Albert A. Michelson and his Interferometer

Albert A. Michelson and his Interferometer:

Lord of the Spinning Worlds, Master of Light

By

Amand Lucas

Cambridge Scholars Publishing

Albert A. Michelson and his Interferometer:
Lord of the Spinning Worlds, Master of Light

By Amand Lucas

This book first published 2023

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN (10): 1-5275-0440-9
ISBN (13): 978-1-5275-0440-0

TABLE OF CONTENTS

Part III. Michelson's Hobbies

Acknowledgments

This book has greatly benefited from the critical reading, in whole or in part, by several colleagues and friends. I am grateful to Milton Cole and Stephane Coutu, PennState University, PA, who looked at some parts with particular attention. I am especially grateful to Joseph Manson, University of Virginia, VA for his thorough reading of the whole manuscript and the many stylistic and other corrections he brought to benefit the work. My great appreciation goes above all to my friend Emile Biémont, University of Liège, Belgium, distinguished spectroscopist and member of the Belgian Academy, who has patiently gone through the complete book, making many judicious suggestions and corrections to both the historical and technical aspects of the narrative.

Part of this book was conceived and planned while I was visiting the Donostia International Physics Center (DIPC), San Sebastian, Spain. The DIPC President, Professor Pedro Echenique, and Director, Professor Ricardo Diez Muino, have over the years extended to me a graceful invitation to visit and benefit from the creative atmosphere of their great institution.

I would like to thank the Belgian Academy and its current Secrétaire Perpétuel, Professor Didier Viviers, Université Libre de Bruxelles, for arranging the Academy Editions to publish several manuscripts which I produced before and since the covid pandemic.

Finally, I dedicate this book to Jenny for her continuous support and to our children and grandchildren. I nurture the hope that they will be among the first to read or just leaf through the book with emotion and love.

A Short Introduction

Our universe is one of spinning worlds. From quarks to galaxies, everything spins. Hadrons, leptons, and gluons have a quantum spin, a fundamental degree of freedom (not a bodily rotation) deriving from relativistic quantum mechanics and the quantum theory of fields. Atomic particles such as electrons and protons, by virtue of their cartesian degrees of freedom, can have classical mechanical rotation, measured by their angular momentum. At the molecular level, multiatom molecules spin (rotational Brownian motion in fluids or even in a solid such as C60 buckyballs in fullerite). In biology, giant molecular complexes, such as the transmembrane motors of mitochondria, have a reversible spinning rotor (driven by proton transfer across the membrane) for the synthesis of ATP (adenosine triphosphate, the universal energy fuel of cells). Cell flagellates are ATP-driven rotors which produce cellular motion. At the human level, the wheel was invented for chariots to carry heavy loads. Many other types of spinning devices and engines have been invented by humanity for capturing wind energy, powering machinery, generating electricity, keeping time, and countless other uses. At the cosmic scale, planets, stars, pulsars, black holes (and their binaries), and entire galaxies spin. The quasi-permanent rotation of cosmic bodies is a consequence of Newton's or Einstein's laws of dynamics, specifically the quasi-conservation of angular momentum. Come to think of it, isolated celestial bodies rotate because there are infinitely more ways to rotate than not to rotate. Spinning is intimately linked to the passage of time. Does the mysterious dark matter also spin? Perhaps our entire universe rotates onto itself or with respect to other universes.

Spinning electrons and nuclei have magnetic moments associated with them. The interaction of such magnetic moments causes fine and hyperfine structures in atomic spectral lines, the elucidation of which was essential for the creation of quantum mechanics (QM). Later, such applications of immense practical interest as masers and lasers, atomic clocks, GPS (global positioning system) and MRI (magnetic resonance imaging), to mention a few of those which will be considered in this book, were developed based on the spectroscopic properties of spinning atomic particles. Binary pulsars and black holes, while spinning around each other, emit Einstein's gravitational waves whose recent detection led to a new branch of astronomy and astrophysics.

