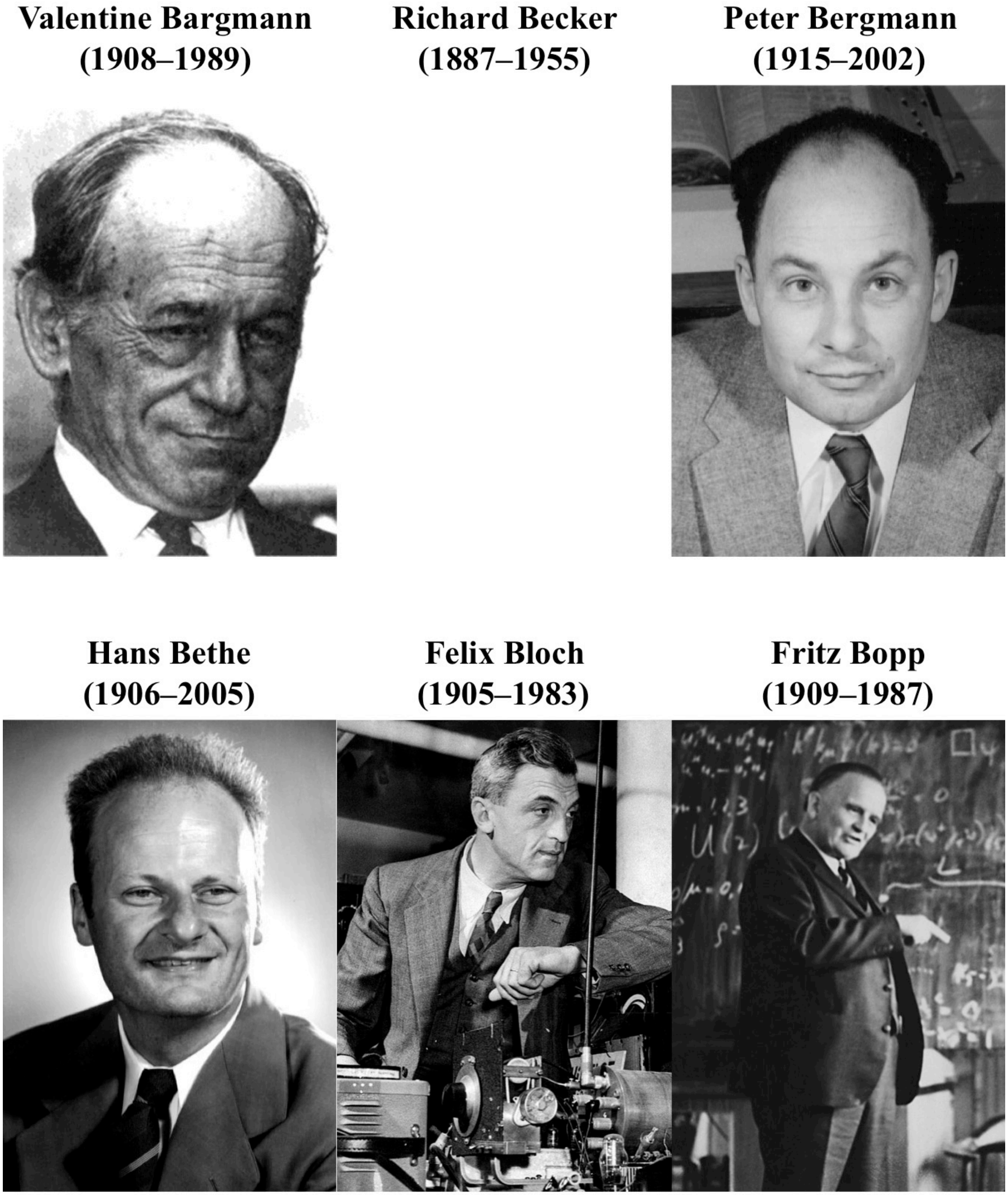
[9] Most references that focus on relativistic quantum theory tend to provide far too little information on the German-speaking world, while references that do consider the German-speaking world in detail generally focus much more on non-relativistic than relativistic quantum theory. References with at least some information on this topic include: Laurie Brown et al. 1995; Laurie Brown and Hoddeson 1983; Cassidy 1992, 2009; Gamow 1966; Greiner and Reinhardt 1994; Jones 2008; Kragh 2002; L'Annunziata 2016; von Meÿenn 1997; Moore 1989; Schweber 1994; Weber 1988. Blum and Rickles 2018 is wonderful but focuses primarily on quantum gravity and not other parts of relativistic quantum theory in the German-speaking world. Historians of science should write more books in this area!

Relativistic quantum physics



Valentine Bargmann
(1908–1989)

Richard Becker
(1887–1955)

Peter Bergmann
(1915–2002)

Hans Bethe
(1906–2005)

Felix Bloch
(1905–1983)

Fritz Bopp
(1909–1987)

Figure 5.50: Some creators who made significant contributions to relativistic quantum physics included Valentine Bargmann, Richard Becker, Peter Bergmann, Hans Bethe, Felix Bloch, and Fritz Bopp.

