Physics of the XIXth century
part 1

From Volta's pile to electromagnetism

Three centuries of the history of electromagnetism

Gilbert

„electrics”
„versorium”

Guericke

electrostatic machine

Musschenbroek

Leyden jar

Coulomb

electromagnetism

Oersted

Maxwell

1600

1700

1800

1900

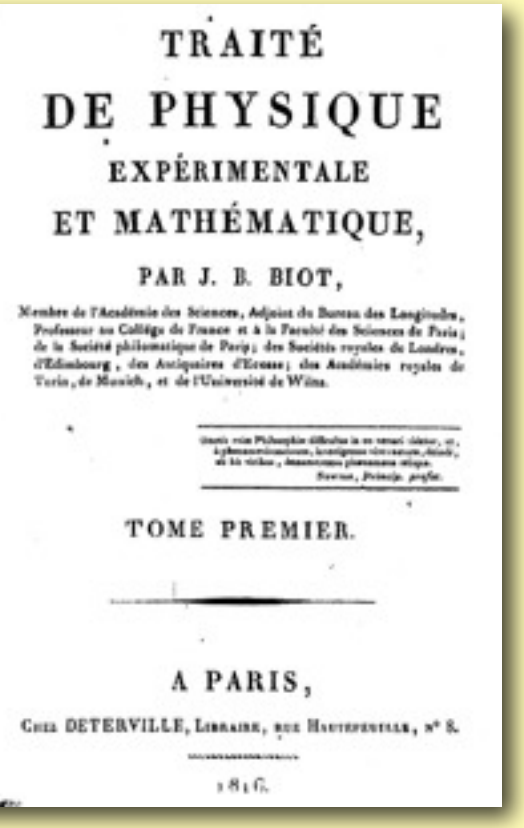
Volta

Faraday

electrostatic machines

batteries

generators



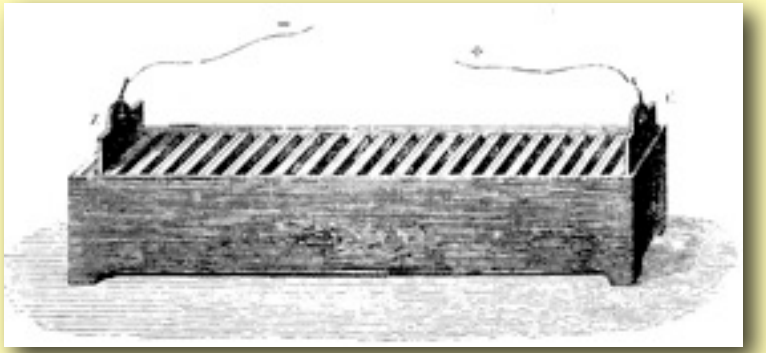
TRAITÉ
DE PHYSIQUE
EXPÉRIMENTALE
ET MATHÉMATIQUE,
PAR J. B. BIOT,
Membre de l'Académie des Sciences, Adjoint du Bureau des Longitudes, Professeur au Collége de France et à la Faculté des Sciences de Paris; de la Société philomatique de Paris; des Sociétés royales de Londres, d'Edimbourg, des Antiquaires d'Ecosse; des Académies royales de Turin, de Munich, et de l'Université de Wilna.
TOME PREMIER.
A PARIS,
Chez DETERVILLE, Libraire, rue Hautefeuille, n° 8.
1816.

Jean Baptiste Biot: ***Traité de physique expérimentale et mathématique***

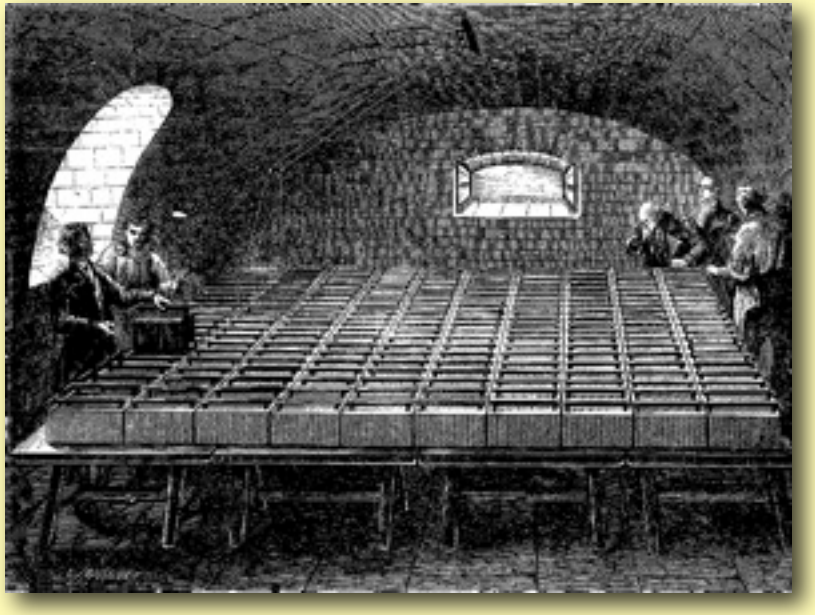
Four volumes: almost 2400 pages, seven books

1) General phenomena, measuring devices (22%)
2) Acoustics (9%)
3) Electricity (15%)
4) Magnetism (6%)
5) Light and 6) Polarization of light, (42%)
7) Caloric, radiant and latent (6%)

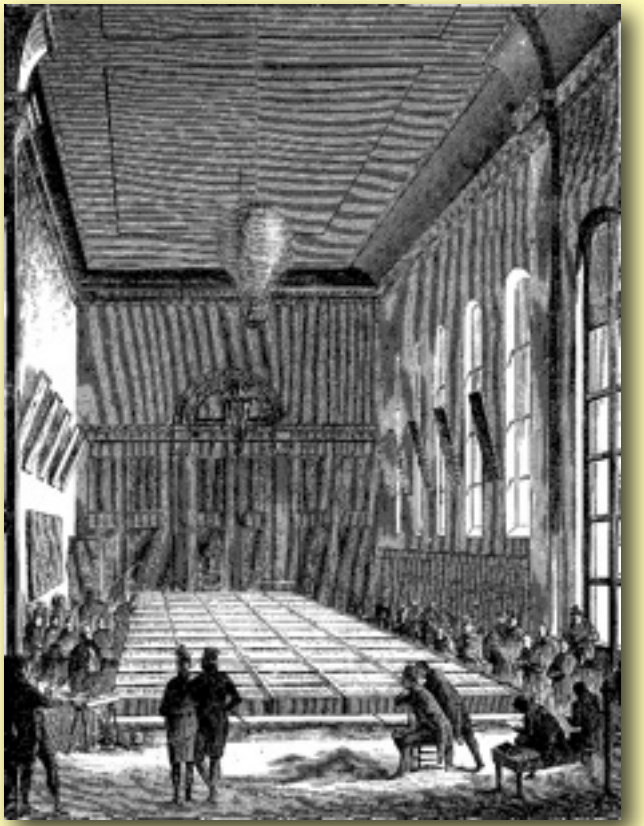
Physics should be limited to ”studying the phenomena produced by the actions of invisible, intangible, and imponderable principles such as electricity, magnetism, caloric, and light.”



A trough pile
(William Cruickshank)



Great pile of the Royal Society



Great pile at École Polytechnique

”It must be confessed that the whole science of electricity is yet in a very imperfect state: we know little or nothing of the intimate nature of substances and actions concerned in it, and we can never foresee, without previous experiment, where or how it will be excited. We are wholly ignorant of the constitution of bodies, by which they become posessed of different conducting powers; and we have only been able to draw some general conclusions respecting the distribution and equilibrium of the supposed electric fluid, from the laws of the attractions and repulsions that it appears to exert. There seems to be some reason to suspect, from the phenomena of cohesion and repulsion, that the pressure of an elastic medium is concerned in the origin of these forces; and if such a medium really exists, it is perhaps nearly related to the electric fluid. The identity of the general causes of electrical and of galvanic effects is now doubted by few; and in this country the principal phenomena of galvanism are universally considered as depending on chemical changes.”

Thomas Young, *A Course of Lectures on Natural Philosophy* (1807)

”Although it may be somewhat hazardous to form predictions respecting the progress of science, I may remark, that the impulse which was given in the first instance, by Galvani’s original experiments, was revived by Volta’s discovery of the pile, and was carried to the highest pitch by Sir H. Davy’s application of it to chemical decomposition, seems to have in a great measure, subsided. It may be conjectured that we have carried the power of the instrument to the utmost extent of which it admits, and it does not appear that we are at present in the way of making any important additions to our knowledge of its effects, or of obtaining any new light on the theory of its action.”

John Bostock, *An Account of the History and Present State of Galvanism* (1818)

The first theoretical approach to electrical phenomena

”The theory of electricity which is most generally accepted is that which attributes the phenomena to two different fluids, which are contained in all material bodies. It is supposed that the molecules of the same fluid repel each other and attract the molecules of the other fluid; these forces of attraction and repulsion obey the law of the inverse square of the distance; and at the same distance the attractive power is equal to the repulsive power; whence it follows that, when all the parts of a body contain equal quantities of the two fluids, the latter do not exert any influence on the fluids contained in the neighbouring bodies, and consequently no electrical effects are discernible.”

Siméon Poisson, *Mémoire sur la distribution de la l’electricite à la surface des corps conducteurs* (1811)

Hans Christian Oersted (1777-1851)

André Marie Ampère (1775-1836)

Jean-Baptiste Biot (1774-1862)

Georg Simon Ohm (1789-1854)

Michael Faraday (1791-1867)

Joseph Henry (1797-1878)

Simeon Denis Poisson (1781-1840)

Carl Friedrich Gauss (1777-1855)

Wilhelm Eduard Weber (1804-1891)

Franz Ernst Neumann (1798-1895)

The discovery of electromagnetism (1820)

EXPERIMENTA

CIRCA EFFECTUM

CONFLICTUS ELECTRICI IN ACUM MAGNETICAM.

Prima experimenta circa rem, quam illustrare aggredior, in scholis de Electricitate, Galvanismo et Magnetismo proxime-superiori hieme a me habitis instituta sunt. His experimentis monstrari videbatur, acum magneticam ope apparatus galvanici e situ moveri; idque circulo galvanico cluso, non aperto, ut frustra tentaverunt aliquot abhinc annis physici quidam celeberrimi. Cum autem hæc experimenta apparatu minus efficaci instituta essent, ideoque phænomena edita pro rei gravitate non satis luculenta viderentur, socium adscivi amicum Esmarch, regi a consiliis justitiæ, ut experimenta cum magno apparatu galvanico, a nobis conjunctim instructo, repeterentur et augerentur. Etiam vir egregius Wleugel, eques auratus ord. Dan. et apud nos præfectus rei gubernatoriæ, experimentis interfuit, nobis socius et testis. Preterea testes fuerunt horum experimentorum vir excellentissimus et a rege summis honoribus decoratus *Hauch*, cujus in rebus naturalibus scientia jam diu inclaruit, vir acutissimus Reinhardt, Historiæ naturalis Professor, vir in experimentis instituendis sagacissimus Jacobsen, Medicinæ Professor, et Chemicus experientissimus Zeise, Philosophiæ Doctor. Sæpius equidem solus experimenta circa materiam propositam institui, quæ autem ita mihi contigit detegere phænomena, in conventu horum virorum doctissimorum repetivi.

In experimentis recensendis omnia præteribo, quæ ad rationem rei invenienda quidem conduxerunt, hæc autem inventa rem amplius illustrare nequeunt; tum ea igitur, quæ rei rationem perspicue demonstrant, acquiescamus.

Apparatus galvanicus, quo usus summus, constat viginti receptaculis cupreis rectangularibus, quorum et longitudo et altitudo duodecim æqualiter est pollicum, latitudo autem duos pollices et dimidium vix excedit. Quodvis receptaculum duabus laminis cupreis instructum est ita inclinatis, ut baculum cupreum, qui laminam zinceam in aqua receptaculi proximi sustentat, portare possint. Aqua receptaculorum $\frac{1}{12}$ sui ponderis acidi sulphurici et pariter $\frac{1}{12}$ acidi nitrici continet. Pars cujusque laminæ Zinceæ in aqua submersa Qvadratum est, cujus latus circiter longitudinem 10 pollicum habet. Etiam apparatus minores adhiberi possunt, si modo filum metallicum candefacere valeant.

Hans Christian Oersted
(1777-1851)

”The first experiments respecting the subject which I mean at present to explain, were made by me last winter, while lecturing on electricity, galvanism, and magnetism, in the University. It seemed demonstrated by these experiments that the magnetic needle was moved from its position by the galvanic apparatus, but that the galvanic circle must be complete, and not open, which last method was tried in vain some years ago by very celebrated physicists. But as these experiments were made with a feeble apparatus, and were not, therefore, sufficiently conclusive, considering the importance of the subject, I associated myself with my friend Esmarck to repeat and extend them by means of a very powerful battery, provided by us in common. Mr. Wleugel, a Knight of the Order of Danneborg, and the head of the Pilots, was present at, and assisted in, the experiments.”

Oersted, *Experimenta circa effectum conflictus electrici...,* 21 July, 1820 (English translation from *Annals of Philosophy,* 1820)

”There were present likewise Mr. Hauch, a man very skilled in the Natural Sciences, Mr. Reinhardt, Professor of Natural History, Mr. Jacobson, Professor of Medicine, and that very skilled chemist, Mr. Zeise, Doctor of Philosophy. I had often made experiment by myself, but every fact which I had observed was repeated in the presence of these gentlemen.
The galvanic apparatus which we employed consists of 20 copper troughs, the length and height of which was 12 inches; but the breadth scarcely exceeded $2^1/_2$ inches. Every trough is supplied with two plates of copper so bent that they could carry a copper rod, which supports the zinc plate in the water of the next trough. The water of the troughs contained 1/60 of its weight of sulphuric acid, and an equal amount of nitric acid...”

Oersted, *Experimenta circa effectum conflictus electrici...*

History of electromagnetism as presented by Oersted himself in an article written for the *Edinburgh Encyclopedia* (1830):

”Electromagnetism itself was discovered in the year 1820, by Professor Hans Christian Oersted, of the university of Copenhagen.
In the winter of 1819-20, he delivered a course of lectures upon electricity, galvanism, and magnetism, before an audience that had been previously acquainted with the principles of natural philosophy. In composing the lecture, in which he was to treat of the analogy between magnetism and electricity, he conjectured, that if it were possible to produce any magnetical effect by electricity, this could not be in the direction of the current, since this had been so often tried in vain, but that it must be produced by a lateral action.”

History of electromagnetism as presented by Oersted himself in an article written for the *Edinburgh Encyclopedia* (1830):

”This was strictly connected with his other ideas; for he did not consider the transmission of electricity through a conductor as an uniform stream, but as a succession of interruptions and re-establishments of equilibrium, in such a manner that the electrical powers in the current were not in quiet equilibrium, but in a state of continual conflict. As the luminous and heating effect of the electrical current goes out in all directions from a conductor, which transmits a great quantity of electricity; so he thought it possible that the magnetical effect could likewise eradiate…”

History of electromagnetism as presented by Oersted himself in an article written for the *Edinburgh Encyclopedia* (1830):

”He was nevertheless far from expecting a great magnetical effect of the galvanical pile; and still he supposed that a power, sufficient to make the conducting wire glowing, might be required. The plan of the first experiment was, to make the current of a little galvanic trough apparatus, commonly used in his lectures, pass through a very thin platina wire, which was placed over a compass covered with glass. The preparations for the experiments were made, but some accident having hindered him from trying it before the lecture, he intended to defer it to another opportunity; yet during the lecture, the probability of its success appeared stronger, so that he made the first experiment in the presence of the audience. The magnetical needle, though included in a box, was disturbed; but as the effect was very feeble, and must, before its law was discovered, seem very irregular, the experiment made no strong impression on the audience.”

History of electromagnetism as presented by Oersted himself in an article written for the *Edinburgh Encyclopedia* (1830):

”It may appear strange, that the discoverer made no further experiments upon the subject during three months; he himself finds it difficult enough to conceive it; but the extreme feebleness and seeming confusion of the phenomena in the first experiment, the remembrance of the numerous errors committed upon this subject by earlier philosophers, and particularly by his friend Ritter, the claim such a matter has to be treated with earnest attention, may have determined him to delay his researches to a more convenient time. . ”

History of electromagnetism as presented by Oersted himself in an article written for the *Edinburgh Encyclopedia* (1830):

”In the month of July 1820, he again resumed the experiment, making use of a much more considerable galvanical apparatus. The success was now evident, yet the effects were still feeble in the first repetitions of the experiment, because he employed only very thin wires, supposing that the magnetical effect would not take place, when heat and light were not produced by the galvanical current; but he soon found that conductors of a greater diameter give much more effect; and he then discovered, by continued experiments during a few days, the fundamental law of electromagnetism, viz. that the magnetical effect of the electrical current has a circular motion round it...”