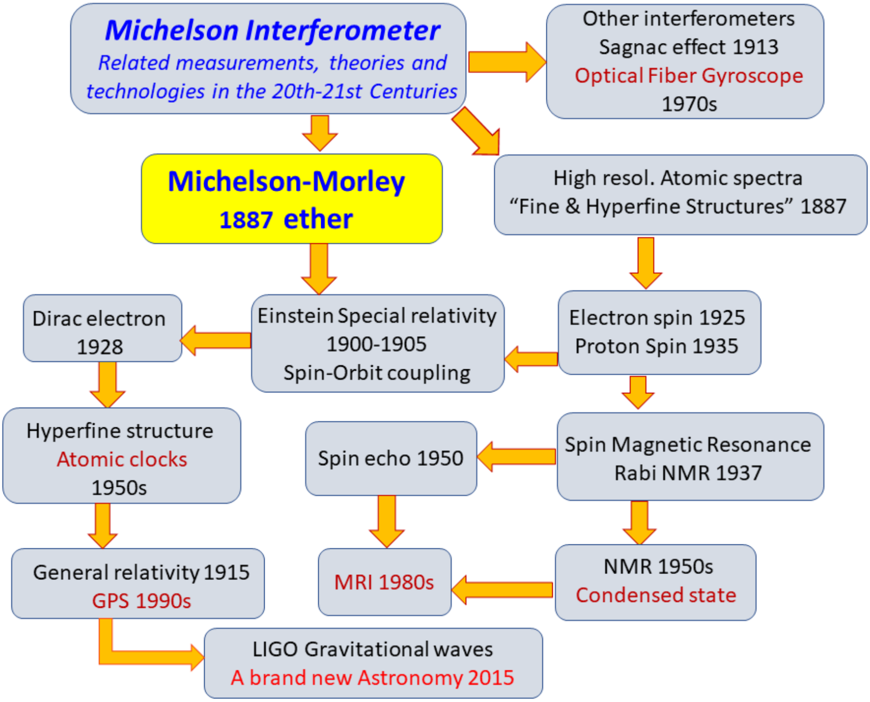

Fig. 1-1. Flow chart of concepts and techniques deriving directly or indirectly from Michelson's Interferometer. Some of the technical and industrial developments are shown in red.

Spinning phenomena will be our thread throughout this book. The rich conceptual connectivity illustrated in Fig. 1-1 justifies Michelson being called "Lord of the Spinning Worlds". The other qualification in the title, "Master of Light", was used by Dorothy Michelson Livingston[1] for her excellent biography of her father. Michelson's mastery of light was essential for the discoveries made after him of the spinning behavior of atomic particles and the creation of modern physical theories.

[1] Dorothy Michelson Livingston, *The Master of Light,* A biography of Albert A. Michelson, Plunkett Lake Press, (2021).

PART I.

BIRTH OF AN INSTRUMENT

1. THE FLOW OF CONCEPTS DERIVING FROM MICHELSON'S INTERFEROMETER

In the diagram of Fig. 1-1, I present the principal ideas discussed in the present book, their interconnections, and their relations to the original Michelson Interferometer (hereafter called the Interferometer). Fig. 1-1 is in effect a table of contents of the book. The Interferometer was invented in 1880 by the physicist Albert Michelson (1852–1931), the first American Nobel laureate for physics (1907). It is an instrument in which two light waves issued from the same coherent source, after having traveled different paths, are made to recombine and create "interference fringes" which can be counted and measured with high precision. It was not Michelson's only invention directly exploiting interference (see Chap. 3). However, the perpendicular arms arrangement of his original instrument is by far the best known (Chap. 3). The present book will discuss the main concepts involved in the working of the Interferometer and a few of its important applications in the previous and present centuries.

Befitting his characterizations as "Lord of the Spinning Worlds" and "Master of Light"[1], Michelson began his research career (in the year 1877) with one spinning object and the ambitious project to improve the measurement of the value of the velocity of light, V. The spinning object was a flat mirror, similar to that used by the French physicist Léon Foucault who invented the method of using a rotating mirror for measuring the speed of light in air. Michelson's method succeeded in greatly improving Foucault's. The measurement of V never left Michelson's preoccupation during his entire scientific life. In 1931, the year of his death, he determined a yet more accurate value of V in a partial vacuum.

For his invention of the interferometer, Michelson's original aim was to provide a new way to test the anisotropy of the speed of light V*,* that is how V depends on the propagation direction as the earth moves through space and the so-called ether. When he failed to discover any such anisotropy, he

---

[1] Dorothy Michelson Livingston, *Loc. cit.*

turned to his new invention to improve the values of the wavelengths of atomic spectral lines. He wanted to enhance the precision of existing methods, the prism and the grating spectroscopes, both perfected by J. Fraunhofer (1787–1826) earlier in the nineteenth century.

The best-known application of the Interferometer was the Michelson–Morley experiment (1887) (Chap. 5). As mentioned above, its purpose was to demonstrate that the velocity of light depends on the direction of motion of the earth on its path through the so-called luminiferous ether. No such dependence was found. Despite Michelson's disappointment and that of his collaborator Edward Morley (1838–1923), this negative result was a paradigm changer. Regarded as the most celebrated null experiment in the history of modern sciences, it led to the abandonment of two former concepts of cosmic scope, that of the ether itself and Newton's notion of absolute time. It established the constancy of the velocity of light, independent of the motion of the source or of the observer, and provided a solid empirical ground for the creation of the theory of special relativity by Albert Einstein in the year 1905.

Soon after this first application (Fig. 1-1), new variants of the Interferometer and other interferometric instruments were created which we will describe briefly in this book (Chap. 4). One of the instruments, the Fabry–Perot Interferometer or Etalon (1899) is another arrangement of exquisite precision. It has had multiple applications in very diverse fields, including recently boosting the Interferometer precision to detect gravitational waves (Chap. 10). Another variant was the Sagnac Interferometer (1913) which led to the invention of high sensitivity gyroscopes for present-day telemetric measurements in aviation and space travel. A further Michelson invention was his Stellar Interferometer, one with which he could evaluate the diameter of not-too-distant stars such as Sirius or the super-giant Betelgeuse (Chap. 3).