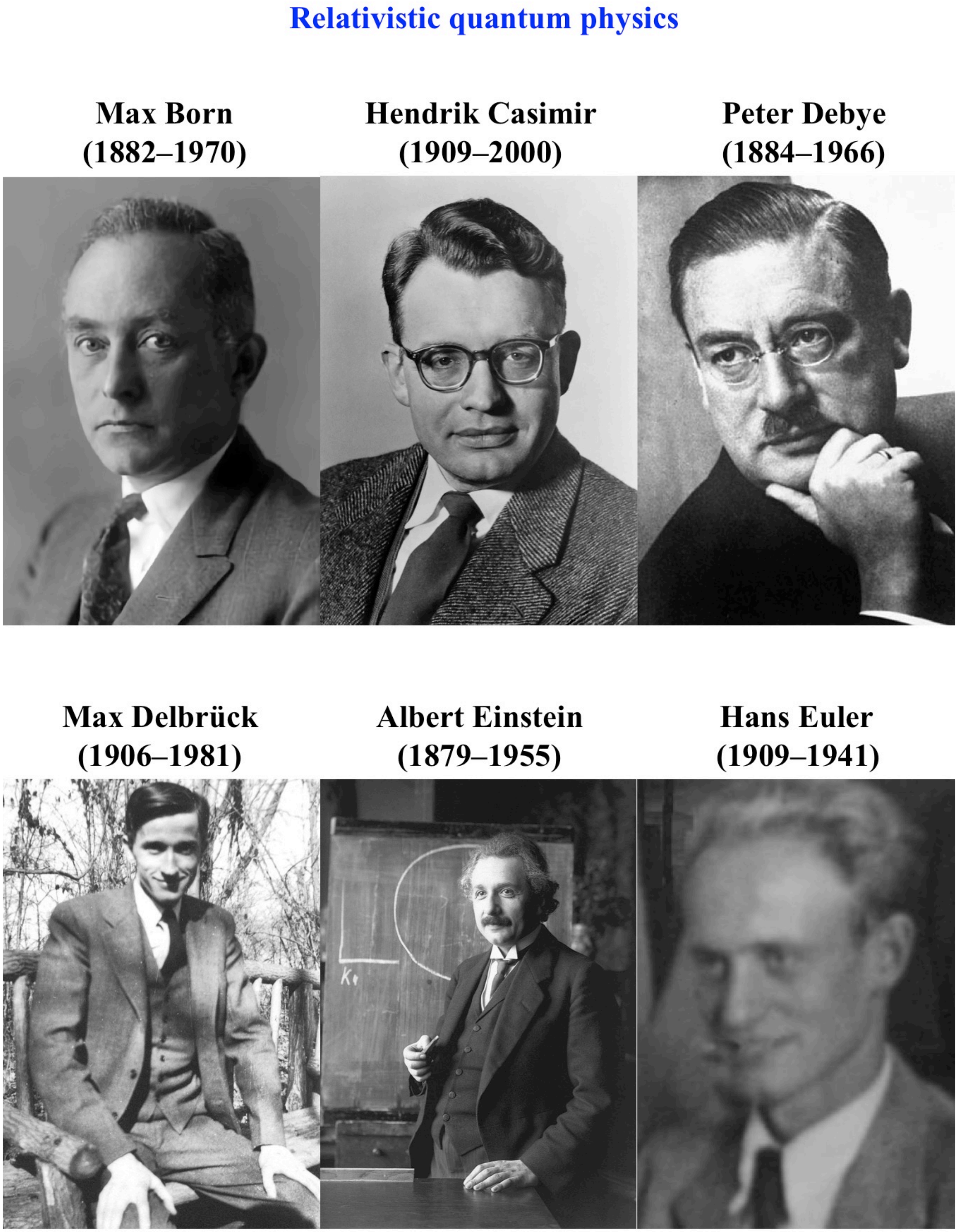
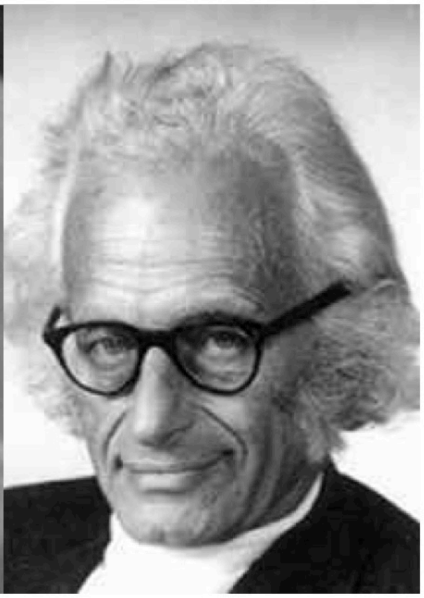


Figure 5.51: Other creators who made significant contributions to relativistic quantum physics included Max Born, Hendrik Casimir, Peter Debye, Max Delbrück, Albert Einstein, and Hans Euler.