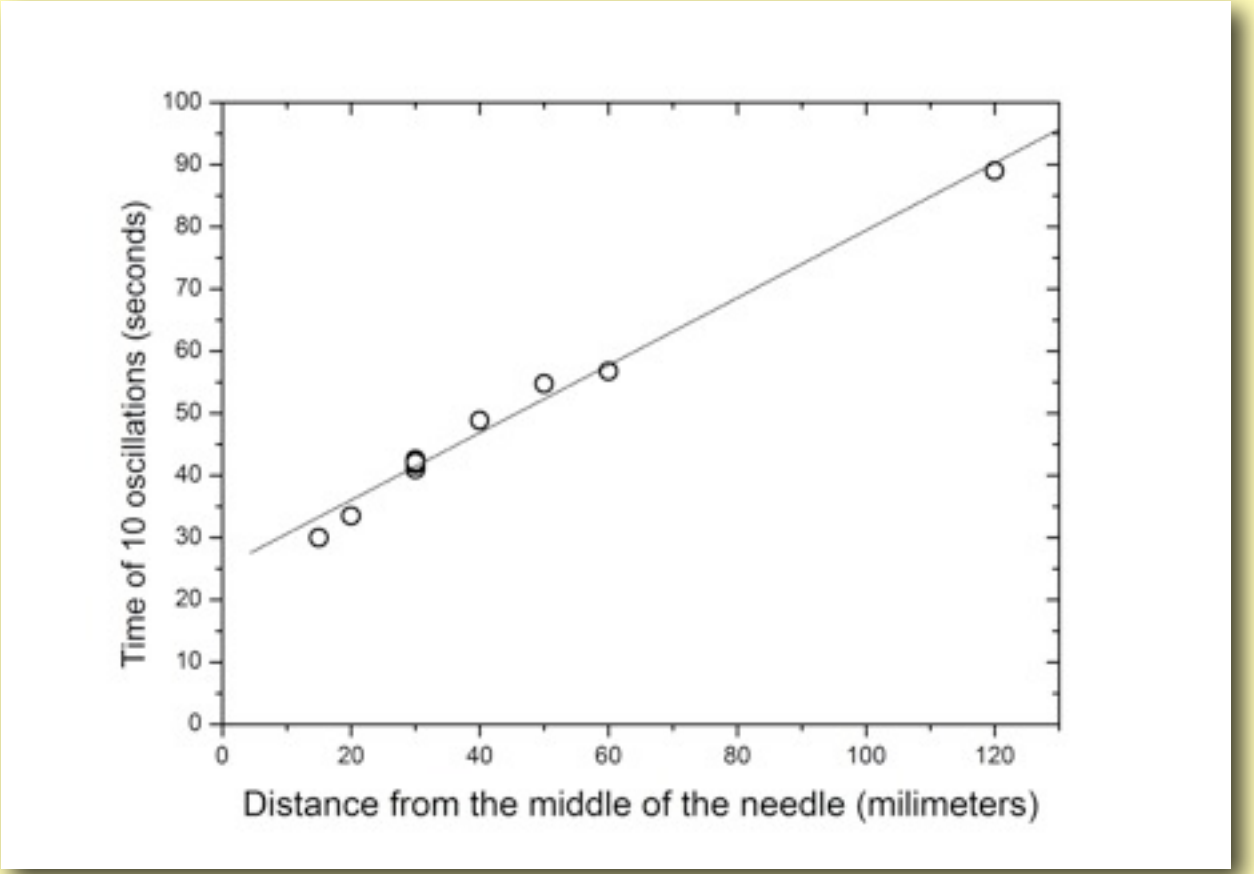
1820 - *annus mirabilis*

21 July	Oersted announced his discovery
4 September	Arago reported it to the Academié des Sciences
11 September	Arago repeated Oersted's experiments
18 September	Ampère's first report
25 September	Ampère's second report

(there were nine more reports by Ampère on consecutive Mondays)

30 October	Biot and Savart reported their results
6 September	in Halle Johann Schweigger reported on his multiplicator

Arago (in Paris), Davy (in London) reported that iron rods inside current carrying coils became magnetised



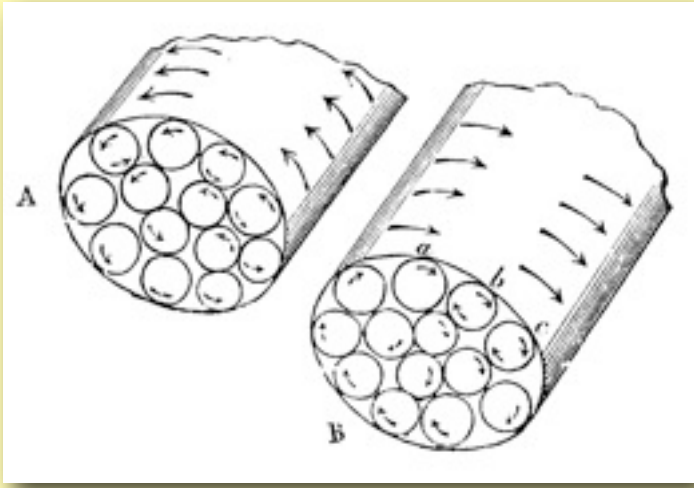
Experimental data which led Biot and Savart to formulate their law

Ampère's notes (September 18, 1820)

"I reduced the phenomena observed by Oersted to two general facts. I demonstrated that the current in the pile acts on the magnetic needle in the same way as the current in the conductor joining the poles. I described experiments in which I discovered attraction or repulsion of the needle by this conductor. I described the instruments which I planned to construct, including the galvanic coils. I announced that such coiled current carrying conductors should act in the same manner as magnets. I also gave details of my understanding of magnets: their actions are caused solely by the electric currents perpendicular to their axes; I assume existence of similar currents inside the earth globe, i.e. I reduce all magnetic manifestations to purely electric phenomena".

Ampère’s notes (25 September, 1820)

”I developed this theory and announced a new fact of attraction or repulsion between two electric currents without mediation of any magnet, and also the new properties of coiled conductors. I repeated these experiments during the meeting”.



Ampère in a letter to his son Jean-Jacques
(in the evening of September 25, 1820):

”Every moment has been taken by an event important in my life. From the very moment I have heard for the first time of the beautiful discovery of M. Oersted at Copenhagen concerning the action of a current on the magnetic needle, I have continuously thought about it. I have written a great theory of these phenomena and of all the others known for magnets and tried the experiments indicated by this theory. All have succeeded and have revealed to me new facts. I read the beginning of the Memoir last Monday. In the following days I performed confirmatory experiments some time with Fresnel, some time with Despretz. I repeated them all on Friday at Poisson’s house...”

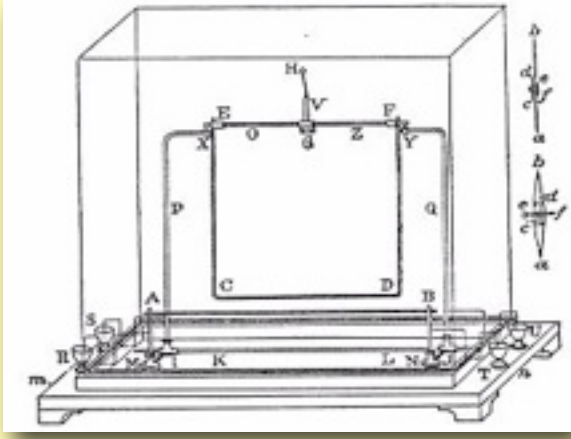
Ampère's letter (cont.)

”Everything succeeded marvellously, but the decisive experiment that I have thought as final proof demanded two galvanic piles. When I tried it in my house with Fresnel with piles that were too weak, it did not succeed. Yesterday I obtained permission from Dulong for Dumorier to sell me the great pile that was under the construction for the Physics course at the Faculty and the experiment has been done at the house of Dumorier with full success and repeated today at 4 o'clock at the séance of the Institute. No objections were raised this time and here we have a new theory of the magnet that reduces all its manifestations to electric currents. This does not agree with all the previous opinions. Tomorrow I shall explain this theory to M. Humboldt, and day after that to M. Laplace...”

André Marie Ampère (1820)

”Electromotive action is manifested by two sorts of effects which I believe I should first distinguish by precise definitions. I shall call the first one *electric tension,* the second *electric current*.
The first is observed when two bodies, between which this action occurs, are separated from each other by non-conducting bodies at all the points of their surfaces except those where it is established; the second occurs when the bodies make a part of a circuit of conducting bodies, which are in contact at points on their surface different from those at which the electromotive action is produced...
In the second case there is no longer any electric tension, light bodies are not sensibly attracted and the ordinary electrometer can no longer be of service to indicate what is going on in the body; nevertheless the electromotive action continues...”

André Marie Ampère



”Considering various attractions and repulsions in nature I assumed that the force of which I seek an expression is also inversely proportional to the distance. For generality I postulated that this force is inversely proportional to the distance in power *n*, which was to be determined. Denoting by ρ an unknown function of angles θ, θ‘ I had $\rho II'\mathrm{d}s\mathrm{d}s'/r^n$ as a general expression for the force of interaction of two elements d*s*, d*s*’ of two currents of intensities *I* and *I*’.”

If θ and θ‘ are the angles between *r* and the elements d*s* and d*s*’, and ε is the angle between elements d*s* and d*s*’, then according to Ampère:

$$F = \frac{II'\mathrm{d}s\,\mathrm{d}s'}{2r^2}(2\cos\varepsilon - 3\cos\theta\cos\theta')$$

James Clerk Maxwell on Ampère

”The experimental investigations by which Ampère established the laws of the mechanical action between electric currents is one of the most brilliant achievements in science. The whole theory and experiment seems as if it had leaped, full grown and full armed, from the brain of the ‘Newton of electricity’. It is perfect in form and unassailable in accuracy, and it is summed up in a formula from which all the phenomena may be deduced, and which must always remain the cardinal formula of electrodynamics.”

(*Treatise on Electricity and Magnetism*, part IV)

Numerous unsuccessful searches of electric current produced by magnetism; the searches were made of a **static** effect !

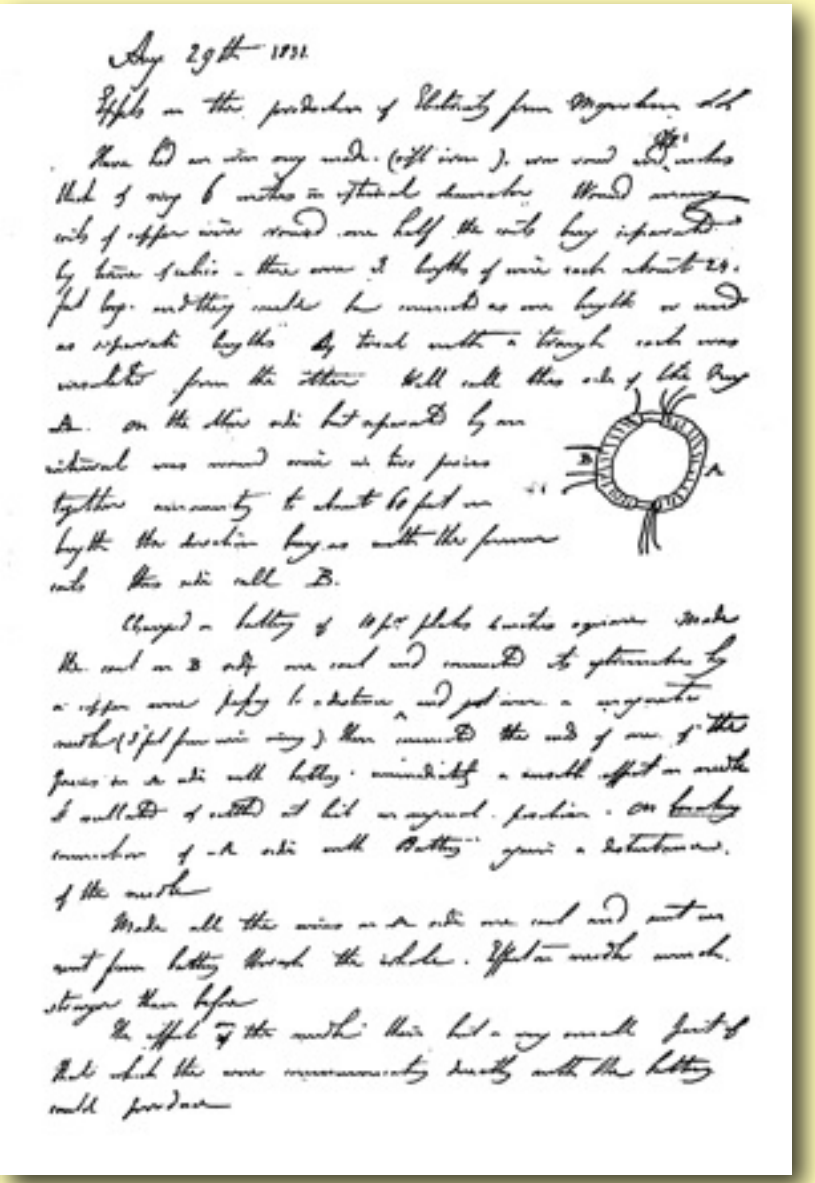
1822	Ampère's and de la Rive experiments - erroneous interpretation of observed electromagnetic induction effect
1824	Arago experiment: quick damping of oscillations of a magnetic needle in a metal box
1825	Arago experiment: magnetic needle dragged by a rotating metal plate
1825	Unsuccessful experiments by Colladon
1824-1829	Unsuccessful experiments by Faraday

1831 August 29, Discovery of electromagnetic induction

Michael Faraday

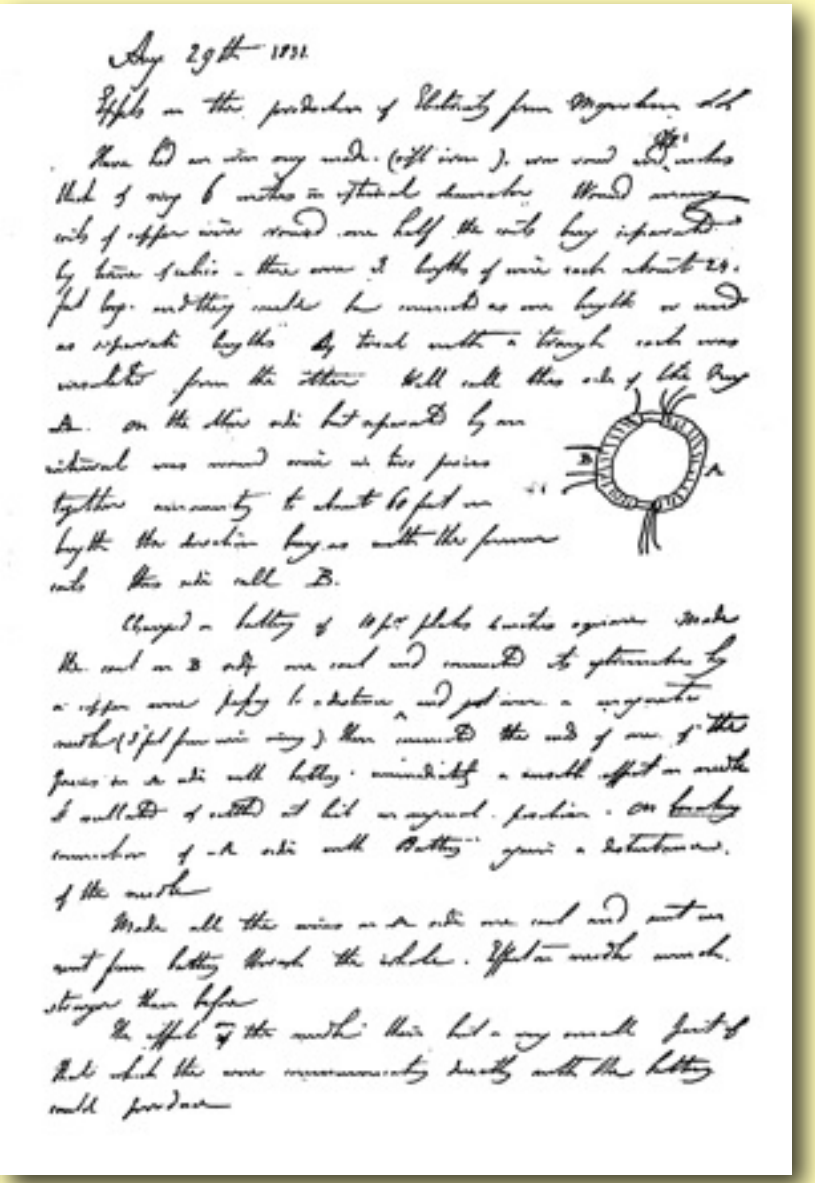
22 IX	1791	Born in London
1 III	1813	Laboratory assistant in the Royal Institution
IX	1821	Discovered ”magnetic rotation”
III	1823	Liquefaction of chlorine
II	1825	Director of the Royal Institution
V	1825	Discovered benzene
29 VIII	1831	Discovered electromagnetic induction
	1832	Proved the identity of five kinds of electricity
1832-1834		The laws of electrolysis
	1836	”Faraday’s cage”
from	1837	Studies of dielectrics
1845-1855		The concept of the electromagnetic field
13 IX	1845	Discovered the magnetooptic effect
4 XI	1845	Discovered diamagnetism and paramagnetism
25 VIII	1867	Died in London

Faraday's discovery of electromagnetic induction



"August 29, 1831
Expts. on the production of Electricity from Magnetism, etc.
Have had an iron ring made (soft iron), iron round and 7/8 inch thick and ring 6 inches in external diameter. Wound many coils of copper wire round one half, the coils being separated by twine and calico - there were three lengths of wire each about 24 feet long and they could be connected as one length or used as separate lengths. By trial with a trough each was insulated from the other. Will call this side of the ring A. On the other side but separated by an interval was wound wire in two pieces together amounting to about 60 feet in length, the direction being as with the former coils; this side call B."

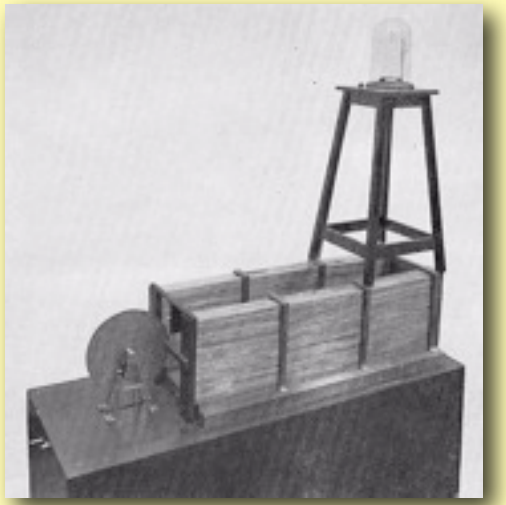
Faraday's discovery of electromagnetic induction



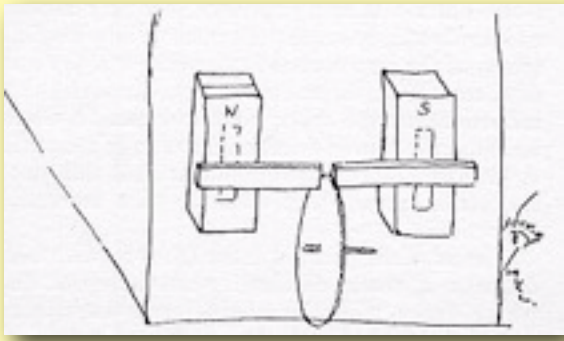
"Charged a battery of 10 pr. plates 4 inches square. Made the coil on B side one coil and connected its extremities by a copper wire passing to a distance and just over a magnetic needle (3 feet from iron ring). Then connected the ends of one of the pieces on A side with battery; immediately a sensible effect on needle. It oscillated and settled at last in original position, On breaking connection of A side with Battery again a disturbance of the needle.
Made all the wires on A side one coil and sent current from battery through the whole. Effect on needle much stronger than before."