On a par with the Michelson–Morley ether experiment for the future of science was Michelson's use of his interferometer to measure the wavelengths of spectral lines of the elements (1887) (Fig. 1-1) with unprecedented accuracy, exceeding Fraunhofer's measurements by orders of magnitude. One of Michelson's goals was to replace the artifact meter standard of the BIPM (Bureau International des Poids et Mesures) with an accurate and universal atomic wavelength. But Michelson soon realized that most atomic spectral lines of elements are not simple, that is, are not made of a single wavelength. At the high resolution of the Interferometer, most lines were found to be complex, comprising two or more closely spaced spectral components, later called fine and hyperfine structures. This was Michelson's second failure, so to speak, but one which turned out to be another discovery of momentous import. It served as one of the strongest empirical bases which led physics into an era of revolutionary advances. Indeed, the unraveling of the origin of Michelson's spectral fine structures required no less than a completely new physical theory, namely quantum mechanics (Fig. 1-1), necessitating the creation of new concepts such as electron spin (1925) and, somewhat later, proton spin (1935) (Chap. 8).

The electron spin and its associated magnetic moment, proposed in 1925 by the Dutch physicists George Uhlenbeck (1900–1988) and Samuel Goudsmit (1902–1978), were essentially ad hoc hypotheses to help explain the atomic spectra. The concept was introduced to take account of the relativistic effects on the spectral lines of hydrogen and the alkali elements as reported by Michelson. The profound relativistic nature of these intrinsic electron properties was elucidated by P. A. M. Dirac (1902–1984) (Fig. 1-1). His utterly beautiful and powerful equation not only explained the relativistic origin of spin and its associated magnetic moment but also predicted the existence of the positron and antimatter in general, thereby launching QED (quantum electrodynamics), one branch of modern physics. We shall try to convey the essential idea which led Dirac to his celebrated equation for the electron (Chap. 9).

Michelson's hyperfine structures of hydrogen, sodium, and other elements (Fig. 1-1) arise, according to quantum mechanics, from magnetic interactions between the electron orbital angular momentum, the electron spin, and the nuclear spin. The hyperfine interactions in the ground states of hydrogen, cesium, and rubidium have been exploited for building atomic clocks of very high precision and stability (Fig. 1-1). As a result, the frequency of the Cs atomic clock has been chosen as one of the seven fundamental constants of physics, perhaps the ultimate status promotion for a formerly measured quantity. These developments are direct or indirect consequences of Michelson's 1887 spectroscopic measurements with the Interferometer.

One major consequence of atomic clocks, in conjunction with the technical developments of space science and artificial satellites, was the creation of highly accurate positioning systems such as the GPS, available in such devices as personal vehicles and mobile phones (Chap. 11).

A kilometer-sized version of the Interferometer, boosted by a no less gigantic Fabry–Perot Interferometer, was used for the construction of a spectacular instrument capable of detecting gravitational waves (GW) (2015). These waves were predicted by Einstein as early as 1916, just after his creation of the theory of general relativity (Chap. 12). This recent triumph of physics and astronomy relied heavily on Michelson's multiple experimental contributions of 1887. These included the creation of the Interferometer itself, with which he eliminated the ether theory, demonstrated the constancy of the velocity of light and with, the help of a Fabry–Perot etalon, provided an ultra-precise method for the measurement of distances such as the tiny disturbances occurring upon the passage of a GW.

On the magnetic branch of Fig. 1-1 (the right-hand side) the magnetic resonance of nuclear spins (nuclear magnetic resonance or NMR), in particular of the proton spin, was discovered in 1937 by the American physicist I. Rabi (1898–1988) in a molecular beam setup (the arrangement which led to the Cs clock, see left-hand side of Fig. 1-1). The demonstration of NMR in the condensed state of hydrogen-containing substances such as water was accomplished by Felix Bloch (1905–1983), Edward Purcell (1912–1997), and their collaborators. The crucial discovery in 1950 of the phenomenon of proton spin echo in NMR by Erwin Hahn (1921–2016) led to the spectacular development of MRI.

Such is the astonishing interlocking of many new concepts and applications developed over a period spanning more than a century. The theme of the present book will be to argue that all of these advances have their roots plunging all the way down to the Interferometer, a sort of LUCAS (last universal common ancestor for spectroscopy). As an exercise in futility, typically employed in biology but sometimes also in physics, one is tempted to ask the "what if…" question, namely what if Michelson had not created this instrument of exquisite precision? Would somebody else have come up with some similar arrangement? And would contingency have affected the recent history of physics and technology the same way as it is purported to have dominated biological evolution since the creation of life? Certainly not to the same extent, given the immensely greater complexity of living matter. But the memes of the "hard" sciences and technologies evolve quite like the genes of living matter, only at a vastly accelerated pace. So, "rewinding and replaying the tape" without the Interferometer would likely have ushered in a very different sequence of events, perhaps delaying by several years the advent of relativity and quantum mechanics with all their attendant consequences displayed in Fig. 1-1.