Relativistic quantum physics

Markus Fierz
(1912–2006)

Herbert Fröhlich
(1905–1991)



Walter Gordon
(1893–1939)

Burkhard Heim
(1925–2001)

Werner Heisenberg
(1901–1976)

Walter Heitler
(1904–1981)

Figure 5.52: Other creators who made significant contributions to relativistic quantum physics included Markus Fierz, Herbert Fröhlich, Walter Gordon, Burkhard Heim, Werner Heisenberg, and Walter Heitler.

Figure 5.53: Other creators who made significant contributions to relativistic quantum physics included Leopold Infeld, Pascual Jordan, Theodor Kaluza, Nicholas Kemmer, Oskar Klein, and Polykarp Kusch.

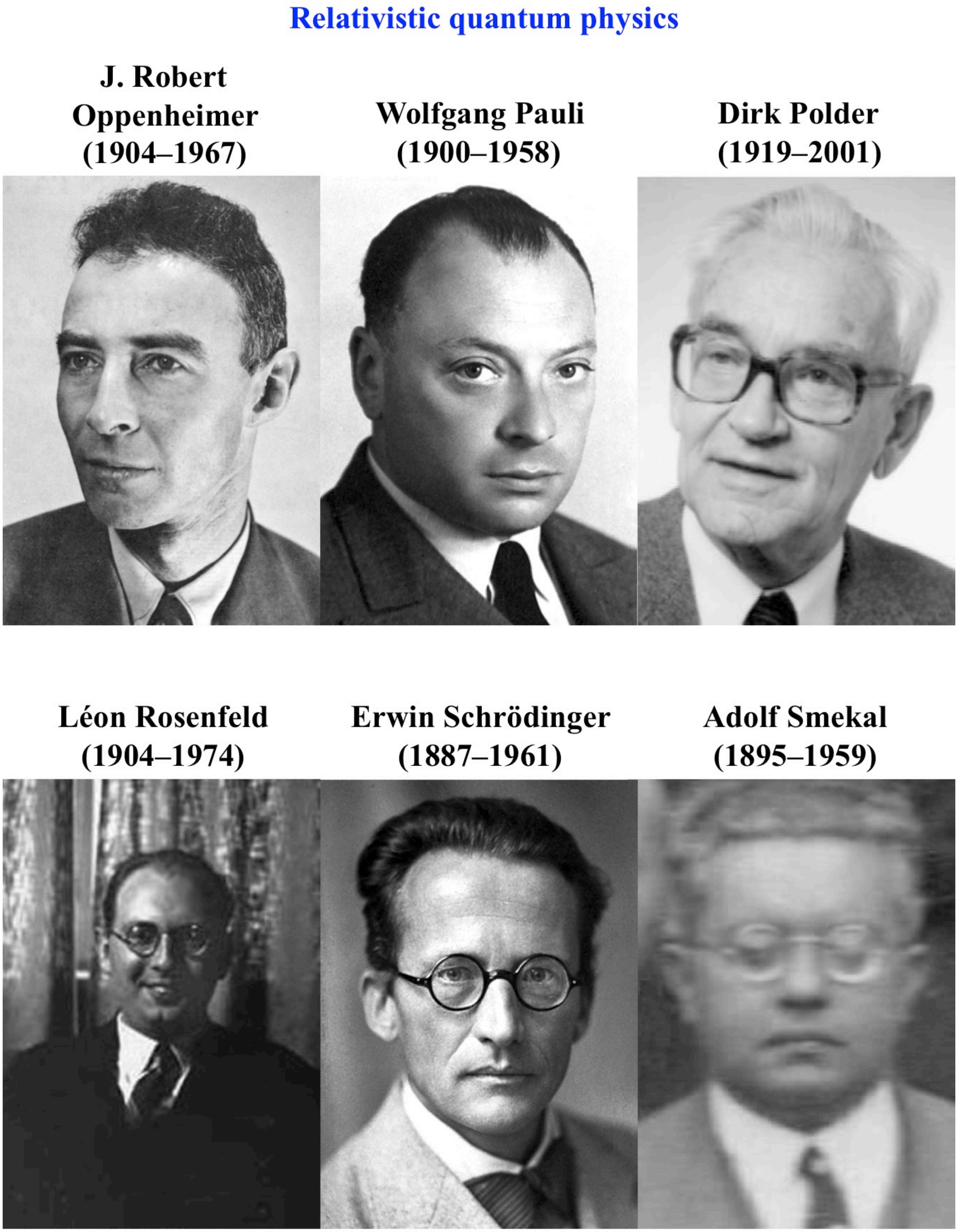
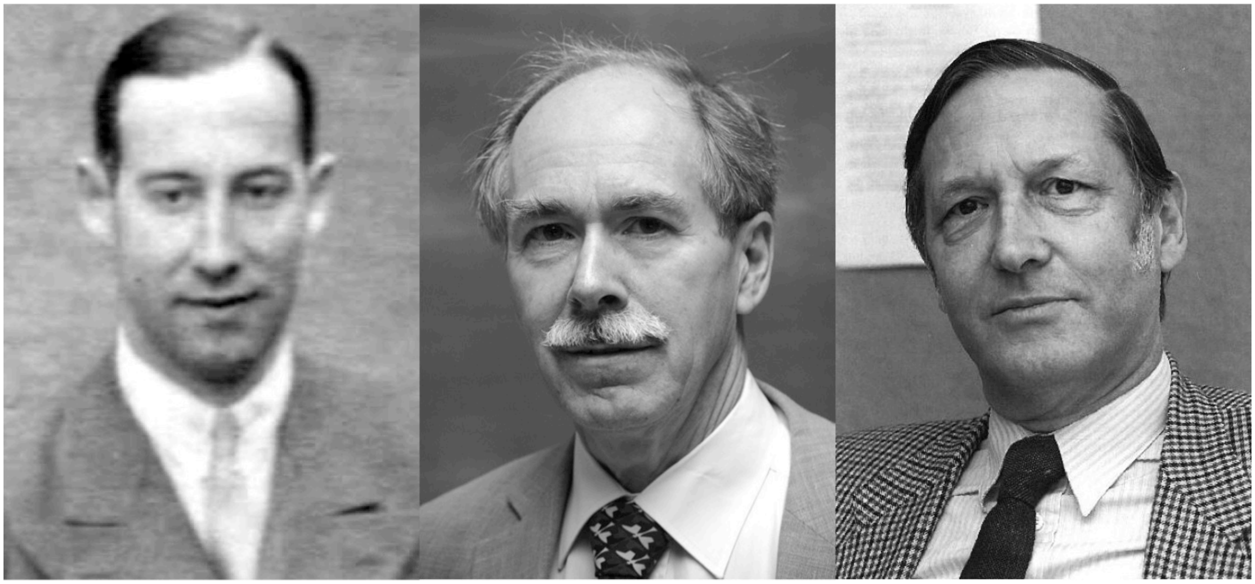