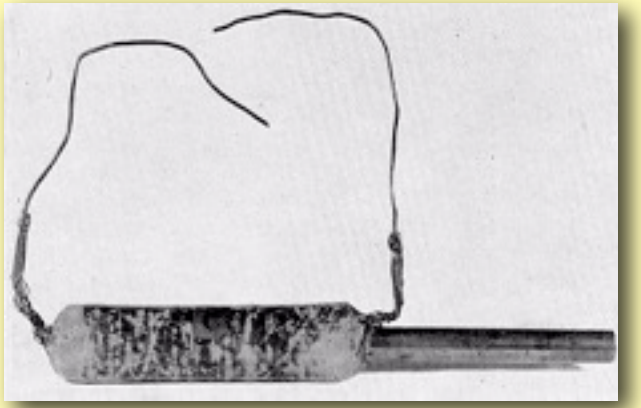
Experiments of Michael Faraday

The coil used on August 29, 1831

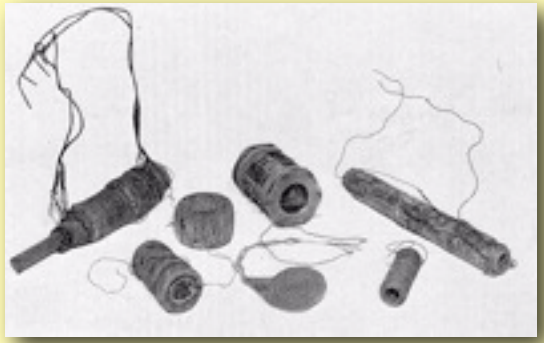


Experiment of October 28, 1831 (sketch)

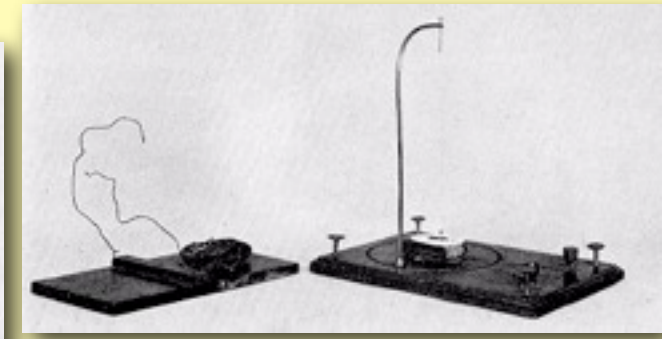




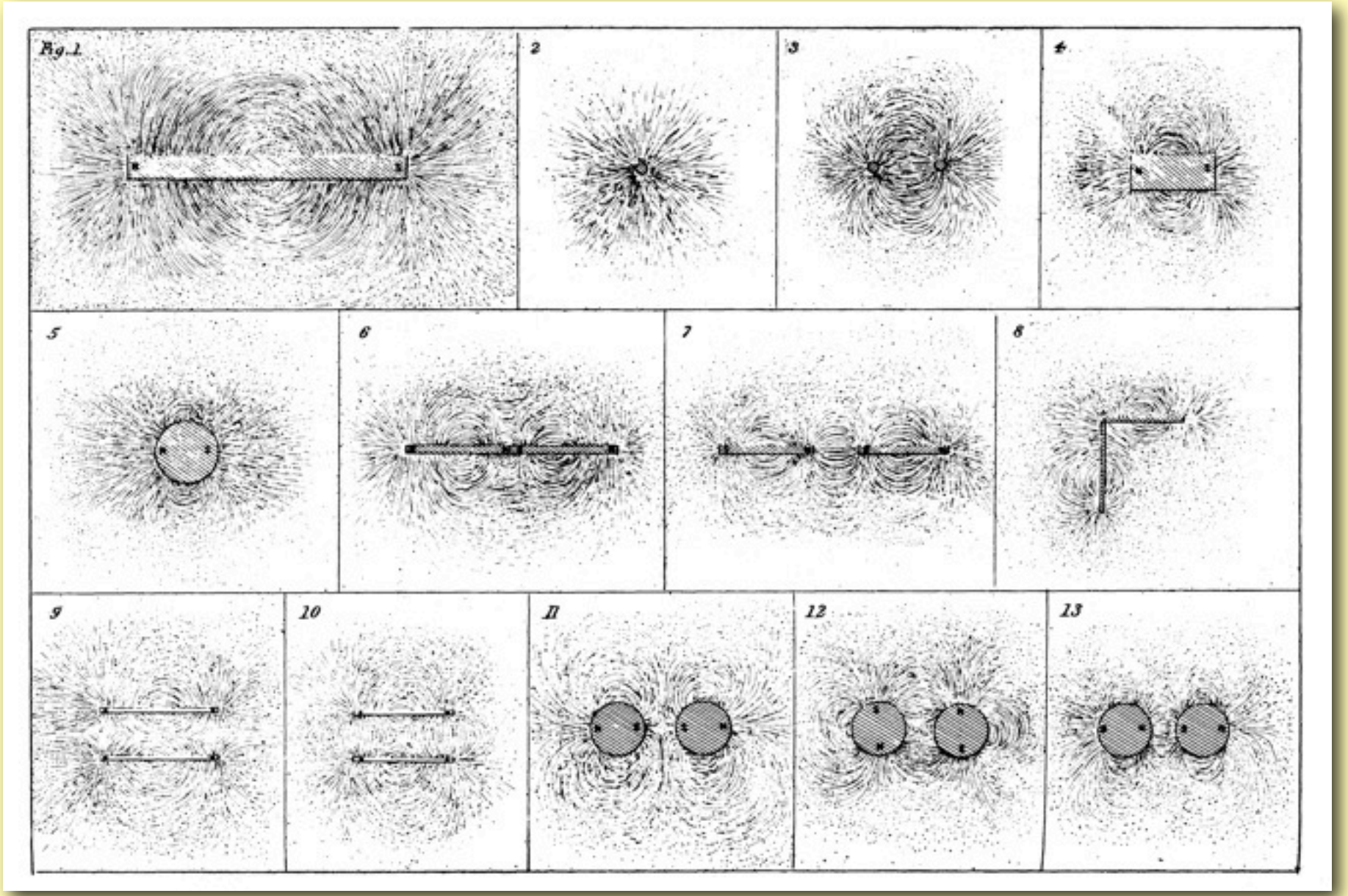
The coil used on October 17, 1831



Faraday's coils

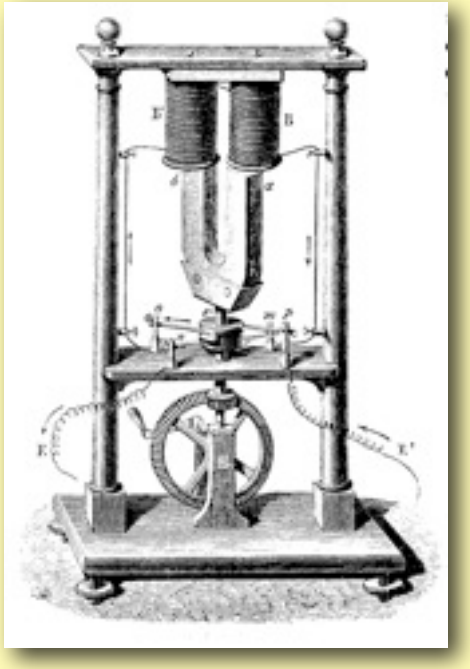


Faraday's galvanometers

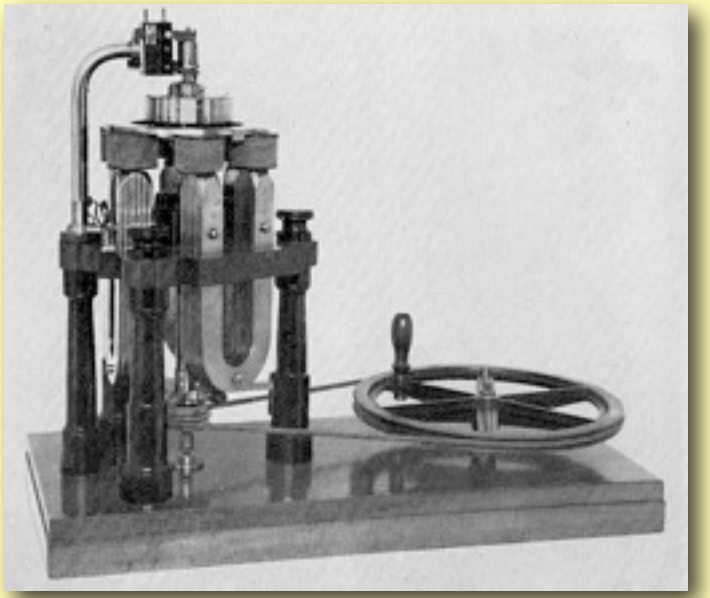


Lines of the magnetic field in Faraday's experiments

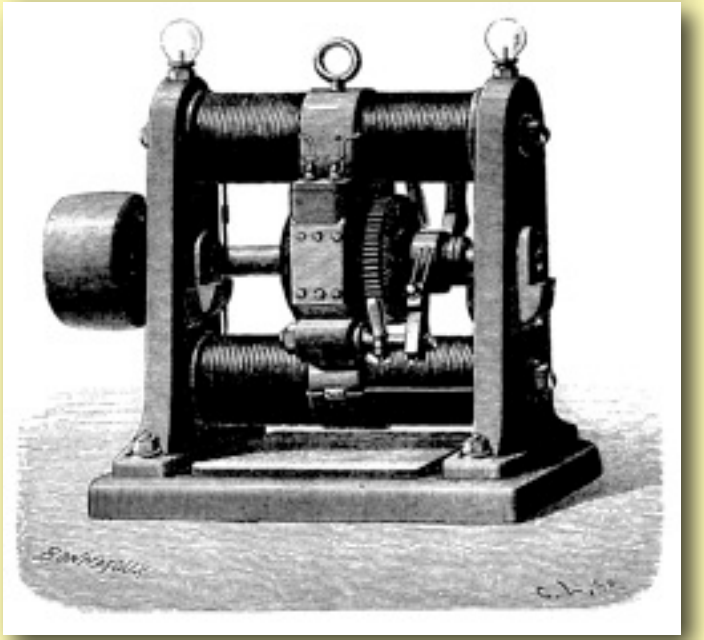
First machines converting mechanical into electrical energy



Magneto Electric Machine
of Hypolyte Pixii (1832)



1843



1876

Maxwell on Faraday's method

”The method which Faraday employed in his researches consisted in a constant appeal to experiment as a means of testing the truth of his ideas, and a constant cultivation of ideas under the direct influence of experiment. In his published researches we find these ideas expressed in language which is all the better fitted for a nascent science, because it is somewhat alien from the style of physicists who have been accustomed to established mathematical forms of thought.”

Treatise on Electricity and Magnetism, part 4

Maxwell on Faraday's method

”It was perhaps for the advantage of science that Faraday, though thoroughly conscious of the fundamental forms of space, time, and force, was not a professed mathematician. He was not tempted to enter into the many interesting researches in pure mathematics which his discoveries would have suggested if they had been exhibited in a mathematical form, and he did not feel called upon either to force his results into a shape acceptable to the mathematical taste of the time, or to express them in a form which mathematicians might attack. He was thus left at leisure to do his proper work, to coordinate his ideas with his facts, and to express them in natural, untechnical language.”

Discovery of self-induction

”I may however mention one fact which I have not seen noticed in any work, and which appears to me to belong to the same class of phenomena as those before described; it is this: when a small battery is moderately excited by a diluted acid, and its poles, which should be terminated by cups of mercury, are connected by a copper wire not more than a foot in length, no spark is perceived when the connection is either formed or broken; but if a wire thirty or forty feet long be used instead of the short wire, though no spark will be perceptible when the connection is made, yet when it is broken by drawing one end of the wire from its cup of mercury, a vivid spark is produced. If the action of the battery be very intense, a spark will be given by the short wire;

...The effect appears somewhat increased by coiling the wire into a helix; it seems also to depend in some measure on the length and thickness of the wire. I can account for these phenomena only by supposing the long wire to become charged with electricity, which by its reaction on itself projects a spark when the connection is broken...”

Joseph Henry, *American Journal of Science and Arts* (1832)

Experiments by Ohm (1825)

Wires of equal diameter and different length

Standard wire: Reading *s*

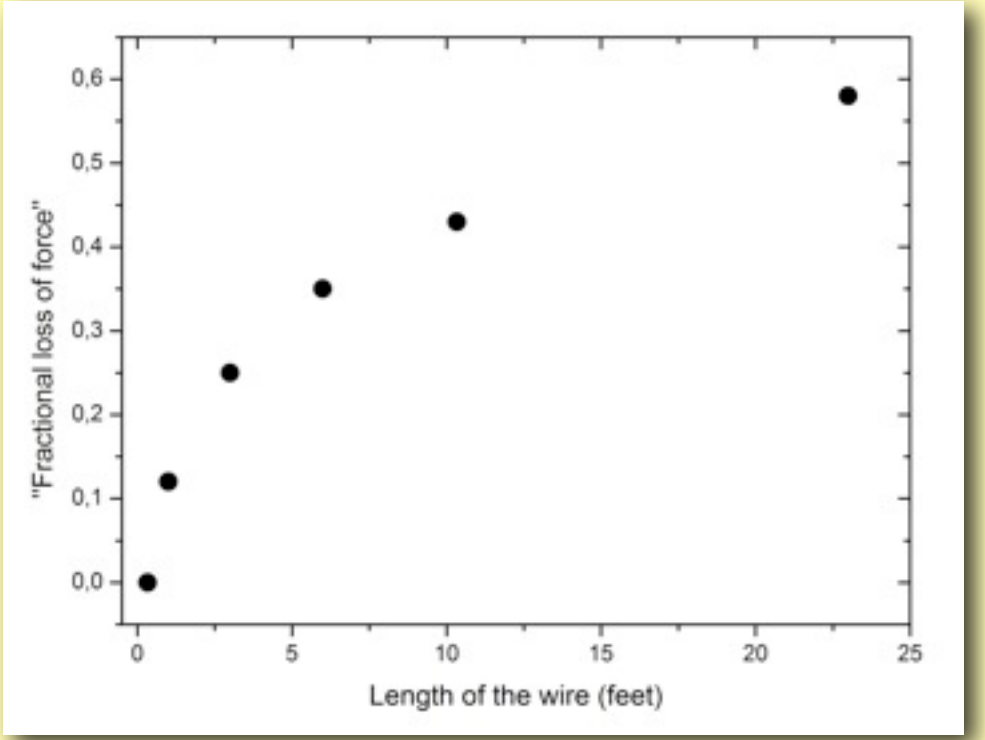
Studied wire Reading *a*

„Fractional loss of force” $v = (s - a)/s$

Ohm’s law (1825):

$v = m \log (1 + x/a)$

(*x* - length of a wire, *m* - parameter)



V.

Vorläufige Anzeige des Gesetzes, nach welchem Metalle die Contaktelektricität leiten;

von

Dr. G. S. Ohm, Oberlehrer zu Köln.

Durch mehrere Wahrnehmungen veranlafst, habe ich sorgfältige und vielfach wiederholte Versuche über die Fortleitung der Contaktelektricität in Metallen angestellt und Resultate erhalten, zu deren schleuniger Mittheilung ich mich um so mehr bewogen fühle, als meine geringe, ziemlich verkümmerte Muse mir es nicht verstattet, das Ende dieser Untersuchung so bald herbeizuführen. Und ich hoffe, dem theilnehmenden Publikum einen Dienst zu erzeigen, indem ich an jeder Stelle den Grund angebe, der mich zu einer neuen Reihe von Versuchen bewog.

Zu den Versuchen selbst gebrauchte ich einen Kupfer-Zink-Trog von 15 Zoll Höhe und 16 Zoll Länge. Aus dem Zink ging ein Drath A in ein Gefäfs mit Queckfilber M, aus dem Kupfer ein Draht B in ein Queckfilbergefäfs N; ferner wurde ein Drath C aus dem Gefäfse M in ein drittes O geleitet. Der Kürze halber werde ich die Dräthe A, B, C zusammengenommen den *unveränderlichen Leiter* nennen. Aufser diesen hatte ich noch 6 andere: o, a, b, c, d, e, deren Längen respektive $\frac{1}{2}$, 1, 3, 6, $10\frac{1}{2}$, 23 Fufs be-

Theilers C vom unveränderlichen Leiter 2 Fufs 0,5 Linien dicken Draht, so dafs also im Ganzen der unveränderliche Leiter jetzt aus 4,5 Fufs von demselben Drahte bestand, woraus die veränderlichen Leiter a bis f gebildet waren. Das Resultat dieser Versuche war folgendes:

Leiter	o	a	b	c	d	e	f
Kraftverlust beob.	0,00	0,04	0,10	0,16	0,23	0,36	0,56

Setzt man in obige Formel, wie hier geschehen mufs, $a = 4{,}5$ und wählt für m den Werth 0,452, wie ihn die letzte Angabe liefert, so findet man

Leiter	o	a	b	c	d	e	f
Kraftverlust berechn.	0,000	0,039	0,100	0,166	0,234	0,355	0,56

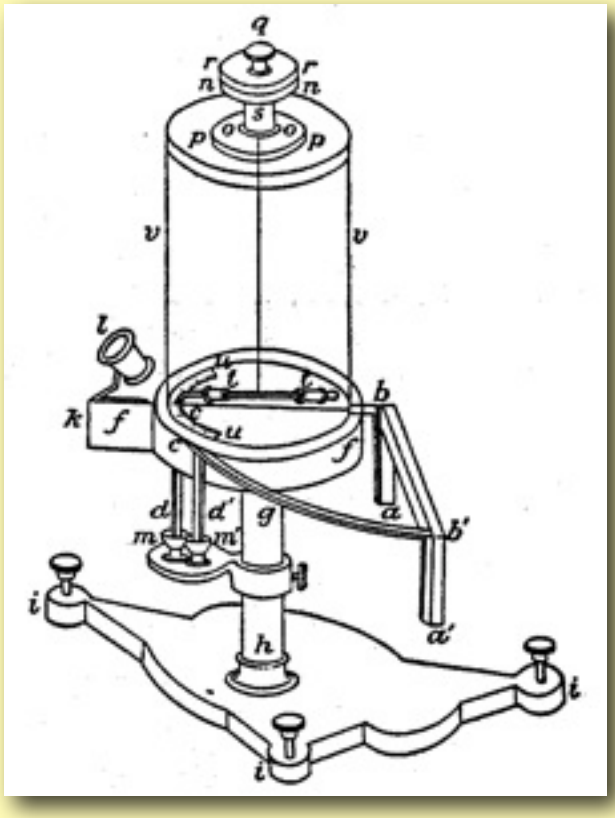
Diese Uebereinstimmung der beobachteten mit den berechneten Werthen ist als vollkommen anzusehen, um so mehr, als bei diesen Versuchen die Normalkraft an der Drehwage stets zwischen 44 und 43 Theilen sich aufhielt, und ich kleinere als halbe Theile nie berücksichtigt habe.