Although I have placed Michelson's invention at the top of the chart in Fig. 1-1, it is worth pointing out that Michelson himself took no part in the "revolutions" in physics that occurred during his lifetime after his discoveries as an extraordinary experimental physicist. Thus, until his death in 1931, he never really abandoned the concept of the ether that his instrument helped discard. He did not embrace relativity nor quantum mechanics, both of which used his discoveries as empirical bases. Michelson, "the Master of Light"[2] as his daughter-biographer called him, was a classical physicist entirely committed to traditional, nineteenth-century physics and to building instruments of extreme precision. Nevertheless, the Interferometer looms over many a modern discovery and fully deserves to stand on top of the chart in Fig. 1-1. In many aspects this device is a quantum mechanical, self-measuring instrument which someone had to invent in order to hasten the exploration of several major facets of twentieth-century physical sciences.

---

[2] Dorothy Michelson Livingston, *Loc. cit.*

2. Physical Instruments that Advanced the Sciences and Technology

I want to make a brief listing of a few instruments which have helped the advent of the scientific method and the development of the sciences and associated technologies in the course of the last five centuries. My short list is shown in Fig. 2-1, where the Interferometer stands out prominently. This list, as established by a Western scientist (not a historian), is probably biased and certainly incomplete. I apologize for that.

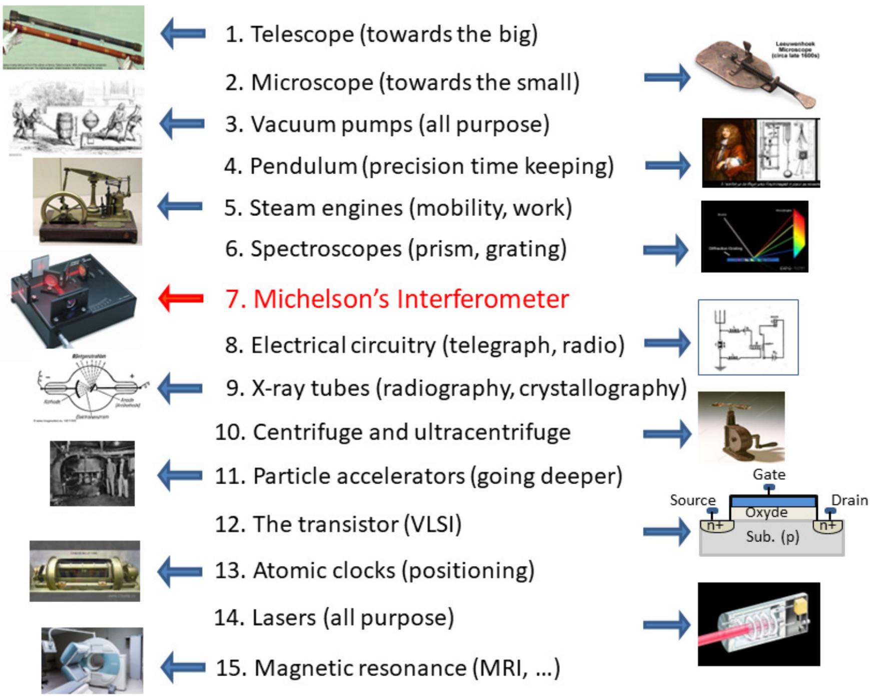

Fig. 2-1. A short list of historical, physical instruments that advanced the sciences and technologies.

In his informative obituary (1938) of Michelson, Robert Millikan[1], a contemporary American scientist (Physics Nobel prize, 1923) declared, "Claude Bernard says that 'a good technique sometimes renders more service to science than the elaboration of highly theoretical speculations', and George Hale (an American solar astronomer and telescope builder, 1868–1938) has often remarked to me that 'after all, the progress of physics is written in the history of the development of new instrumental techniques'". Be this as it may, the history of the interferometer shows how vitally *theory and experiment cooperate in the progress of science* (my emphasis). It is this latter viewpoint that I tried to develop in the previous chapter and in this whole book. This is generally acknowledged among scientists, with occasional reservations, such as that expressed by Einstein himself who, for instance, stated that he was little influenced by the Michelson–Morley experiment when creating the theory of special relativity[2]. Also, in his celebrated 1906 paper on Brownian motion, he said that he only vaguely knew of (half a century of) observations when he wrote his game-changing theory of diffusion. But Einstein is Einstein!

Coming back to Fig. 2-1, the first item in the list shows an early telescope which Galileo used to stare upwards, toward the big. With the great astronomical discoveries made with this instrument, Galileo contributed to the launch of the scientific method. He was risking his head, but he made minimum accommodations to the "Saint Inquisition", notably by making such astute comments as "the Bible teaches how to go to the heavens, not how the heavens go".