Figure 5.54: Other creators who made significant contributions to relativistic quantum physics included J. Robert Oppenheimer, Wolfgang Pauli, Dirk Polder, Léon Rosenfeld, Erwin Schrödinger, and Adolf Smekal.

Relativistic quantum physics



Ernst Stückelberg
(1905–1984)

Gerard 't Hooft
(1946–)

Simon van der Meer
(1925–2011)

Martinus Veltman
(1931–)

Felix Villars
(1921–2002)

Victor Weisskopf
(1908–2002)

Figure 5.55: Other creators who made significant contributions to relativistic quantum physics included Ernst Stückelberg, Gerard 't Hooft, Simon van der Meer, Martinus Veltman, Felix Villars, and Victor Weisskopf.

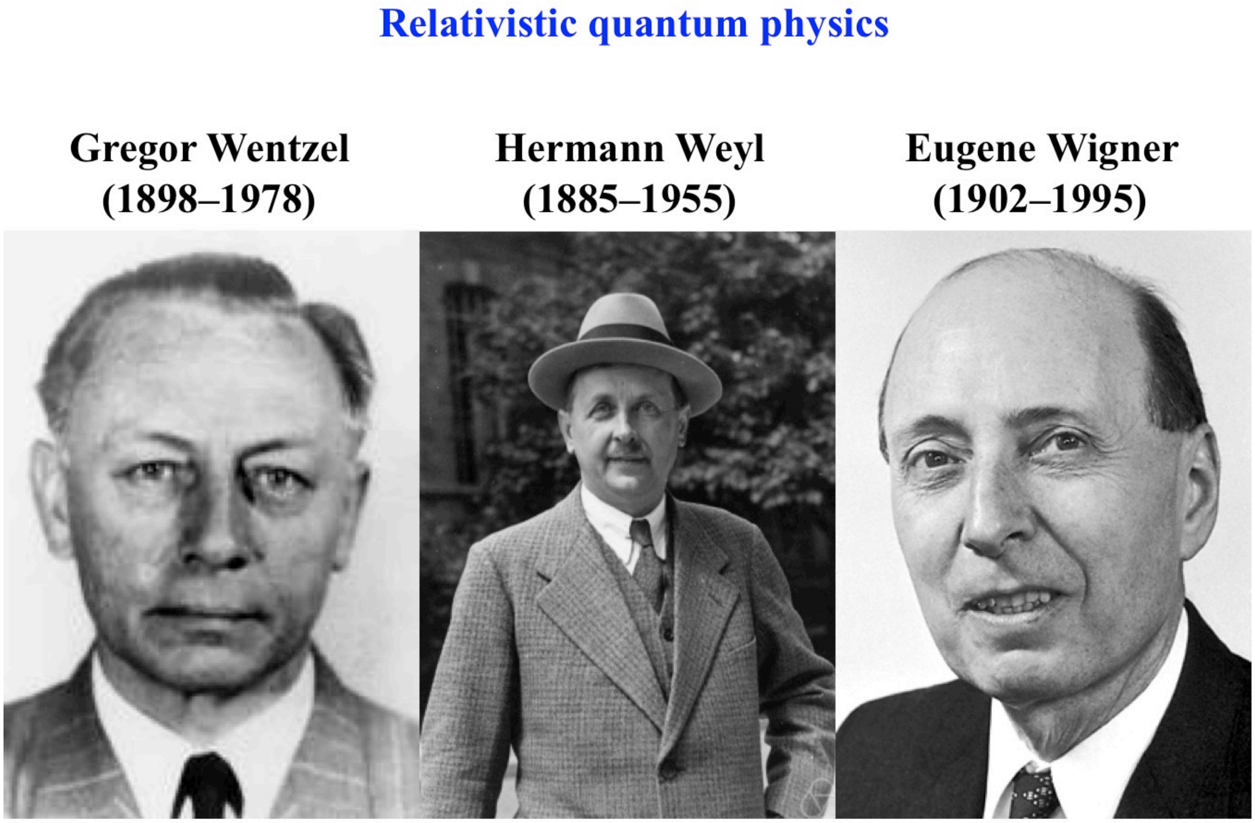


Figure 5.56: Other creators who made significant contributions to relativistic quantum physics included Gregor Wentzel, Hermann Weyl, and Eugene Wigner.

Physicist and historian Alexander Blum made it clear that relativistic quantum theory came out of the same German-speaking world that had just produced non-relativistic quantum theory, and that it was founded by many of the same physicists, including Max Born, Werner Heisenberg, Pascual Jordan, Wolfgang Pauli, and Erwin Schrödinger [Blum and Rickles 2018, pp. 49, 255]:

> In the years 1925 to 1927, the old quantum theory was replaced by the newly developed theory of quantum mechanics, which grew out of the matrix mechanics of Heisenberg, Born, and Jordan and the wave mechanics of Schrödinger. Both of these theories were initially formulated entirely non-relativistically. But it was clear from the outset that contact would have to be made with the special theory of relativity for two important reasons: On the one hand, the mechanics would have to be complemented with a quantum electrodynamics (QED), in order to describe the emission and absorption of radiation, as well as the particulate properties of light itself, which by this time (in the wake of the discovery and interpretation of the Compton effect) was a generally accepted fact. On the other hand, the mechanics itself would have to be made relativistic, as it was known, already since the mid 1910s, that relativistic corrections to the kinematics of the electron would have a measurable effect in the fine structure of atomic spectra.
>
> It was Schrödinger's wave mechanics, rather than matrix mechanics, that provided the ideal starting point for a relativistic kinematics of matter: One needed to find a new, relativistic matter wave equation, but at first glance there were no immediate other conceptual difficulties, such as the problem of a non-commuting time variable in matrix mechanics. Schrödinger himself had initially attempted to find a relativistic wave equation, following de Broglie's program of matter waves, which had been formulated in a relativistic manner. But de Broglie had stopped short of addressing the dynamical equations. Schrödinger in fact arrived at the Klein Gordon equation, but he dismissed it, due to its empirical inadequacy (later understood as the absence of spin in the Klein Gordon equation). Others were not as scrupulous, and the Klein Gordon equation was rediscovered (and published) multiple times in the immediate aftermath of Schrödinger's first papers on wave mechanics. [...]