Nach diesen Versuchen sehe ich das Gesetz

$$v = m \log\left(1 + \frac{x}{a}\right)$$

als hinlänglich durch die Erfahrung bestätigt an. Dafs es für $x = -a$, $v = -\infty$ giebt, widerspricht keineswegs unserer anderweitigen Vorstellung von der Natur der galvanischen Kraft. Aus ihm erklärt sich von selbst die auffallend starke Wirkung des von

Experiments by Ohm (1826)



’Magnetic action of a current’

$$X = a/(b + x)$$

x - length of wire

a - dependent on ΔT

b - characteristics of unchanged part of a circuit

Heinrich Friedrich Emil Lenz

”The law, according to which the magnetoelectric phenomena are reduced to electromagnetic phenomena, is the following:

If a metallic conductor moves in the neighbourhood of a galvanic current or of a magnet, a galvanic current will be produced in it which will have such a direction that it would have occasioned in the wire, if it were at rest, a motion which is exactly opposite to that here given to the wire, provided that the wire when at rest is movable only in the direction of the motion and in the opposite direction.

In order therefore to represent the sense of the direction of the current excited in the moving wire by electrodynamic induction, we consider in what sense the current must be directed, according to the electromagnetic laws, if it were to produce the motion; the current in the wire will be excited in the opposite direction.” (1834)

Weber's formula (1846) for the total force of electrostatic repulsion between two moving point charges *e* and *e*':

$$F = \frac{ee'c^2}{r^2}\left[1 + \frac{r}{c^2}\frac{d^2r}{dt^2} - \frac{1}{2c^2}\left(\frac{dr}{dt}\right)^2\right]$$

r – distance between the charges,

c – a constant of the dimensions of velocity, equal approximately to $3 \cdot 10^{10}$ cm/s.

According to Weber, the physical meaning of *c* was that at relative velocity of two point charges *e* and *e*' equal to

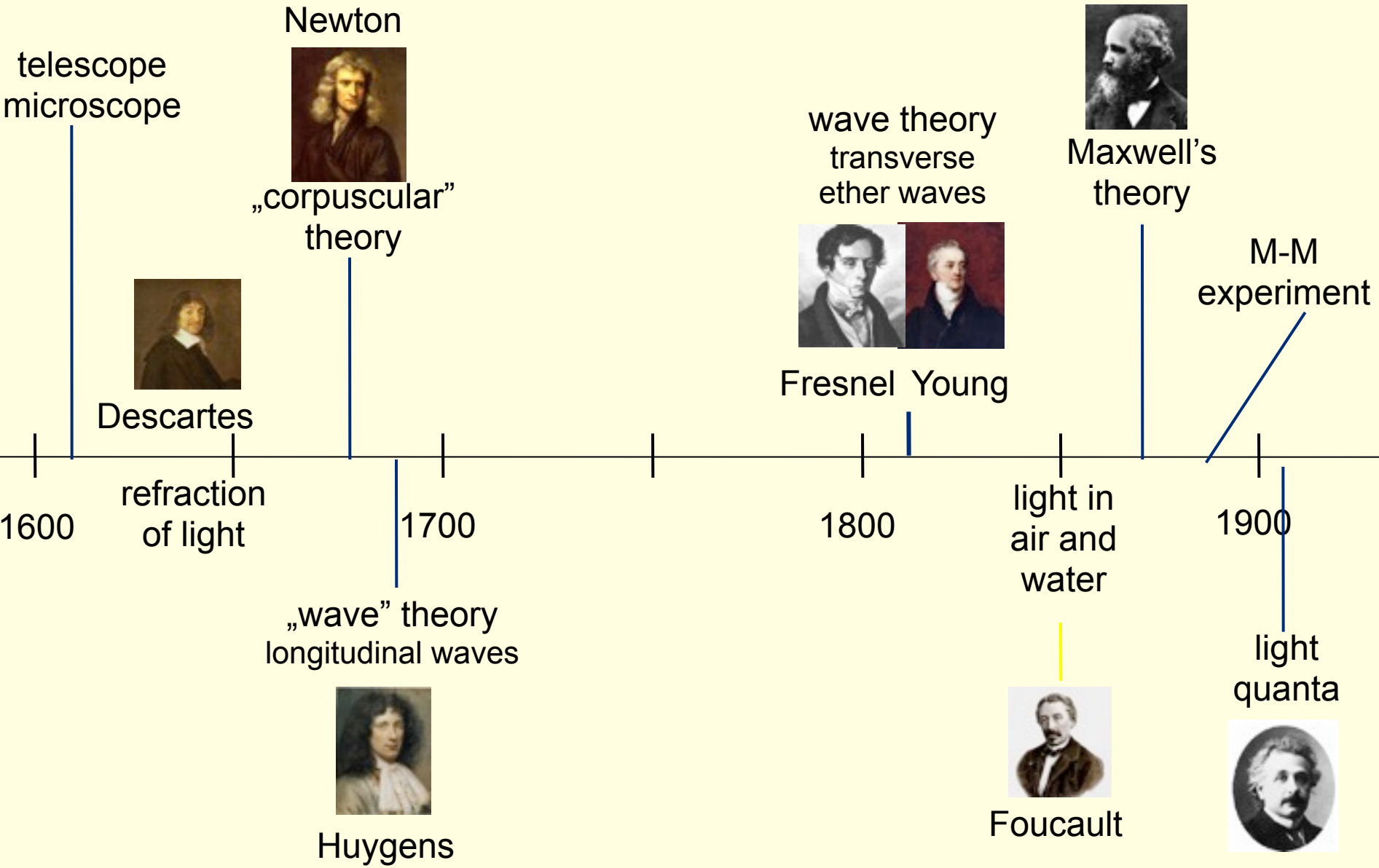
$$dr/dt = c\sqrt{2}$$

their electrostatic attraction is entirely compensated by electrodynamic repulsion, so that the resultant force equals to zero. The value of *c* could be determined be measuring the ratio of electrostatic and electromagnetic units.

Weber and Kohlrausch (1856) measured $c\sqrt{2} = 4.3944\ 10^{10}$ that is $c = 3.107\ 10^{10}$

Development of optics

Three centuries of studies of the nature of light



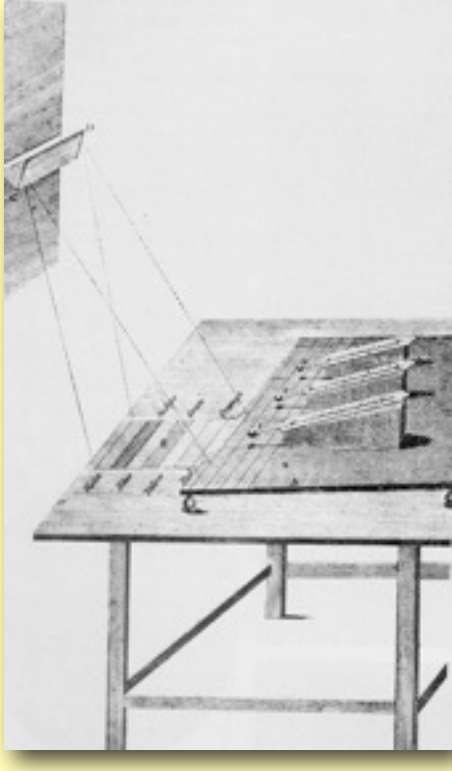
„Light consists of an inconceivably great number of particles flowing from a luminous body in all manner of directions; and these particles are so small, as to surpass all human comprehension..

That the number of particles of light is inconceivably great, appears from the light of a candle; which, if there be no obstacle in the way to obstruct the passage of its rays, will fill all the space within two miles of the candle every way with luminous particles, before it has lost the least sensible part of its substance...
Dr Niewentyt has computed, that there flows more than 6,000,000,000,000 times as many particles of light from a candle in one second of time, as there are grains of sand in the whole earth, supposing each cubic inch of it to contain 1,000,000”

***Encyclopaedia Britannica*, 1st edition (1771)**

William Herschel

Discovery of the infrared radiation (1800)



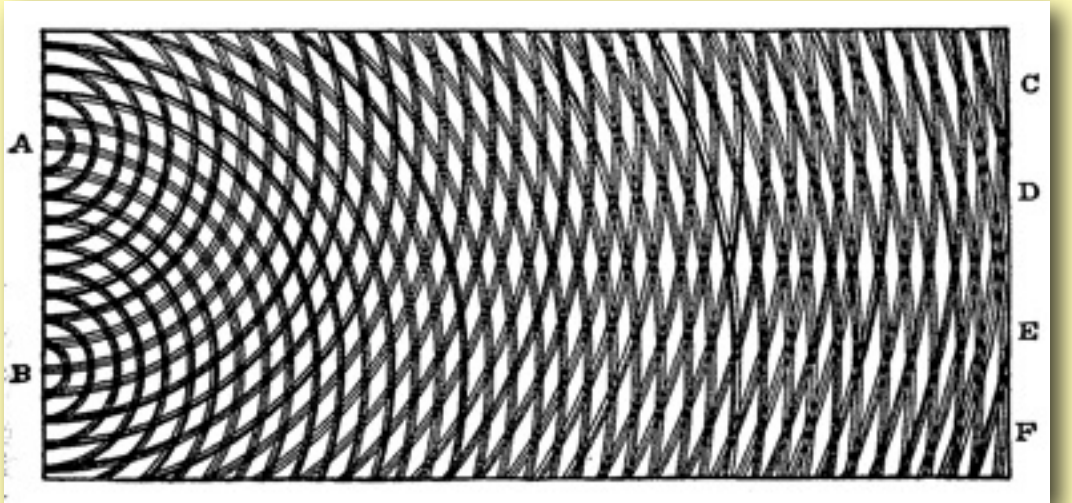
Johann Wilhelm Ritter
(1776-1810)

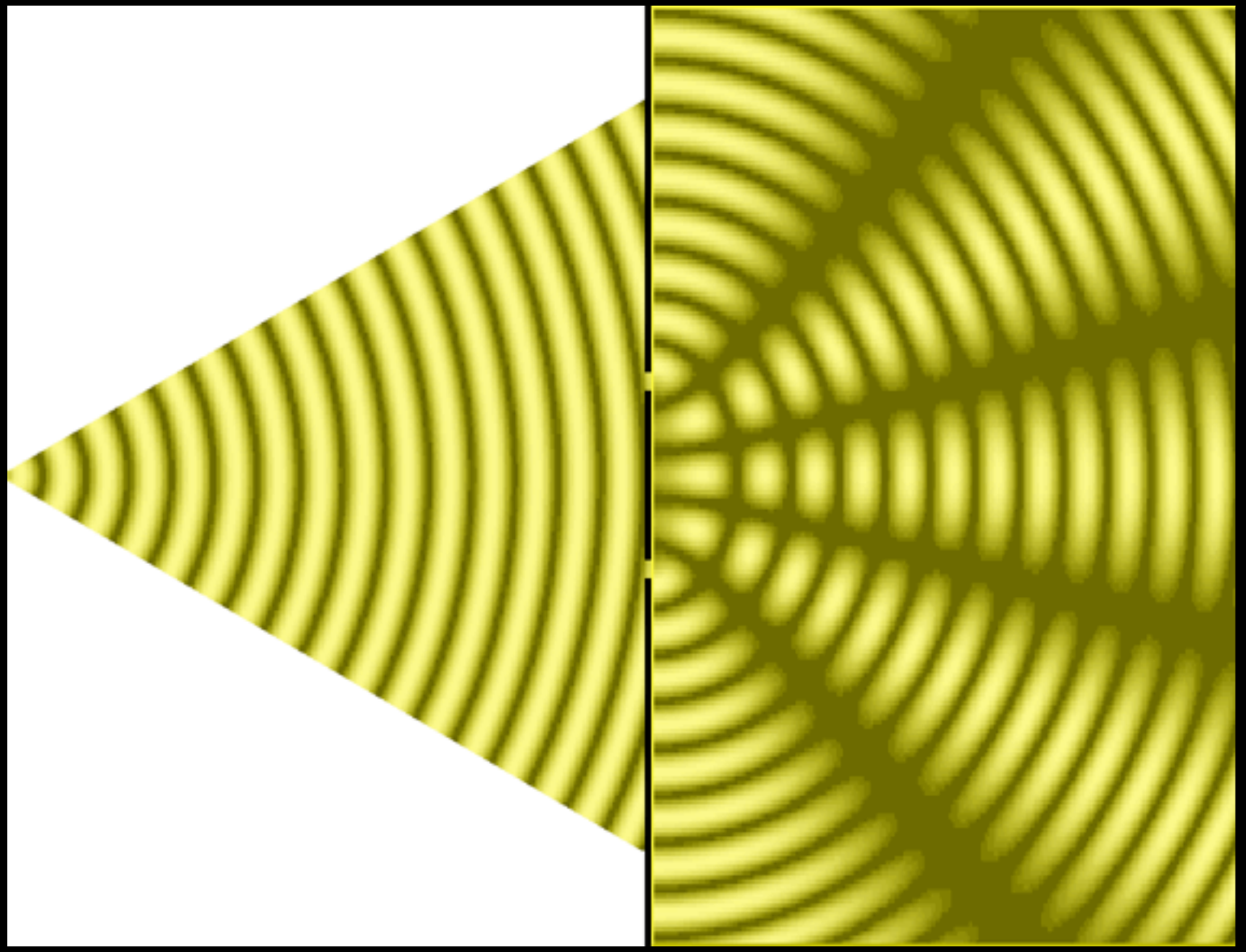
Discovery of the ultraviolet radiation (1801)

William Hyde Wollaston
(1766-1828)

Thomas Young (1773-1829)

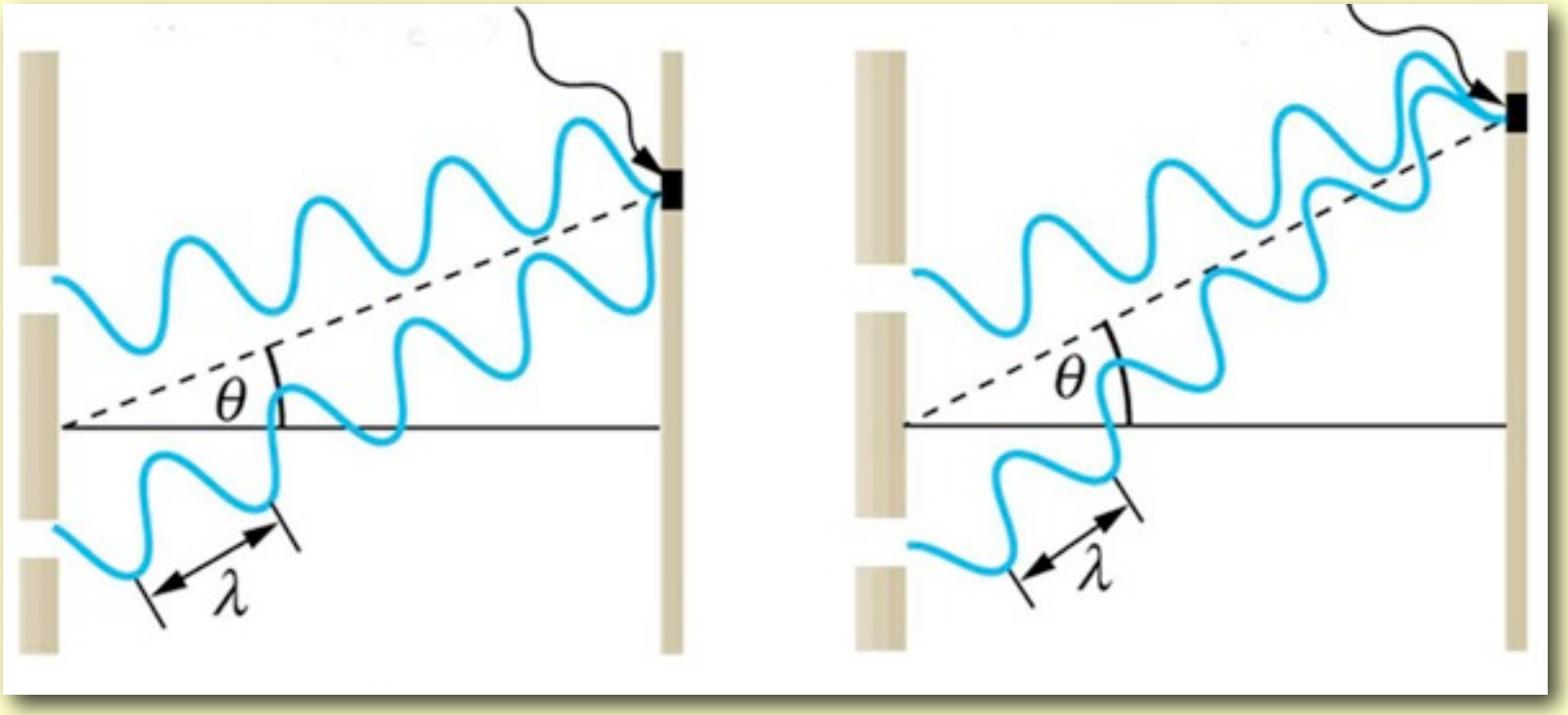
The general law of the interference of light
”...whenever two portions of the same light arrive to the eye by different routes, either exactly or very nearly in the same direction, the light becomes more intense when the difference of the routes is any multiple of a certain length, and least intense in the intermediate state of the interfering portions; and this length is different for light of different colours...” (1802)