The second item in Fig. 2-1 is the first instrument to stare downwards and inwards, toward the small. It is an early single lens microscope with which van Leeuwenhoek (1632–1723), a Dutch draper and lens maker, first observed cells and many other things of microbiological interest. His invention was a great achievement during the Dutch Golden Age of the seventeenth century. It launched optical microscopy, whose resolution would later turn out to be limited (by diffraction) to a small fraction of one

---

[1] Robert Millikan, National Academy of Sciences of the United States of America Biographical Memoirs, Vol. XIX, Fourth Memoir, p. 134 (1938).
[2] Jeroen van Dongen, Arch. Hist. Exact Sci. (2009) 63:655–663.
DOI: 10.1007/s00407-009-0050-5

micron. Other types of microscopes invented in the twentieth century reached atomic resolution.

The third item is a picture of Otto von Guericke's invention, in the year 1650, of the first vacuum pump. Four years later in Magdeburg, von Guericke organized his celebrated experiment showing that teams of horses were unable to separate two tightly sealed hemispheres from which the air had been evacuated using his vacuum device. Later, vacuum technology evolved into a glorious dynasty of inventions and, in modern times, became widely used in cryogenics. Among many other applications, evacuated glass vessels were essential to create electrical discharges in rarefied gases. This led J. J. Thomson (1856–1940) to a fundamental discovery, that of the electron (1897), which earned him a Nobel prize in Physics (1906) and launched the atomic revolution of the twentieth century. A little later the diode (1904), triode (1906) and other vacuum tubes were essential for electronics and later computers after WWII. These "vacuum valves" survived for over forty years until superseded by the transistor invented in the year 1948. The cathode ray tube (CRT), a vacuum glass tube, also dates back to the early 1900s and led to the invention of television in the 1930s. The CRT was displaced by flat screens only in the 2010s.

The next item in the list of Fig. 2-1 depicts the creation of the pendulum clock (1656) by the Dutch physicist and inventor Christiaan Huygens (1629-1695). The further rapid improvements of his creation led to "sea clocks", accurate to better than one second per day and allowed the measurement of longitude at sea with sufficient accuracy to greatly improve the secure crossing of oceans by ships[3].

The fifth item is the steam engine, invented in the year 1712 by the English engineer Thomas Newcomen (1664–1729) but greatly improved (1777) by the Scottish engineer James Watt (1736–1819)[4]. The steam engine was one of the driving forces of the industrial revolution with all its advances in mechanical machines for work, transportation, etc. The unit of power, the watt (symbol W), bears the name of the great inventor.

Next on our list in Fig. 2-1 is the grating spectroscope. The Bavarian scientist Joseph von Fraunhofer (1787–1826) exploited (1814) the refraction

[3] Dava Sobel, *Longitude*, Harper Collins, London 1995.

[4] https://www.britannica.com/biography/James-Watt

of light by a prism (already used by Newton) or the diffraction/interference (1821) by a ruled grating (already used by the American scientist David Rittenhouse (1732–1796) in 1786 to study the wavelength components of a source of light. von Fraunhofer is credited with the correct interpretation of the dark lines (von Fraunhofer lines) first reported by Wollaston (1766–1828) in the visible solar spectrum, which he attributed to light absorption by different elements in the atmosphere of the sun. Quantitative spectroscopy was born, which would open a new window on the study of light and light interacting with matter, leading to revolutions in physics, chemistry, and astronomy in the nineteenth and twentieth centuries. Simultaneously with his Interferometer work, Michelson also tried his hand at building precision gratings throughout his scientific career, about which he made the remark, not so palatable today: "One comes to regard the machine as having a personality—I had almost said a feminine personality—requiring humoring, coaxing, cajoling, even threatening".

The Interferometer is our central piece which improved the precision of length and wavelength measurements by several orders of magnitude over von Fraunhofer spectroscopes. Millikan, quoted above[5], characterized Michelson as "the coming six-decimal-place physicist". There will be more on this invention in later chapters. As we will emphasize later in the book, merely improving von Fraunhofer's spectroscope was not the only impact of Michelson's creation. His Interferometer led to no less than four "Kuhnian revolutions": discarding the ether, discarding the Newtonian notion of absolute time, helping the creation of quantum mechanics and, more recently, starting new gravitational wave astronomy.

The eighth item in Fig. 2-1 is the development of electrical circuitry for the telegraph, telephones, radio, television, etc. Much of the initial impetus for this development was due particularly to the English electrical engineer and mathematical physicist Oliver Heaviside[6] (1850–1925), who contributed fundamental discoveries in electromagnetic theory in the context of electrical circuitry. One such discovery particularly worth mentioning is the concept of self-induction for time-dependent currents.