>
> In the years 1926–1928, immediately following the creation of matrix and wave mechanics, the protagonists of this development elaborated and expanded the techniques of the new quantum mechanics, so as to apply them to field theories. This work culminated in the theory of interacting quantum electrodynamics (QED), published in 1929 by Werner Heisenberg and Wolfgang Pauli.

As Blum noted, Schrödinger derived the Klein-Gordon relativistic quantum wave equation for spinless particles years before Klein and Gordon. Schrödinger also worked on quantum gravity, and made numerous other contributions to relativistic quantum field theory [Moore 1989; Weber 1988, pp. 99–100]. Walter Gordon (German, 1893–1939) and Oskar Klein (Swedish but closely coupled to the German-speaking scientific world, 1894–1977) were also part of the same German-speaking physics community.

Historian of science David Cassidy confirmed the foundational roles of German-speaking scientists such as Heisenberg, Jordan, and Pauli in relativistic quantum field theory [Cassidy 1992, p. 276]:

> Since electromagnetic radiation is a manifestation of electric and magnetic fields, the search began almost immediately for what is now called a relativistic quantum field the-

> ory. This extremely technical and mathematical branch of quantum physics, the foundations of which were laid by Heisenberg, Dirac, Pauli, Jordan, and their colleagues during the late 1920s and early 1930s, continues to this day with much the same program and approach. [...] The enormous high-energy accelerators, bubble chambers, and data analysis equipment that were built after World War II, employing vast teams of physicists, technicians, and students, are technological wonders in themselves. They were stimulated by the discovery of new types of nonelectromagnetic fields in the middle 1930s, the quantum behavior of which comes into play only when particles smash into each other at such extremely high energies that their internal workings become evident.
>
> Large-scale experimental research was paralleled by the continuing search for a unified field theory—a quantum field theory encompassing all four types of fields known today, rather than just the electromagnetic field. [...] Werner Heisenberg was again a leading member of the small band of abstract theorists who established the program and laid the foundations of relativistic quantum field theory as it has been pursued ever since.