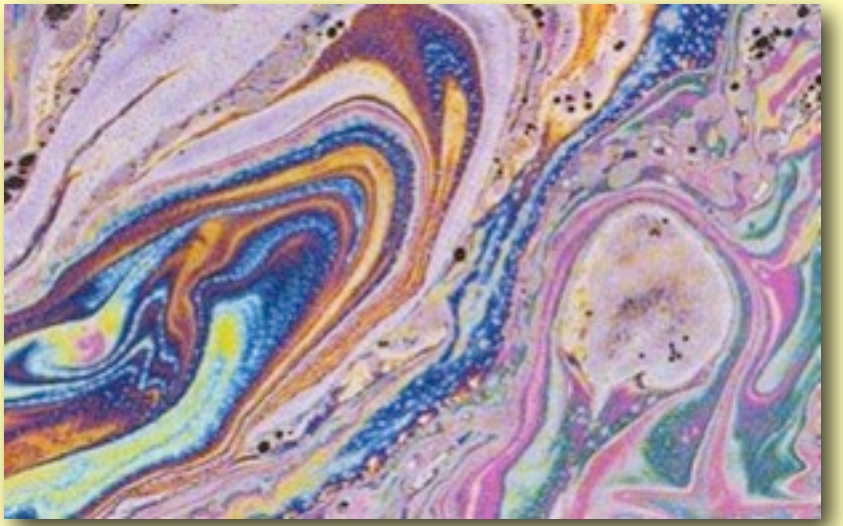


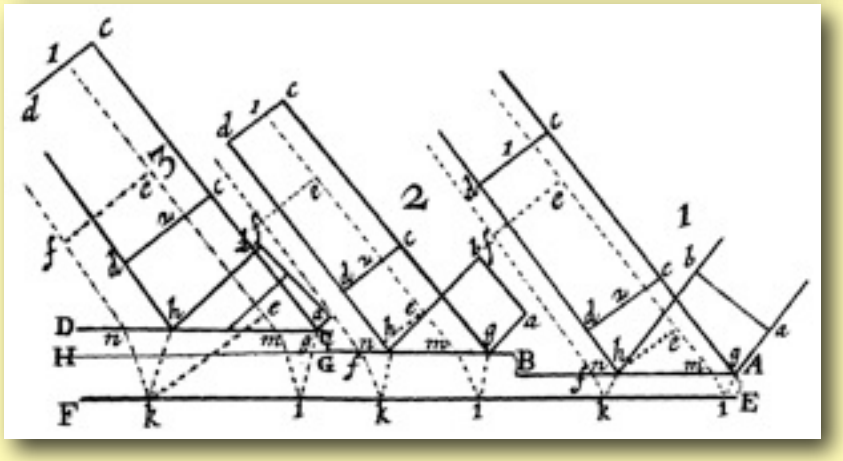
destructive interference

constructive interference

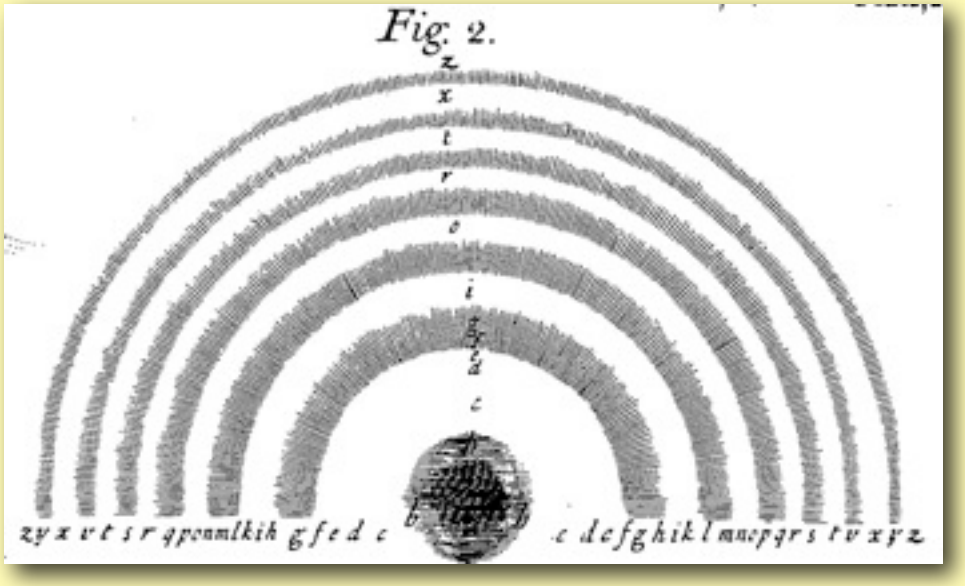


Interference phenomena have been known earlier





Hooke’s explanation of colours of thin plates



”Newton’s rings”

Four basic hypotheses
of Thomas Young (1801):

1. A luminiferous ether pervades the universe, rare and elastic in a high degree.
2. Undulations are excited in this ether whenever a body becomes luminous.
3 .The Sensation of different Colours depends on the different frequency of Vibrations excited by Light in the Retina.
4. All material Bodies have an Attraction for the ethereal Medium, by means of which it is accumulated within their substance, and for a small Distance around them, in a state of greater Density, but not of greater Elasticity.

”We now dismiss, for the present, the feeble lucubrations of this author, in which we have searched without success for some traces of learning, acuteness, and ingenuity, that might compensate his evident deficiency in the powers of solid thinking, calm and patient investigation, and successful development of the laws of Nature, by steady and modest observation of her operations. We came to this examination with no other prejudices than the very allowable prepossession against vague hypothesis, by which all true lovers of science have for above a century and a half been swayed...

...and we feel ourselves more particularly called upon to express our disapprobation, because, as distinction has unwarily been bestowed on his labours by the most illustrious of scientific bodies, it is the more necessary that a free protest should be recorded before the more humble tribunals of literature.”

Lord Henry Brougham on Young’s work (*Edinburgh Reviev*, 1802)

Study of polarized light

1808 polarization of light by reflection
Etienne Louis Malus
(1775-1812)

1810 chromatic polarization
Dominique François Arago
(1786-1853)

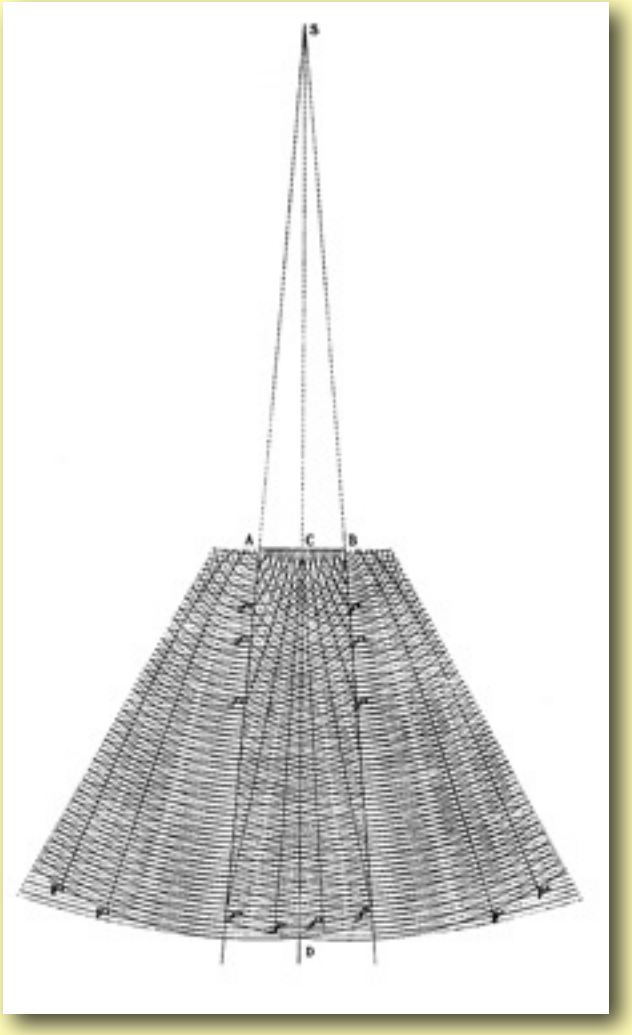
1815 Brewster's angle
David Brewster (1781-1868)

Augustin Fresnel (1788-1827)

Diffraction of light made the subject of the Academié des Sciences prize for 1818

The jury consisting of Arago, Biot, Gay-Lussac, Laplace, and Poisson was forced to award the prize to Fresnel

Poisson's spot

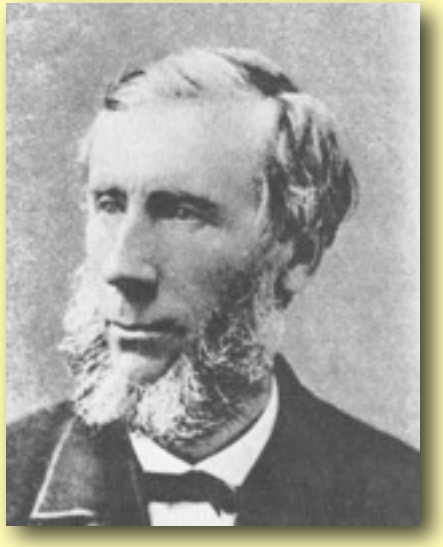


Diffraction fringes as drawn by Fresnel in his first paper on the diffraction of light (1816)

In order to explain polarization of light Fresnel and Young, independently of each other and simultaneously (1817) proposed that light waves are transverse, not longitudinal, as it had been previously accepted by everyone since Hooke and Huygens. The wave theory of light in its modern form is justly called Fresnel-Young theory.

The idea of Fresnel and Young about transverse light vibrations inaugurated a long period of studies of the properties of the hypothetical ether, a medium of very large elasticity, but transparent and presenting no resistance in the motions of heavenly bodies.
Among the authors of important works on the properties of the ether were, for example,

Augustin Cauchy, George Fitzgerald, George Green,
Oliver Heaviside, Hermann Helmholtz,
Gustav Kirchhoff, Joseph Larmor, Hendrik Lorentz,
James Mac Cullagh, James Clerk Maxwell,
Arnold Sommerfeld, George Stokes,
William Thomson (Kelvin)



”...but the stretch of imagination which filled all space with a luminiferous ether trembling with the waves of light was so bold as to shock cautious minds.
In one of my latest conversations with Sir David Brewster, he said to me that his chief objection to the undulatory theory of light was that he could not think the Creator guilty of so clumsy a contrivance as the filling of space with ether in order to produce light..”

John Tyndall, *Six Lectures on Light delivered in America 1872-1873*

Christian Doppler (1805-1853)

Ueber das

farbige Licht der Doppelsterne

und

einige andere Gestirne des Himmels.

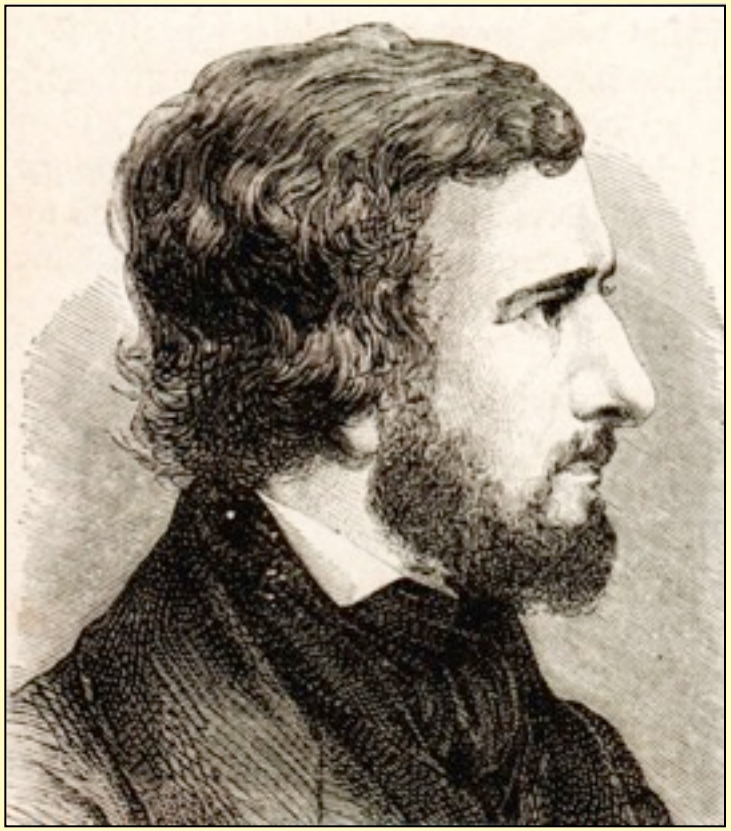
Christian Doppler.

Doppler's assumptions

- All stars are intrinsically white and their observed colour results only from their motion
- There is no radiation outside the visible part of the spectrum, hence already at small star velocities one can see a change in their colour

These assumptions were completely wrong!

Doppler effect for light



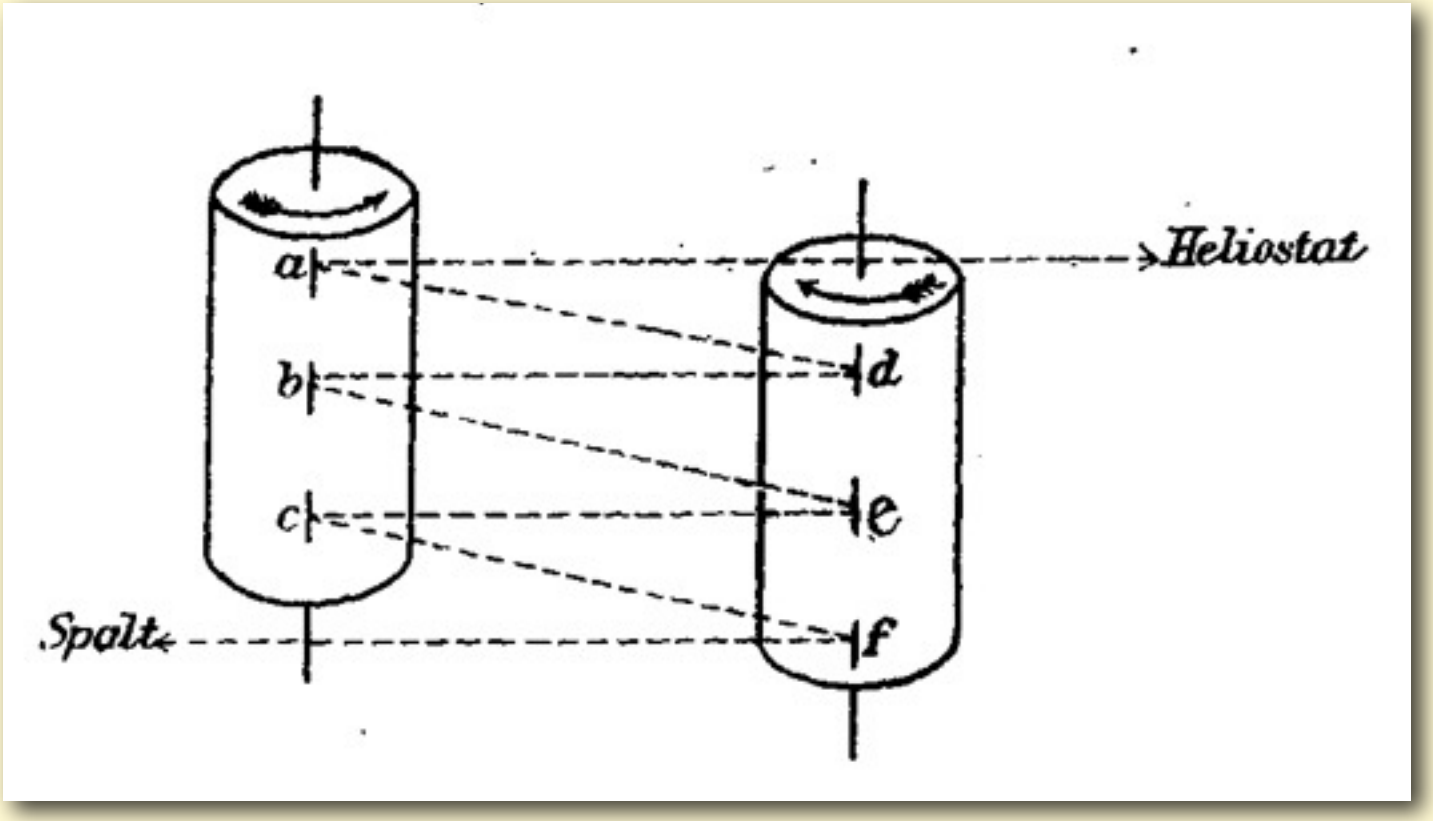
Armand Hippolyte Fizeau
(1848)

One should look
for the effect
not in the continuous
spectrum but in the shift
of spectral lines