---

[5] *Loc. cit.*

[6] Nahin, Paul J. *Oliver Heaviside: The Life, Work, and Times of an Electrical Genius of the Victorian Age*. JHU Press. 9 October 2002. ISBN 978-0-8018-6909-9.

This was the circuit equivalent[7] of Maxwell's general concept of displacement current, which unified electricity and magnetism. This unification is usually attributed solely to Maxwell, but Heaviside deserves to share the glory for achieving that milestone in one branch of the history of physics and engineering— electric circuitry.

Ninth on our list is the development of X-ray tubes shortly after the discovery of X-rays in the year 1895 by the German physicist Wilhelm Roentgen (1845–1943), the very first Nobel prize in Physics (1901). The availability of this controllable source of X-rays created the fields of X-ray radiography as well as the all-important X-ray crystallography for the determination of atomic structures of inorganic and organic matter.

Item ten in Fig. 2-1 is the centrifugation machine for industrial, laboratory or analytical separation of fluid mixtures according to their density. Particularly important was the ultracentrifuge created by the Swedish chemist Theodor Svedberg (1884–1971), Nobel prize for Chemistry (1926). Ever since, the device has been a standard piece of equipment in biological laboratories to separate cell components. It was used[8] for "the most beautiful experiment in biology", which demonstrated the semi-conservative replication of DNA, a milestone in molecular biology[9]. Yet another illustration of the double-edged sword characteristic of great inventions, ultracentrifugation was and is also used to separate the isotopes of nuclides such as uranium isotopes.

Eleventh in our short list is charged particle accelerators such as the cyclotron created in the year 1932 by the American physicist Ernest Lawrence (1901–1958), Nobel prize in Physics (1939). The Cockcroft–Walton linear accelerator was also developed in the year 1932, one of the so-called "wonder years" of physics with the discoveries of the neutron, the positron, and deuterium, all advances crowned by a Nobel prize[10]. The

---

[7] A. Lucas, *Scribbles that changed the course of human affairs,* Mémoire de la Classe des Sciences, Académie Royale de Belgique, Tome XX (2004).

[8] Meselson, M. and Stahl, F.W. *The Replication of DNA in Escherichia coli*, PNAS **44**, 671–82 (1958).

[9] Holmes F.L., Meselson, *Stahl and the replication of DNA*, Yale UP, New Haven (2001).

[10] A. Lucas, *L'Hydrogène, Elément du « Livre Sacré des Sciences et des Techniques »*, Mémoire de la Classe des Sciences, Académie Royale de Belgique, 4ème série, Tome 9, p.85 (2020).

further development of particle accelerators after WWII led to many discoveries in high-energy physics, culminating with the present standard model of elementary particles.

Then came the atomic clocks (item 12, 1949), the present-day instrument for accurate timekeeping[11], and masers and lasers (1953, item 13) of immense impact in all fields of human activity. There will be more on these later.

The last item in our list concerns magnetic resonance devices and machines such as NMR in analytical chemistry and the MRI imaging system, which we will also describe later in the present book.

It is worth noting that the last three items in the list of Fig. 2-1 are direct or indirect consequences of the discoveries made by Michelson with his Interferometer. Indeed, these scientific and technical advances involved the precision knowledge of atomic spectra brought about by the use of Michelson's great invention by Michelson himself or by his successors.

[11] https://qt.eu/discover-quantum/underlying-principles/atomic-clocks/

3. MICHELSON'S INVENTIONS

In this short chapter, I briefly review the principal innovations that Michelson contributed to science.

The speed of light (1879)

In the year 1879, while serving in the US Naval Academy, Michelson undertook research to improve the knowledge of the speed of light V (today noted as c), an exercise at the frontier of physics in the nineteenth century. He used the method of the rotating mirror originally devised by the French physicist Léon Foucault (1819–1868). True to the title of the present book, he stepped into a spinning world right from the start of his research career. The elementary principle of the Foucault method is sketched in Fig. 3-1.

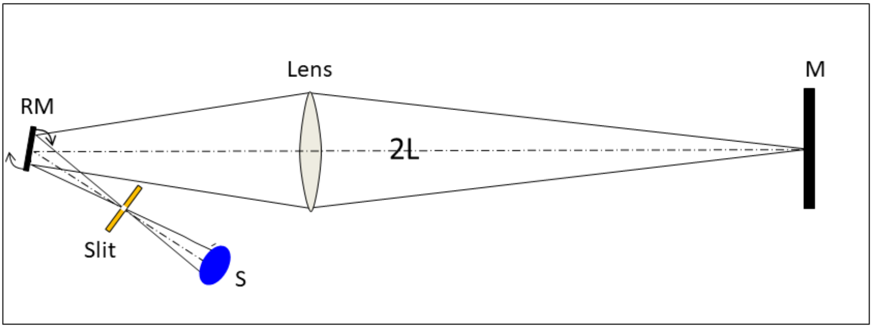

Fig. 3-1. Foucault's rotating mirror method to measure the speed of light, adapted by Michelson. S: light source; RM: rotating mirror; M: mirror; L: distance between RM and M. Redrawn by the author.