Physicist Silvan Schweber further described Pauli's contributions to relativistic quantum physics [Schweber 1994, p. 583]:

> Quantum electrodynamics and quantum field theory became Pauli's main concern after 1927. [...] Pauli and Heisenberg formulated the canonical approach to the quantization of field systems in 1929. During the thirties many of the seminal papers in quantum field theory were either written by Pauli, had Pauli as one of its authors, or were written under the acknowledged guidance of Pauli. [...]
>
> Pauli spent the war years, from 1940 to 1946, at the Institute of Advanced Study in Princeton. Most of his efforts during that period were devoted to meson theory.

Felix Villars (Swiss, 1921–2002) collaborated with Pauli on what is now called Pauli-Villars regularization, a mathematical technique of getting physically sensible results (instead of mathematically infinite answers) from relativistic quantum calculations.

J. Robert Oppenheimer (1904–1967) was born in New York but had a German father and second-generation German-American mother, was raised speaking German, repeatedly visited family in Germany during his childhood, and received his Ph.D. under Max Born in Germany. He began working in relativistic quantum theory under Born and Pauli, and continued to work in that field in the United States.

Gregor Wentzel (German, 1898–1978) also began relativistic quantum research with Pauli and then continued in the United States.

Some physicists from the greater German-speaking world won Nobel Prizes related to relativistic quantum theory. Born, Heisenberg, Pauli, and Schrödinger won Nobel Prizes, although those were primarily for their earlier work on non-relativistic quantum physics. Peter Debye (Dutch, 1884–1966) won a Nobel Prize in Chemistry in 1936, yet he also made unrelated contributions to relativistic quantum theory (p. 914). Hans Bethe (German, 1906–2005) also made a number of important contributions to relativistic quantum theory, but his Nobel Prize was for unrelated work on nuclear fusion in stars (p. 1542). Similarly, Felix Bloch (Swiss, 1905–1983) won a Nobel Prize in Physics in 1952, but that was for his research on nuclear magnetic resonance, not his research on relativistic quantum theory (p. 1516). Eugene Wigner (Hungarian, 1902–1995) won a Nobel Prize in Physics in 1963 for his work on mathematical groups and symmetries in physics, which was highly applicable to both nuclear physics and relativistic quantum physics (p. 1535).

Polykarp Kusch (German, 1911–1993) won a Nobel Prize in Physics in 1955 for his contributions to quantum electrodynamics. Professor I. Wailer of the Nobel Committee for Physics explained Kusch's work [https://www.nobelprize.org/prizes/physics/1955/ceremony-speech/]:

> The discovery of Kusch refers directly to an important property of the electron, namely its magnetic moment. It had been known since long that the electron is a small magnet. The strength of this magnet is measured by its moment. The magnitude of the moment should be uniquely determined by the electron theory of Dirac, mentioned before. [...]
>
> Starting from this idea Kusch made a series of very careful investigations and found in 1947 that the magnetic moment of the electron is larger than the Bohr magneton by about one part in a thousand.

In 1936, Walter Heitler (German, 1904–1981) published the first complete textbook on quantum electrodynamics, *The Quantum Theory of Radiation*, which was so farsighted and useful that it is still in print.

Ernst Stückelberg (Swiss, 1905–1984) was one of the German-speaking scientists who made some of the most advanced and yet some of the most historically overlooked contributions to relativistic quantum field theory. He was the first to produce many of the major innovations and solutions in QED for which Richard Feynman later became famous, and he also made revolutionary suggestions regarding the nuclear strong force and other topics in relativistic quantum theory. Physicists Walter Greiner and Joachim Reinhardt gave a very short description of his work [Greiner and Reinhardt 1994, pp. 37–38]:

> Stückelberg [...] made pioneering contributions to quantum field theory. In 1942 he first conceived the idea that positrons can be interpreted as electrons running backward in time. The use of the causal propagator for calculating the scattering matrix was introduced in 1949 independently by R. Feynman and S. [Stückelberg] (with his student D. Rivier). Later S. (with A. Petermann) developed the idea of the renormalization group.

Markus Fierz (Swiss, 1912–2006) studied under and collaborated with Pauli, scrutinized the ideas of Stückelberg, and made a long and extremely fruitful research career of his own in quantum electrodynamics and other areas of relativistic quantum theory. Like Stückelberg, Fierz's many contributions have often been overlooked by those outside the German-speaking world.