Checking Doppler's principle by observing well known astronomical objects

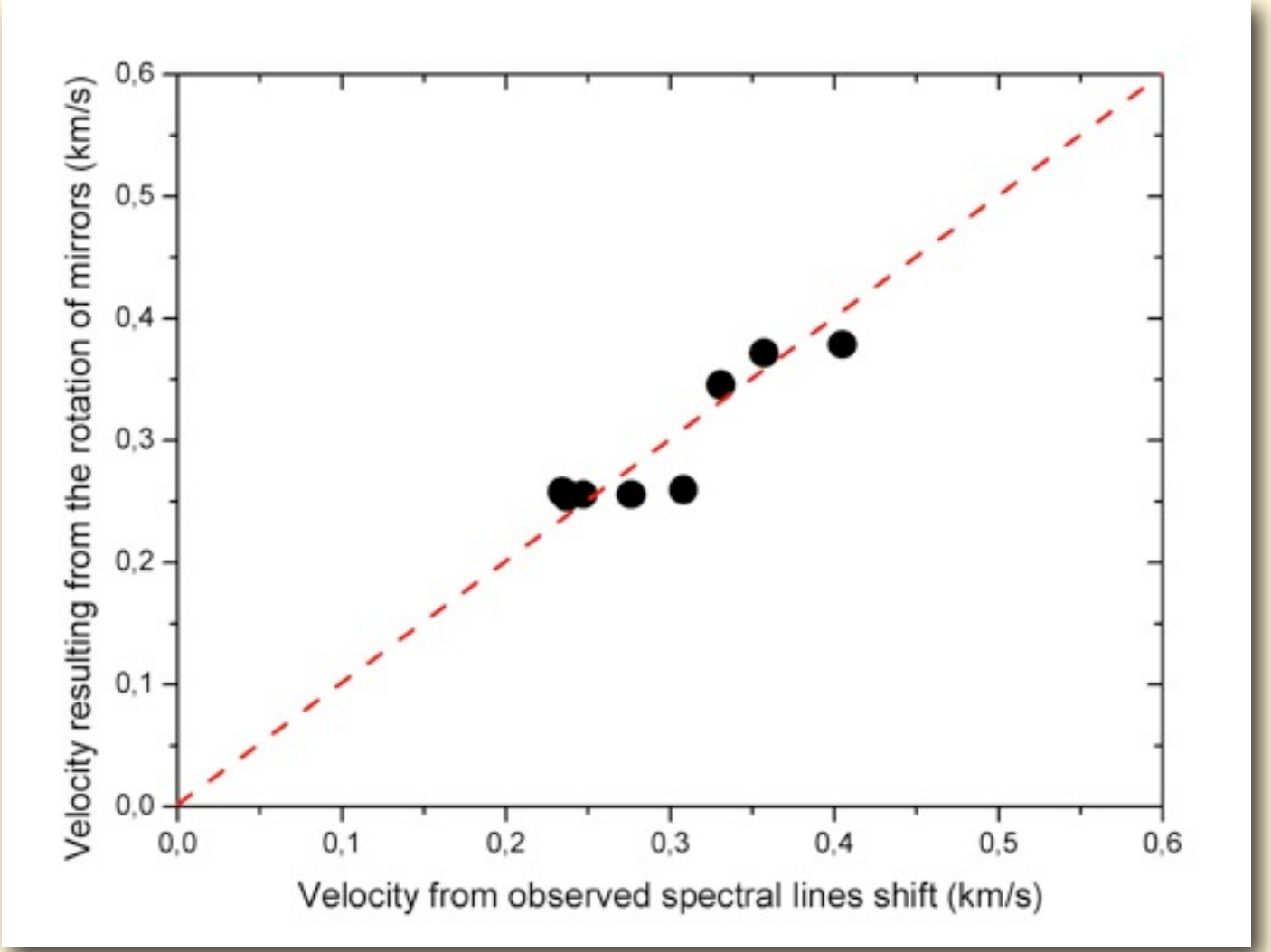
Nils Christopher Dunér

Checking Doppler's principle for light waves



Aristarkh Belopolski, *Astroph. Journ.* **13**, 15 (1901)

B. Galitzin & J. Wilip, *Astroph.Journ.* **26**, 49 (1907)
(improved version of Belopolski's apparatus)

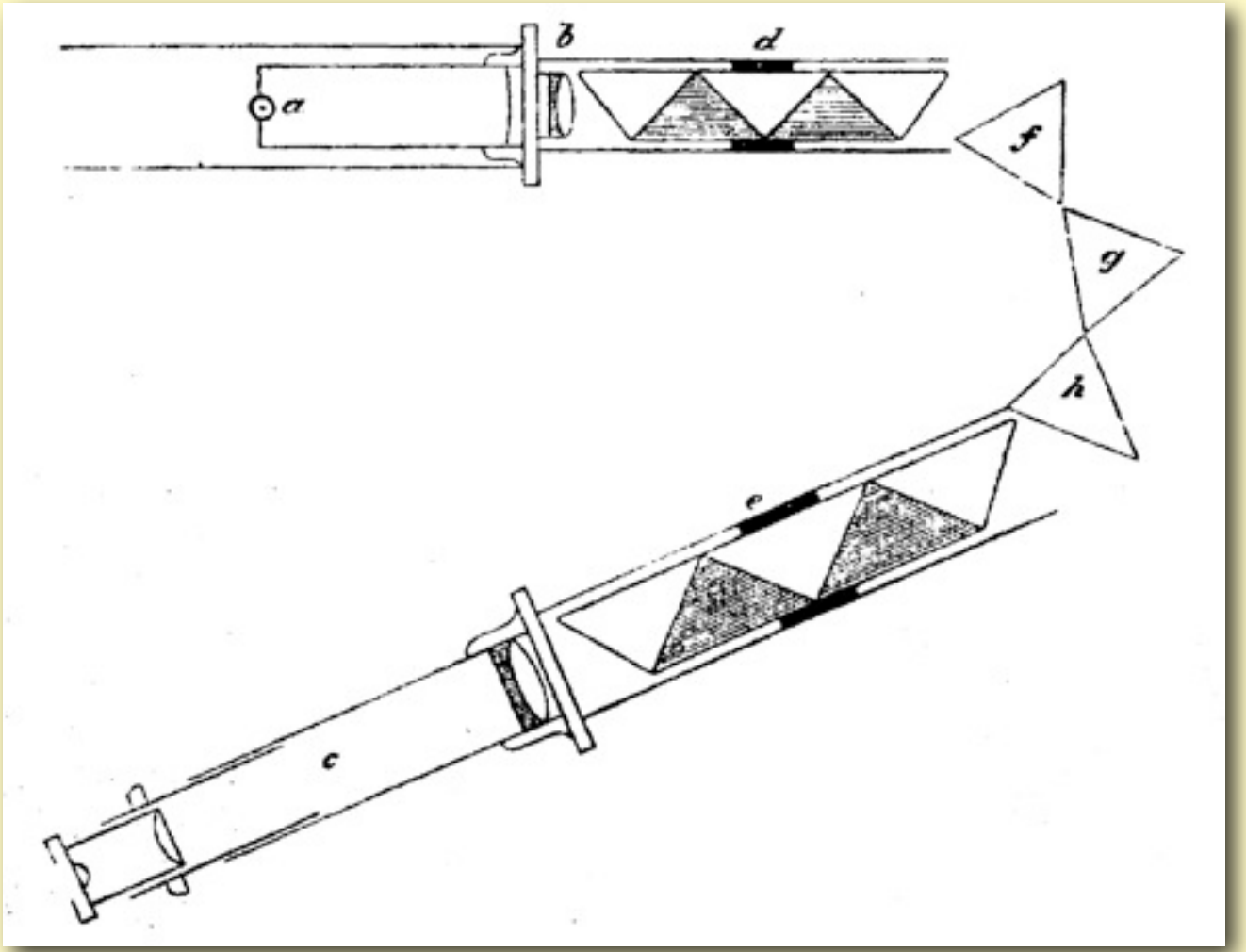


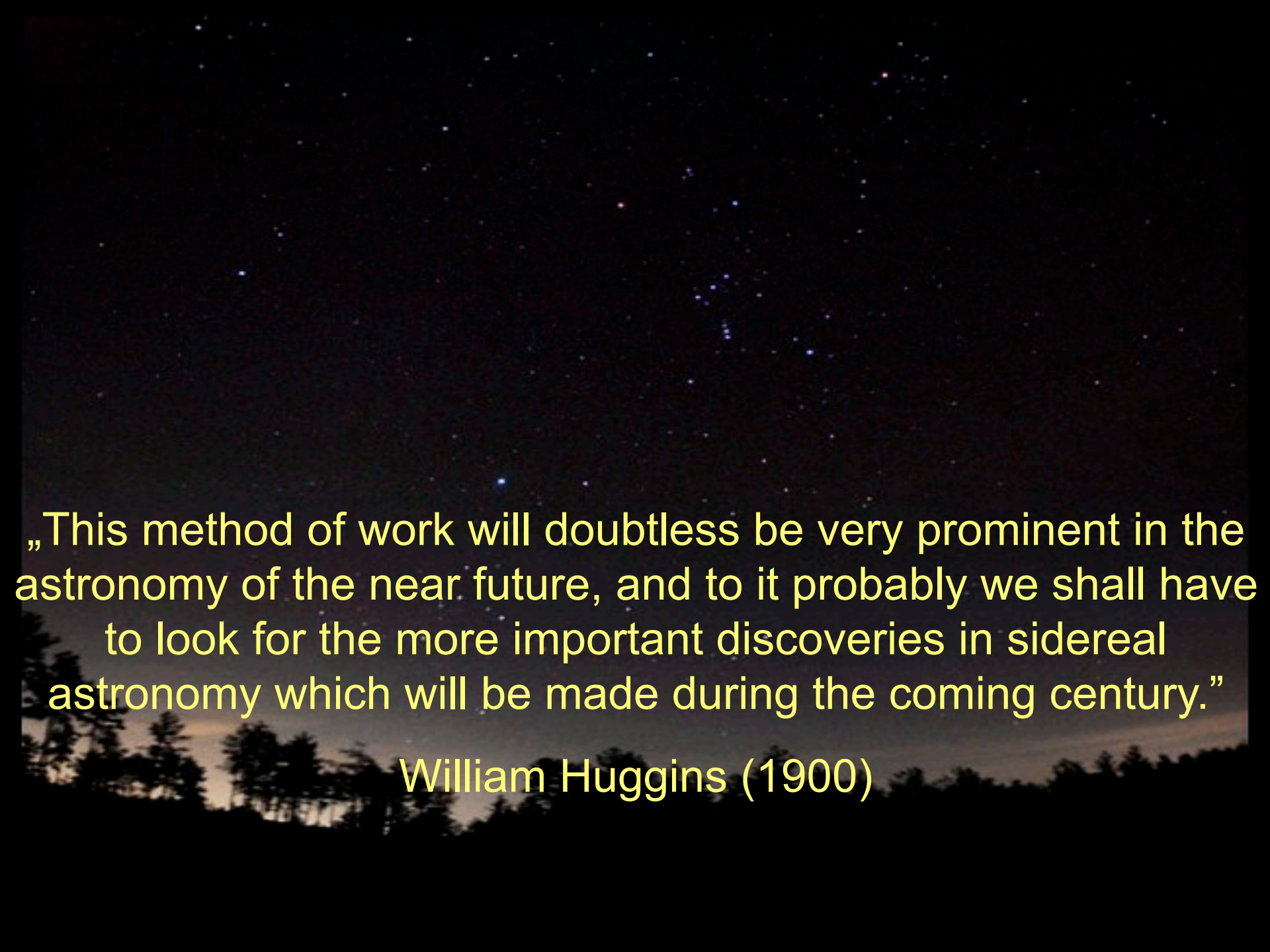
William Huggins – pioneer of astrospectroscopy

First identified lines in the spectra of stars and nebulae (1864)

Estimated the velocity of recession of Sirius at 29 miles per second (1868)

Multi-prism spectrometer used by William Huggins (1868)




„This method of work will doubtless be very prominent in the astronomy of the near future, and to it probably we shall have to look for the more important discoveries in sidereal astronomy which will be made during the coming century.”
William Huggins (1900)

Some other applications of the Doppler effect

astronomy → - Doppler tomography
stellar surface imaging

meteorology - Doppler radar

medicine - Doppler imaging tomography
→ cardiovascular disease diagnosis

optics - Doppler cooling

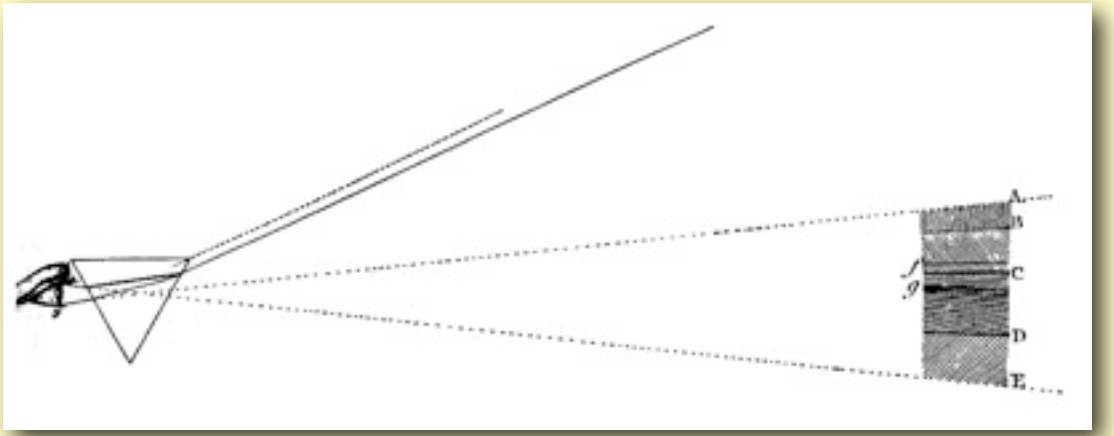
nuclear physics - Doppler Shift Attenuation Method

air-traffic navigation

space navigation

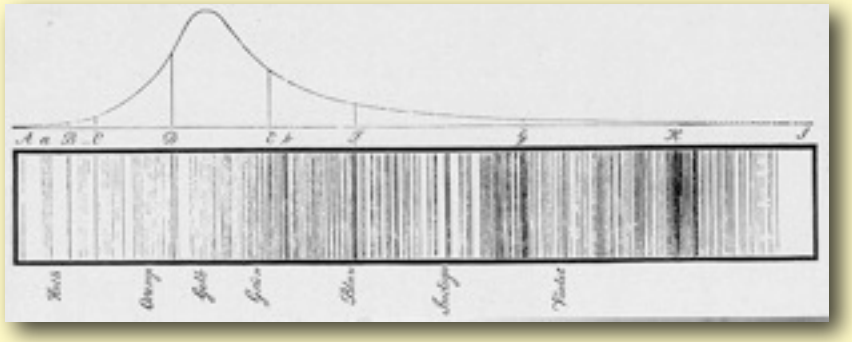
road police weapon against speeding drivers

Dark lines in the solar spectrum were first noticed by William Wollaston (1802), who, however, took them simply for boundaries between diffferent colours and did not continue studies



Phil. Trans. Roy. Soc. London **92**, 365-380 (1802)

Josef Fraunhofer



Prepared a catalogue of 574 dark lines in the solar spectrum

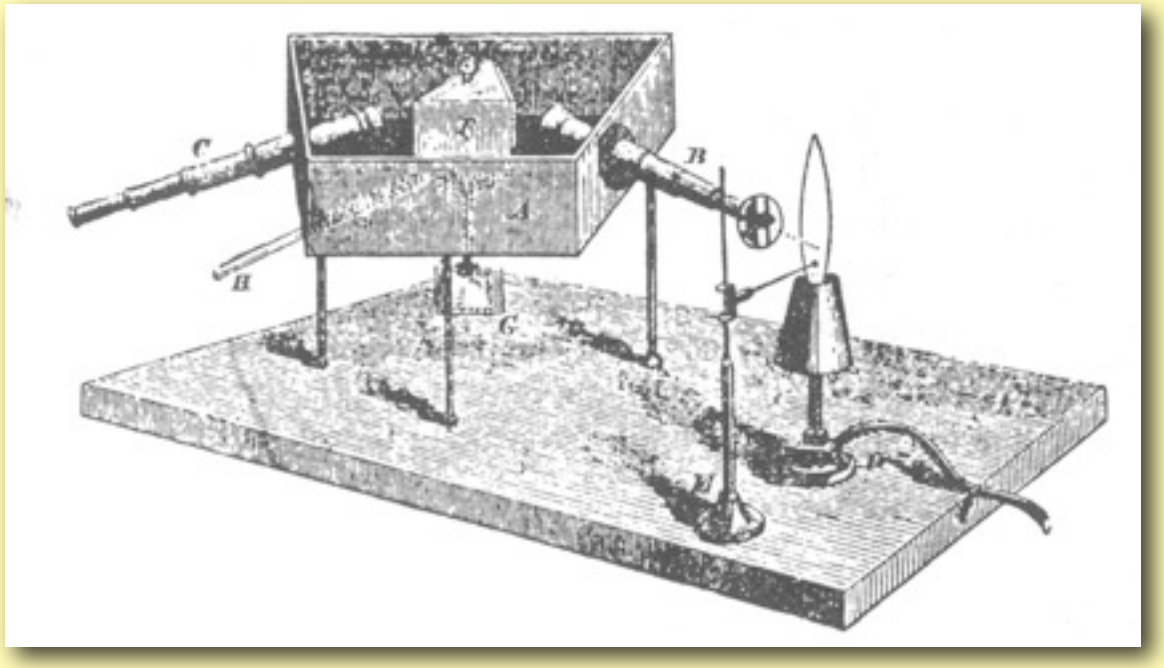
„…almost innumerable strong and weak vertical lines which however are darker than the other part of the coloured image; some seem to be almost completely black…”

Denkschr.d.Königl.Akad.d.Wiss. zu München **5**, 193-226 (1815)