Using several crucial improvements on Foucault's design, notably considerably lengthening the light round trip 2L between the stationary and spinning mirrors, Michelson managed to make the method more efficient and obtained a value for V good to four significant figures. A report by

Michelson, with all the technical details, is given in reference[1]. This report shows the extreme care brought to every part of the measurement by young Michelson. The final value he obtained[2] was V = 299,944 ± 51 km/s, a value that remained the best for a generation, until it was improved by Michelson himself.

This was Michelson's first extensive scientific work, and it already bore the mark of "the coming six-decimal-place physicist", an apt characterization used by Millikan.

Later in his life (1929), Michelson made another measurement of V in collaboration with Francis G. Pease and Fred Pearson[3]. They used a 1.6 km tube evacuated to 0.5 mm of mercury to reduce the effect of air on the speed of light. By using multiple reflections, the effective path of the beam was increased to 8 km. Michelson died before this series of measurements was completed. The result, V = 299,774 ± 11 km/s, was published posthumously in the year 1935.

The present-day value for the velocity of light in a vacuum is the fundamental physical constant c = 299,792,458 m/s. This exact number, one of the present-day fixed constants of the SI system of units, was adopted by the Fifteenth *General Conference on Weights and Measures* in 1986. This brought to an end the measurement of this fundamental property of nature.

High-resolution atomic spectra (1887)

During a trip of extensive study in Europe in the 1880s, Michelson conceived the fundamental principle of his Interferometer. As will be explained in later chapters, with this instrument Michelson made a first attempt at determining the effect of ether drift on V. He wanted to demonstrate that the velocity V depended on the direction of motion of the earth traveling through the hypothetical ether. This attempt, conducted in Leipzig with his first Interferometer, failed to detect any ether drift effect.

---

[1] https://www.gutenberg.org/files/11753/11753-h/11753-h.htm#ch02

[2] *Ibid.*

[3] A. A. Michelson, F. G. Pease and F. Pearson, *Measurement of the velocity of light in a partial vacuum,* Contribution from the Mount Wilson Observatory **522**, (2091): 100-1 (1935).

The Michelson–Morley experiment (1887)

Michelson is remembered primarily for this application of his Interferometer, which was a second, improved attempt at measuring ether drift, this time with the collaboration of Edward Morley. Chap. 5 will be devoted to explaining the experiment. After the disappointment of the null result of this second attempt, Michelson turned to investigating atomic spectra.

Late in the 1880s (1887), Michelson used his instrument to measure, with high precision, what would be called the fine and hyperfine structures of atomic spectral lines. He could measure even finer features of atomic lines, such as their further shift and splitting in a magnetic field, an effect first investigated (1886) by the Dutch physicist Pieter Zeeman (1865–1943), who received the second Nobel prize awarded in physics with Hendrik Lorentz in 1902, after that of Wilhelm Roentgen in 1901.

The echelon spectrometer (1899)

The echelon spectrometer is a special kind of diffraction grating conceived by Michelson. It has resolving power vastly superior to mechanically ruled gratings. Fig. 3-2, redrawn from the original Michelson[4] proposal, illustrates the ingenious staircase construction with stacked plates of optical glass of uniform thickness and its use in reflection or transmission[5].

[4] A.A. Michelson, *The Echelon Spectroscope,* Proceedings of the American Academy of Arts and Sciences, Vol. **35**, No. 7, pp. 111–119 (1899).

[5] See other original descriptions in C. Riborg Mann, *The Echelon Spectroscope*, Science, VOL. VIII., No. 190; p. 208 (1898); and Charles P. Butler, *The Michelson echelon spectroscope*, Nature VOL. **59**, N° I539, p. 607 (1899).

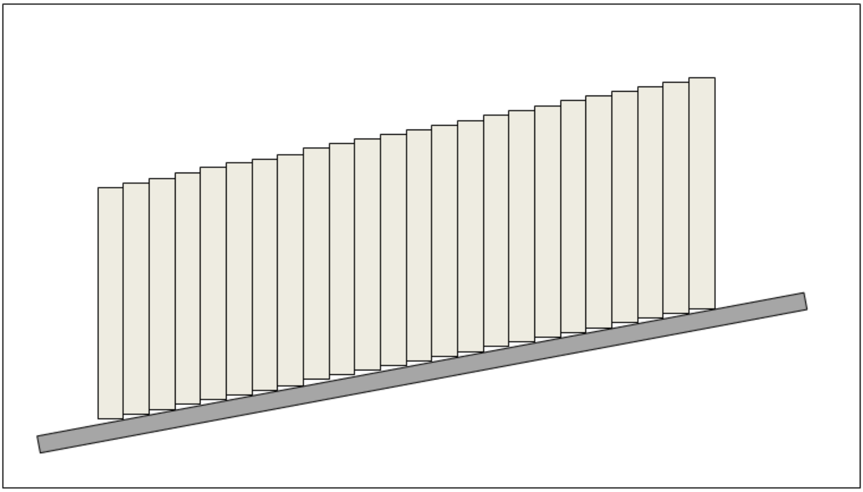

Fig. 3-2. Michelson's echelon grating realized by stacking vertical glass plates on an inclined plane.