Greiner and Reinhardt also mentioned some other German-speaking scientists who made important contributions to relativistic quantum theory. Those included: Max Delbrück (German, 1906–1981), who was much better known for his work on DNA and viruses (pp. 103 and 200); Hans Euler (German, 1909–1941), who obtained his Ph.D. in physics under Werner Heisenberg in 1935 and began a very promising career in quantum field theory that ended with his death during the war; and Victor Weisskopf (Austrian, 1908–2002), who worked in many areas of quantum field theory [Greiner and Reinhardt 1994, p. 381]:

> Delbrück [...] published a short addendum to an experimental paper on the coherent scattering of hard γ rays where he pointed out the possible interaction of photons with

> the vacuum polarization charge induced by a nucleus. The existence of this effect was demonstrated much later and called Delbrück scattering by H. Bethe. [...]
>
> Euler [...] The airplane in which he served as a meteorological observer was shot down in 1941. In his PhD thesis E. [Euler] calculated the QED process of scattering light by light. Subsequently he worked on the theory of high-energy cosmic ray collisions.
>
> Weisskopf [...] In 1934 W. [Weisskopf] formulated a relativistically covariant quantum field theory of bosons (with W. Pauli) and in 1936 introduced concepts which led to renormalization theory.

In 1923, Adolf Smekal (Austrian, 1895–1959) predicted one of the first QED effects, inelastic scattering of photons. That effect was demonstrated several years later by C. V. Raman, who won a Nobel Prize for it.

In 1947, Hendrik Casimir (Dutch, 1909–2000) and Dirk Polder (Dutch, 1919–2001) predicted the Casimir effect, a minute but real force exerted on electrically conductive objects by particles that quantum-mechanically appear out of nothingness and immediately disappear back into nothingness. This effect was actually demonstrated in the 1990s.

Some other physicists who made various early contributions to relativistic quantum theory in the German-speaking world included Richard Becker (German, 1887–1955), Fritz Bopp (German, 1909–1987), Herbert Fröhlich (German, 1905–1991), Nicholas Kemmer (Russian but educated and worked in Germany and Switzerland, lived 1911–1998), and Léon Rosenfeld (Belgian but worked in Germany and Switzerland, lived 1904–1974).

For completeness, some later contributions should also be mentioned. Martinus Veltman (Dutch, 1931–) and Gerard ’t Hooft (Dutch, 1946–) developed the electroweak theory that showed how the electromagnetic force and the weak nuclear force are two different aspects of the same theory. For that insight, they won the Nobel Prize in Physics in 1999. The Royal Swedish Academy of Sciences summarized their research [https://www.nobelprize.org/prizes/physics/1999/veltman/facts/]:

> According to modern physics, four fundamental forces exist in nature. Electromagnetic interaction is one of these. The weak interaction—responsible, for example, for the beta decay of nuclei—is another. In the 1960s, a unified theory was formulated for these two forces: the electroweak interaction. However, certain problems still remained to be solved. In the early 1970s, Martinus Veltman and Gerardus t’Hooft formulated and tested a mathematical theory that further explained the electroweak interaction.

In closely related work, Simon van der Meer (Dutch, 1925–2011) made improvements to particle accelerators that allowed electroweak theory to be confirmed experimentally. He won the Nobel Prize in Physics in 1984. The Royal Swedish Academy of Sciences noted [https://www.nobelprize.org/prizes/physics/1984/meer/facts/]:

> According to modern physics, there are four fundamental forces in nature. The weak interaction, responsible for e.g. the beta-decay of nuclei is one of them. According to the theory forces are mediated by particles: the weak interaction by the so called heavy bosons W, Z, about 100 times more massive than the proton. Simon van der Meer developed a method to accumulate a large number of energetic antiprotons in an accelerator ring. These were used in experiment where antiprotons and protons of high energy were brought to collide. In these experiments W and Z particles were discovered in 1983.

5.6.2 Quantum Gravity

Many of the physicists already mentioned in the previous section not only wrote papers on how to combine quantum theory with special relativity to describe quantum electrodynamics and other aspects of quantum field theory, but they also wrote papers with early ideas for how to combine quantum theory with general relativity in order to describe gravitational effects [Blum and Rickles 2018].

Relativistic quantum theory applied to the gravitational force is called quantum gravity, as illustrated in Fig. 5.57. Since it must incorporate general relativity as well as special relativity, it is far more complex than theories describing the other forces. One way to view the complexity of quantum gravity is to realize that gravitons (particles of the gravitational field) can be produced by anything with mass or energy, but gravitons themselves have energy and can therefore create unlimited numbers of additional gravitons. Another way to view the complexity of quantum gravity is to consider that calculations of particle interactions are made with reference to locations in space and time, yet gravitational interactions warp space and time themselves. For these reasons, even today physicists remain far from a satisfactory theory of quantum gravity (or at least experimental evidence that one of the many proposed approaches to quantum gravity is correct).

Other physicists bypassed mainstream quantum field theory and focused directly on quantum gravity or other approaches for combining gravity with other fundamental forces and theories [Blum and Rickles 2018; Pais 1982, pp. 325–354].

One of the earliest and most important physicists in this latter category was Theodor Kaluza (German, 1885–1954). In 1919, Kaluza combined Albert Einstein's equations of general relativity with the equations of electromagnetism by using an extra fifth dimension in addition to the usual three spatial dimensions and fourth time dimension. In 1926, Oskar Klein suggested ways to incorporate some aspects of quantum theory as well, so the resulting approach remains known as Kaluza-Klein theory.