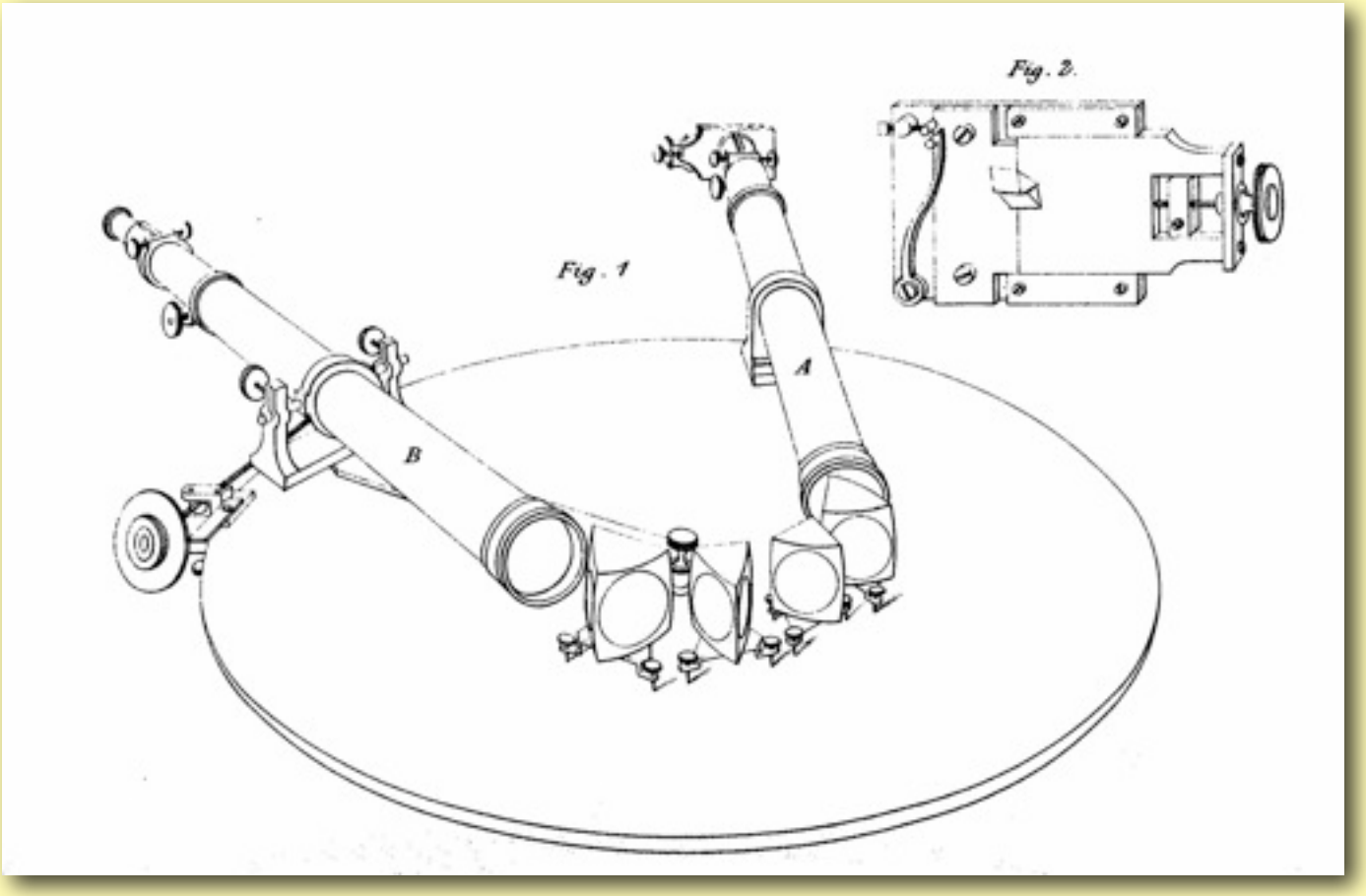
Discovery of spectral analysis

Robert Bunsen
(1811-1899)

Gustav Kirchhoff
(1824-1887)



Spectroscope (1859)

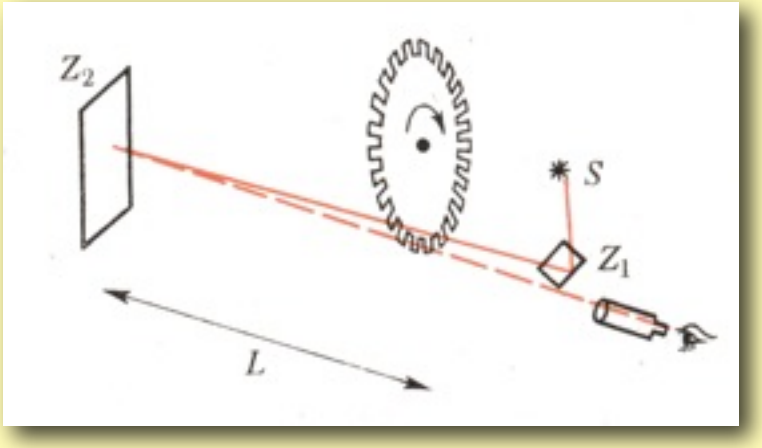


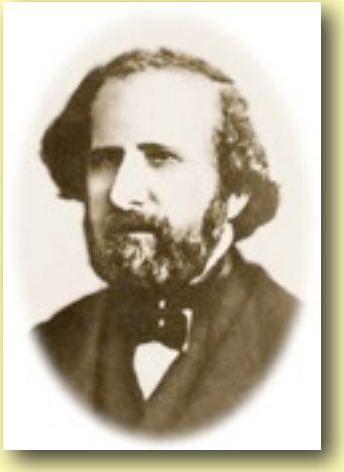
Kirchhoff's apparatus for the study of spectra of the sun and chemical elements (1861)

„On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are ... necessarily denied to us. While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure ... Our knowledge concerning their gaseous envelopes is necessarily limited to their existence, size ... and refractive power, we shall not at all be able to determine their chemical composition or even their density... I regard any notion concerning the true mean temperature of the various stars as forever denied to us."

August Comte, *Cours de la Philosophie Positive* (1835)

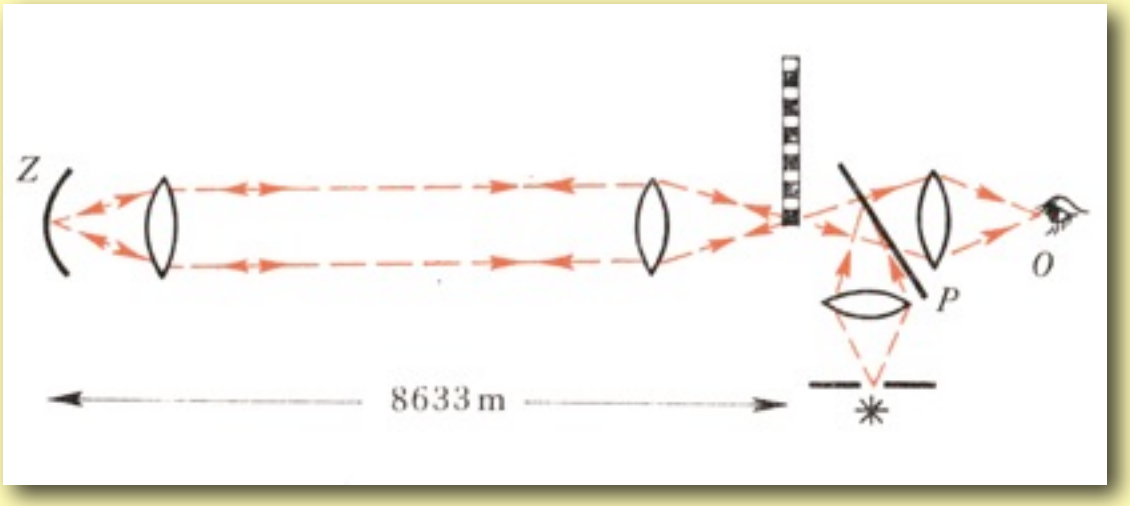
First laboratory measurements of the velocity of light



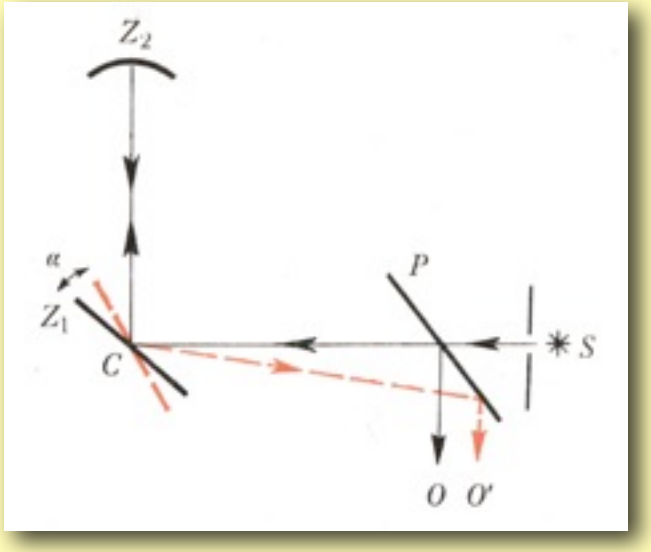


Fizeau's rotating wheel method

c = 314,000 km/s (1849)



First laboratory measurements of the velocity of light

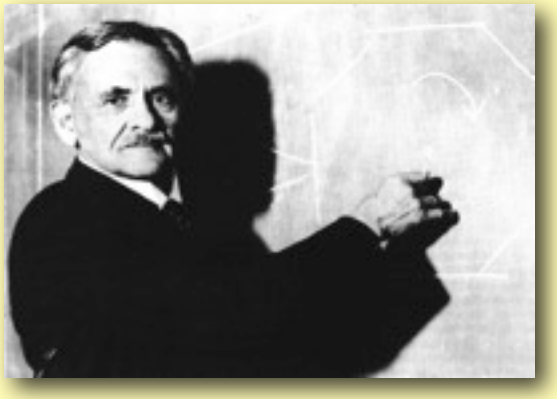


Foucault's rotating mirror method

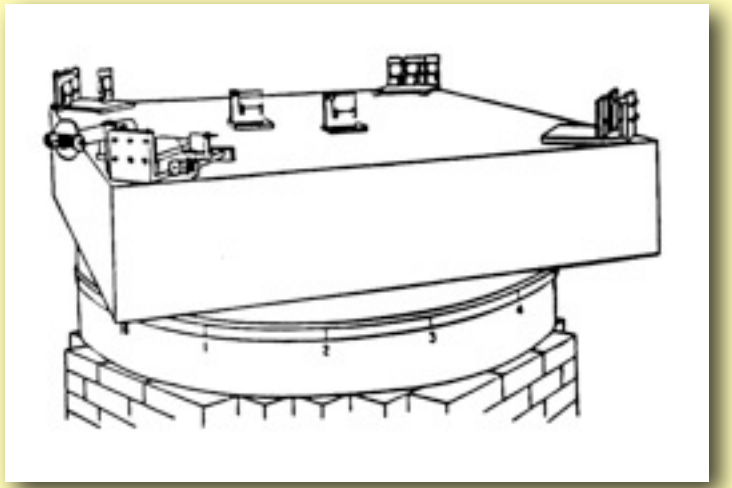
c = 298,300 km/s (1850)

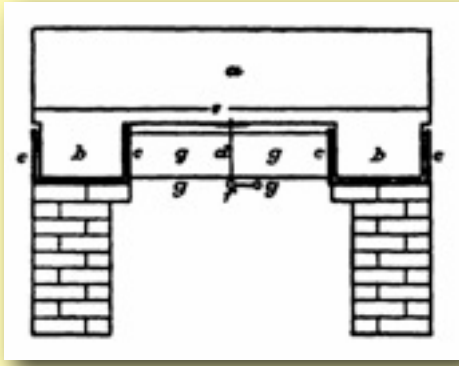
Velocity of light in water smaller than in air

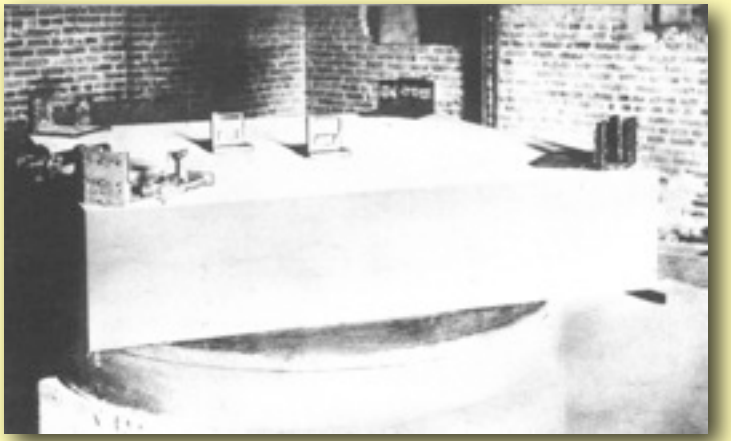
The Michelson-Morley experiment (1887)

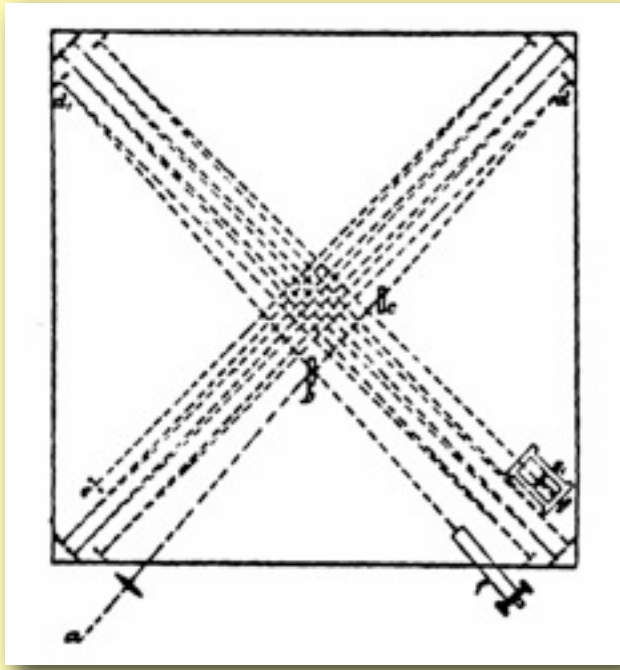


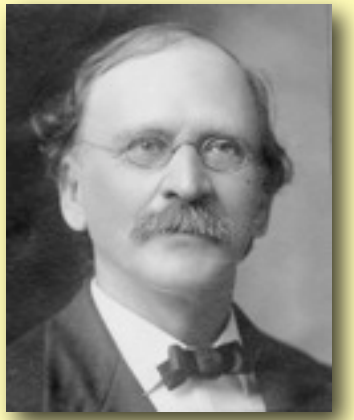
Albert Michelson
(1852-1931)



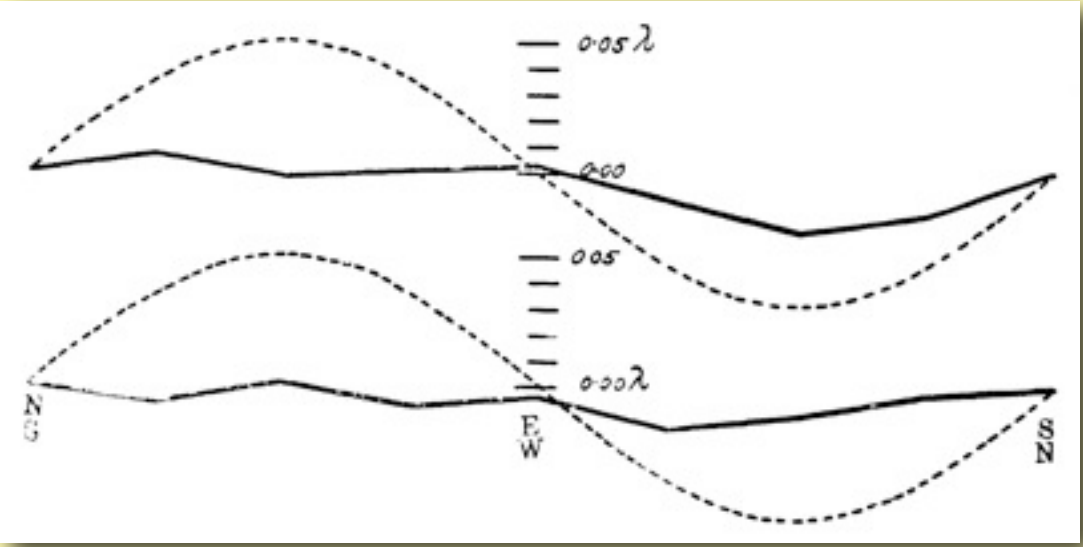








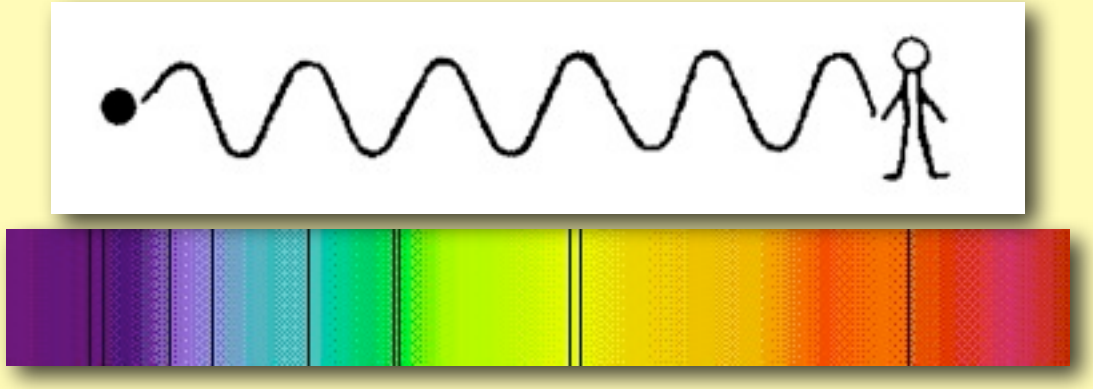
Edward Morley

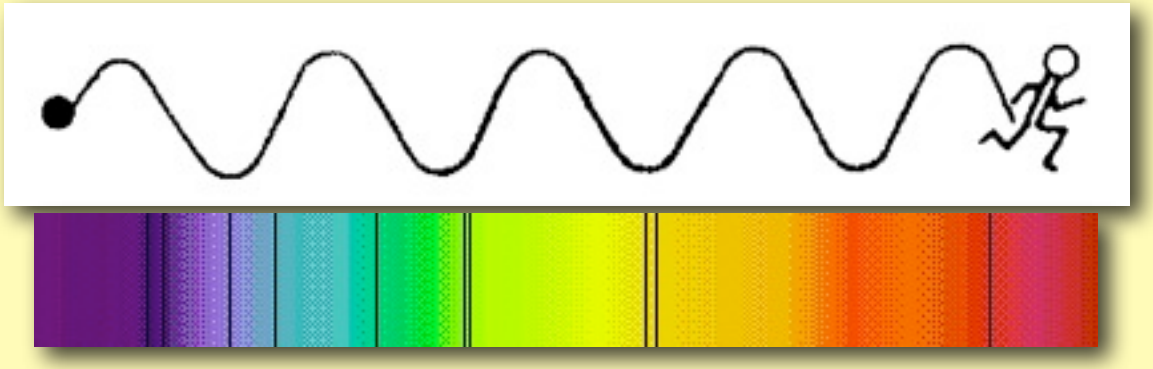


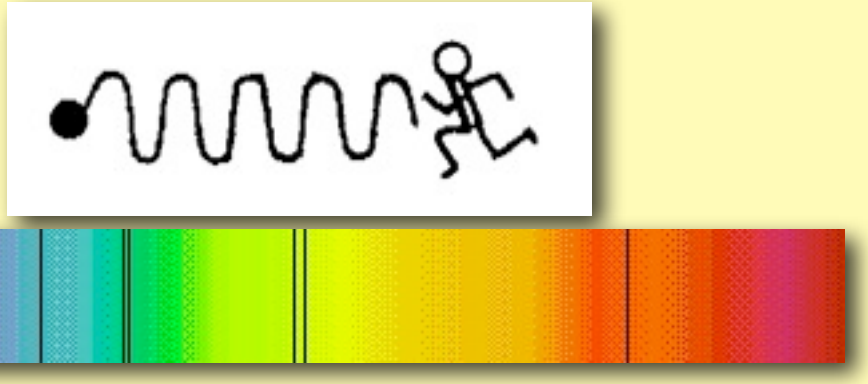
”The results of the observations are expressed graphically The upper is the curve for the observations at noon, and the lower that for the evening observations. The dotted curves represent *one-eight* of the theoretical displacement. It seems fair to conclude from the figure that if there is any displacement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than 0,01 of the distance between the fringes.”