This is the sort of imaginative invention about which every physicist contemporary to Michelson must have thought, "why did I not think of this myself?" Depending on the number of plates and their thickness, the resolution could be sufficient to resolve spectral structures 500 to 1000 times finer than the distance between the D1 and D2 doublet of the sodium D line, which amounts to about 0.6 nm. The mathematical theory of the echelon was developed in Michelson's original paper[4]. Using this new instrument, Michelson was able to study the Zeeman effect and the pressure broadening of spectral lines. Michelson's echelon, or its implementations developed later under the generic name "echelle spectrometer", is standard equipment in astronomical observatories for studies of star spectra. Reference[6] gives examples.

[6] Steven S. Vogt, Publications of the Astronomical Society of the Pacific, Volume 99, Number 621 (1987): https://iopscience.iop.org/journal/1538-3873. See also Daniel J. Schroeder: https://iopscience.iop.org/article/10.1086/129030/pdf

Stellar interferometer (1920)

The principle of the stellar interferometer conceived by Michelson[7] for visible starlight is sketched in Fig. 3-3.

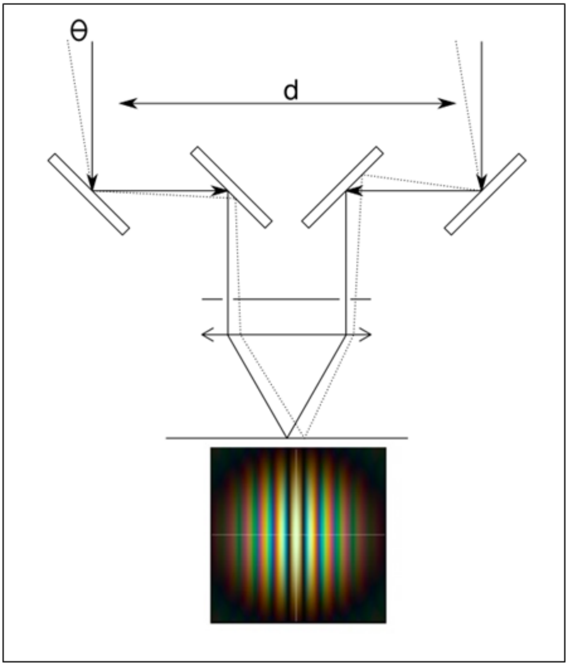

Fig. 3-3. Michelson stellar interferometer showing white-light interference pattern from a star with angular extent θ of 1 arcsecond.

Technical details and a theory of the instrument were given by Michelson and Pease[7]. The (angular) diameter of Sirius A (α Canis Majoris), the brightest star in the sky, was measured to be 62 milliarcseconds (corresponding to a radius of 1.7 $R_\odot$ in units of the solar radius $R_\odot$). Sirius A is a main sequence white star 8,611 light years from earth, with a companion, Sirius B, a white dwarf unknown to Michelson. The diameter

[7] A.A. Michelson and F.G. Pease, *Measurement of the diameter of a-Orionis, Astrophysical* Journal **5I**, 257-263 (*1920)*.

of Betelgeuse (α Orionis, variable red supergiant[8], distance 642.5 light years) was 50 milliarcseconds (radius 887 $R_\odot$). Since Michelson's invention, stellar interferometry across all of the electromagnetic spectrum has grown into a major observational tool in astronomical centers of the world.

Michelson–Gale–Pearson interferometer (1925)

In the year 1904, Michelson devised a rectangular ring interferometer[9] in order to test whether the earth's rotation had any effect on the velocity of light. This was a modified version of his cross-arm Interferometer and a precursor of the ring interferometer (1913) constructed by Georges Sagnac (1869–1928) to verify the so-called Sagnac effect. This effect had been predicted theoretically in 1911 by Max von Laue, who is better known for his discovery, in 1912, of X-ray diffraction (1914 Nobel prize in Physics). Only in 1925 did Michelson, in collaboration with Henry G. Gale and assisted by F. Pearson, construct a rectangular ring interferometer. The result of the Michelson–Gale–Pearson (MGP) experiment was consistent with Einstein's theory of relativity. The MGP and Sagnac interferometers started the very active field of ring interferometry (see Chap. 4).

[8] Taniguchi, D., Yamazaki, K. & Uno, S. *The Great Dimming of Betelgeuse seen by the Himawari-8 meteorological satellite*. *Nat Astron* (2022). DOI: https://doi.org/10.1038/s41550-022-01680-5

[9] A. A. Michelson, *Relative Motion of Earth and Aether,* Philosophical Magazine **8** (48), 716–719 (1904).