Einstein himself was very impressed by Kaluza-Klein theory and spent the rest of his career (until his death in 1955) working on various versions and extensions of it. In that pursuit, Einstein was assisted at different points by Valentine Bargmann (German, 1908–1989) and Peter Bergmann (German, 1915–2002), who in turn each also contributed some of their own original ideas to the field.

Hermann Weyl (German, 1885–1955) and Leopold Infeld (Austrian, 1898–1968) also had some important early ideas about how to combine general relativity with other aspects of physics.

Burkhard Heim (German, 1925–2001) is an interesting case that deserves closer scrutiny. He was badly injured while doing research on novel explosives during the war, then spent the rest of his career pursuing his own ideas for how to combine quantum theory and general relativity [https://www.engon.de/protosimplex/index.htm]. Because his papers were published outside mainstream physics journals and employed Heim's own mathematical notation for his new approaches, his work has never been fully and properly evaluated. Some current or future German-speaking physicists with a detailed knowledge of quantum field theory and quantum gravity research should examine Heim's major papers to determine how sound his reasoning was and whether he had any physics insights that should be more widely known and utilized.

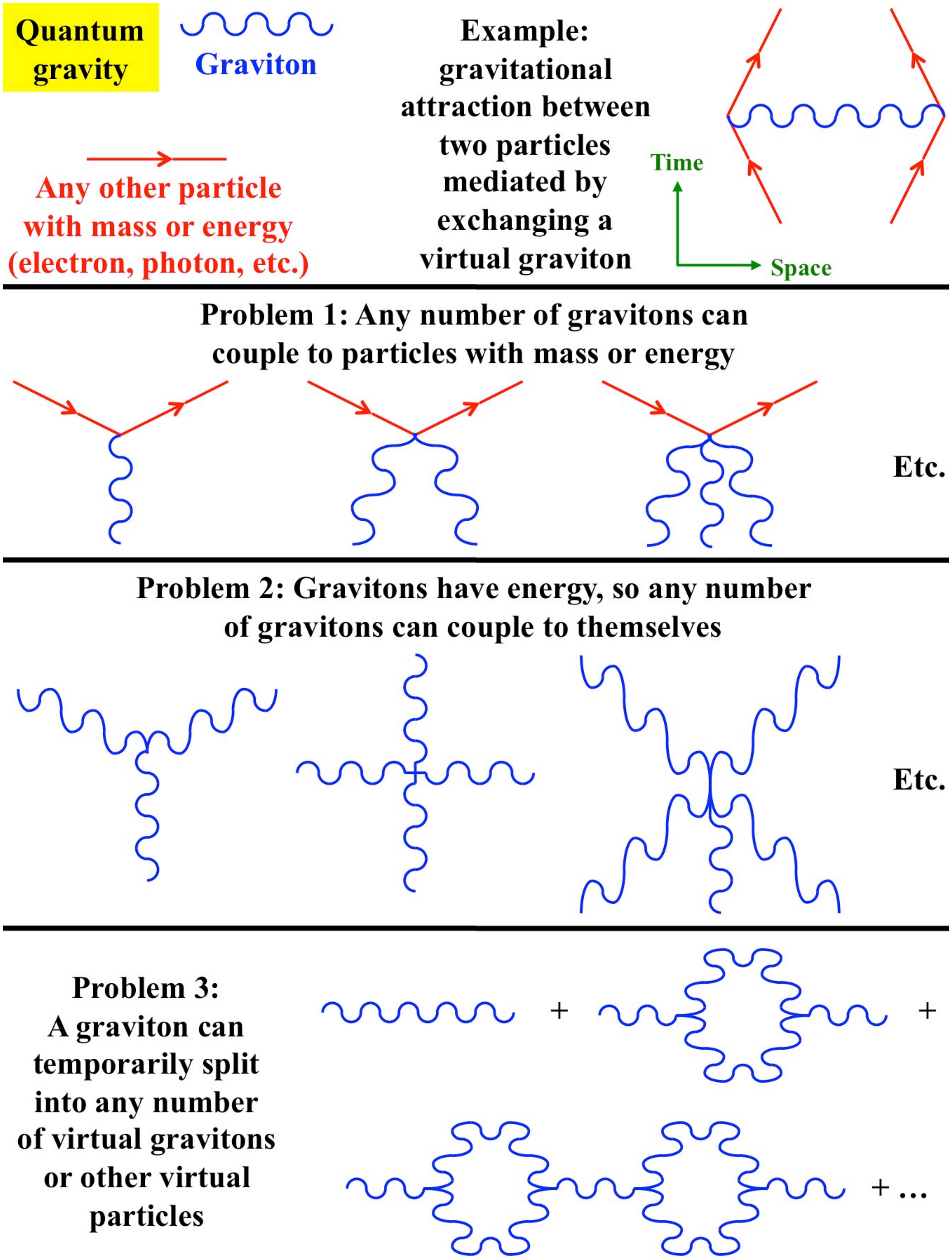


Figure 5.57: Combining special and general relativity with quantum physics yields a theory of quantum gravity, which still suffers from several unresolved mathematical problems.