Michelson i Morley, *Amer. J. Sci.* XXXIV, No. 203, 333-345 (1887).

Additional explanatory slides







1845. ANNALEN No. 11.
DER PHYSIK UND CHEMIE.
BAND LXVI.

I. *Akustische Versuche auf der Niederländischen Eisenbahn, nebst gelegentlichen Bemerkungen zur Theorie des Hrn. Prof. Doppler* [1]*); vom Dr. Buijs Ballot zu Utrecht.*

Sobald mir das Schriftchen des Hrn. Doppler in die Hände gekommen war, reizte mich der Scharfsinn der darin entwickelten Theorie; es wurden aber auch Zweifel in mir erregt über die Anwendbarkeit dieser Theorie auf die Farben der Doppelsterne. Ich faſste schon damals den Vorsatz, einige Versuche dieserhalb anzustellen und zugleich die Anwendung der Theorie an anderen bekannten Thatsachen zu prüfen, allein, durch Umstände daran verhindert, begnügte ich mich, am Schlusse meiner Dissertation [2]) eine Thesis aufzustellen, welche mir auch zu der folgenden Discussion als Motto dienen kann:

Theoriam Doppleri probandam existimo; ad stellarum autem duplicium colores explicandos non sufficientem dico.

Obgleich man schwerlich berechtigt ist, die Aussage einer wohlbegründeten Theorie zu bezweifeln, — und wer möchte dieses bei der Theorie des Lichts oder des Schalls, — so hielt ich es doch nicht für überflüssig, den von Hrn. Doppler zuerst zur Sprache gebrachten Einfluſs der relativen Geschwindigkeit eines tönenden Instruments auf die wahrgenommene Tonhöhe durch directe Versuche nachzuweisen, besonders da einige Musiker, denen ich diese Theorie mittheilte, die Haltbarkeit derselben bestimmt verneinten. Sie stützten sich dabei un-

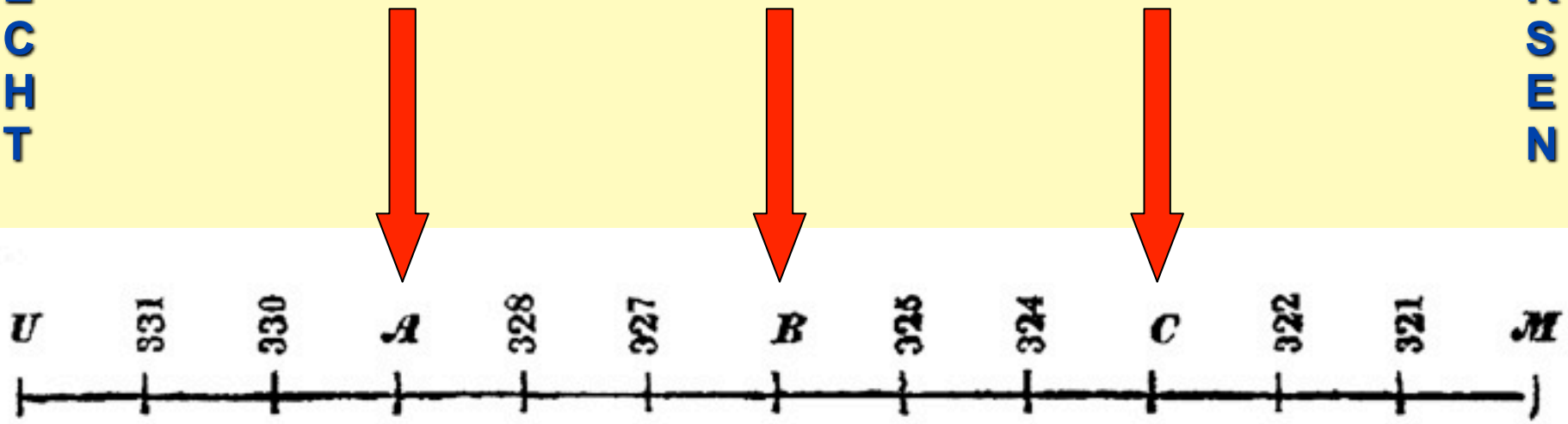
1) Ueber das farbige Licht der Doppelsterne u. s. w. Prag 1842.
2) *De Synaphia et Prosaphia. Traject. ad Rhen.* 1844.

Christopher Buys-Ballot

UTRECHT

Observers

MAARSEN



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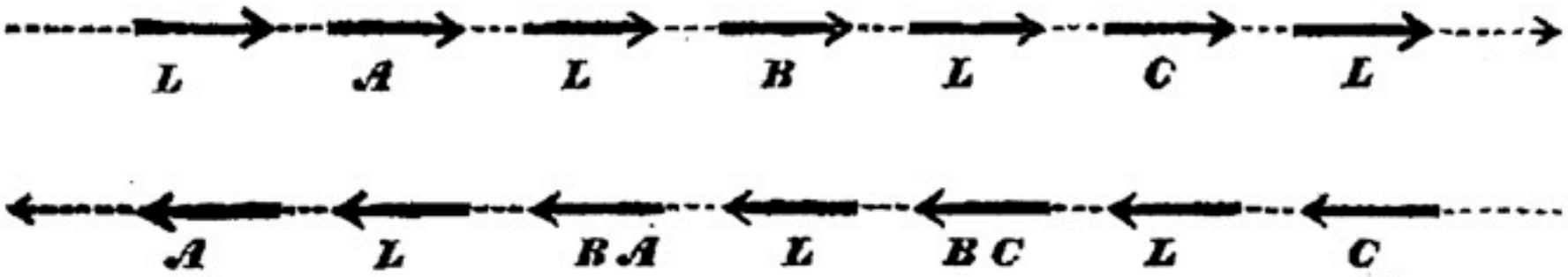
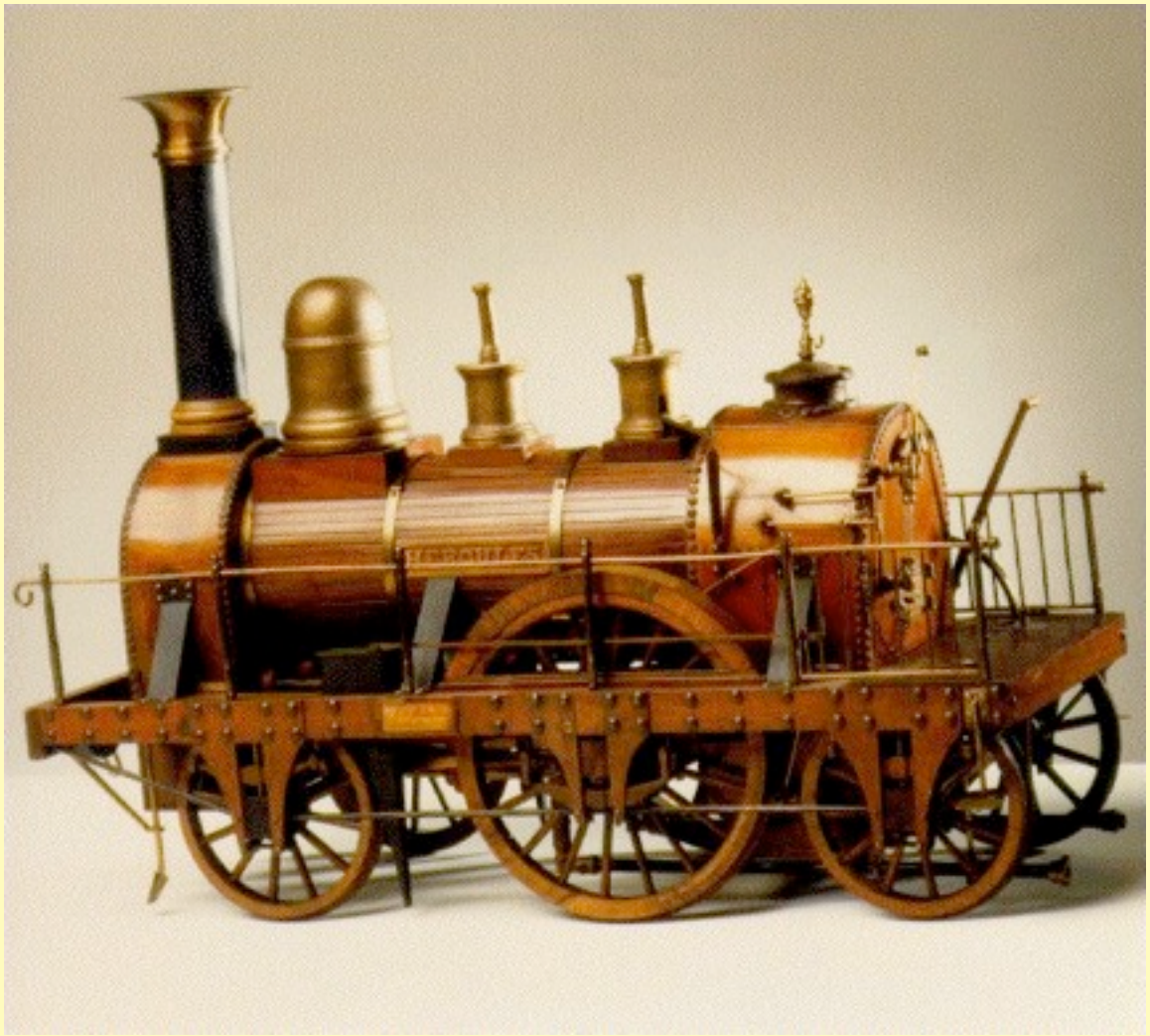




Sharp-Roberts
locomotive
of 1843
probably used by
Buys-Ballot
in his experiment

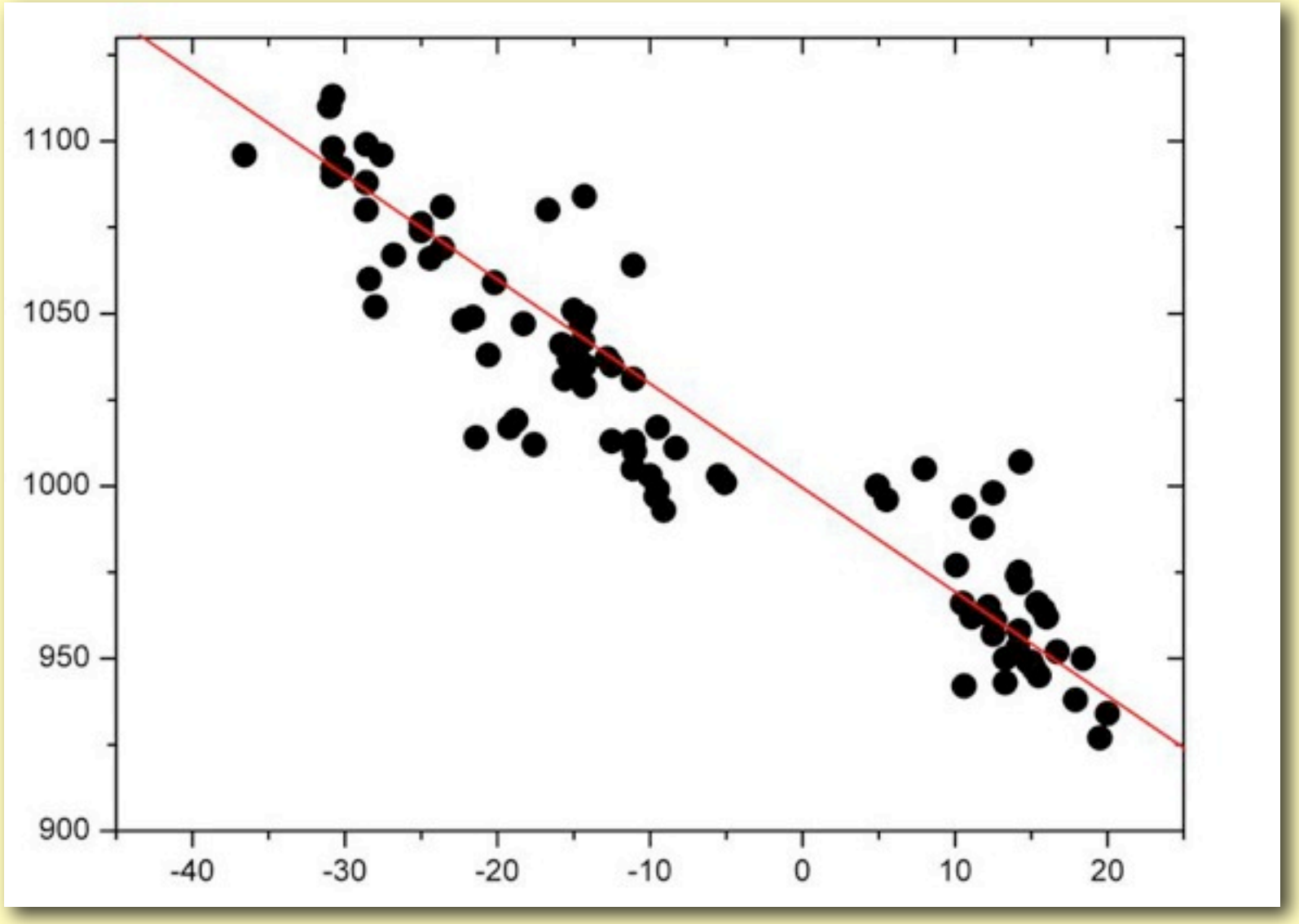
http://www.knmi.nl/voorl/nader/dewettenvanbuysballotferrelendoppler.htm

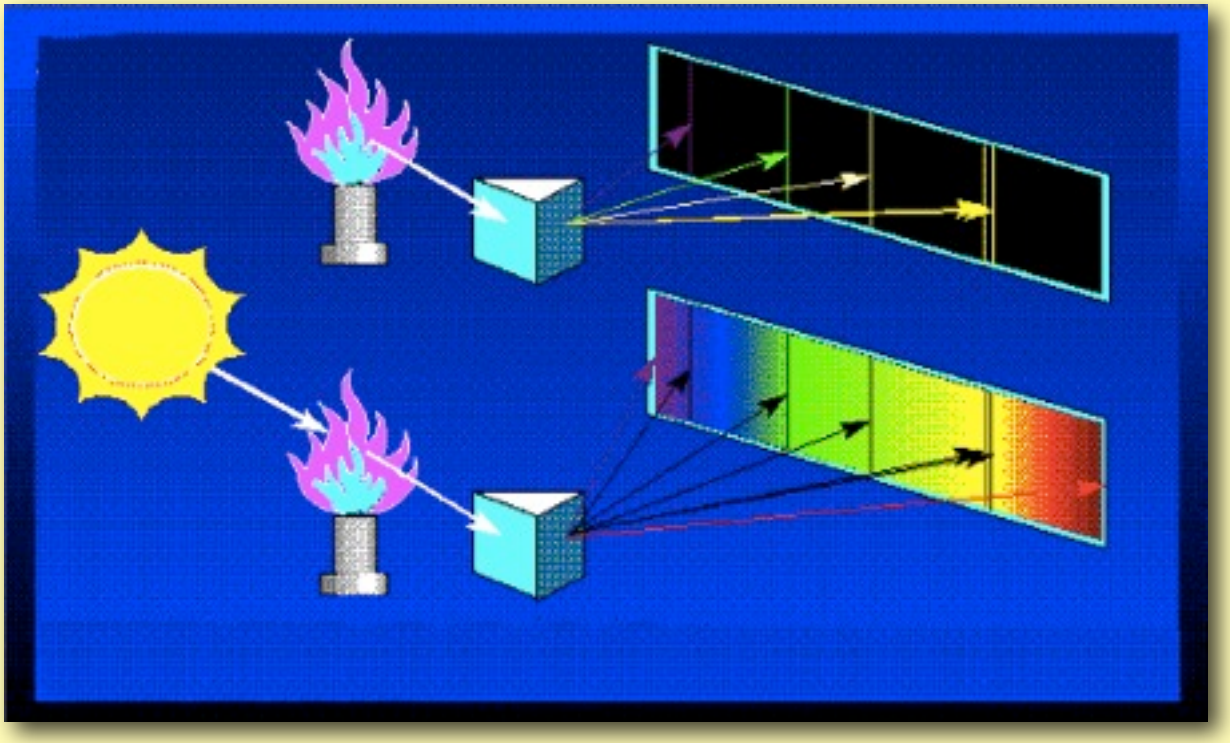
- June 3, 1845 – preliminary measurements
- June 5, 1845 – main measurements

- locomotive speed 18 – 72 km/h
- 14 musicians altogether
- two instruments: a valve trumpet and a bugle
- estimates of frequency by individual musicians
  up to 1/16 tone !
- about 150 estimates in total

”one sees therefore that in general the theory is confirmed”

Buys-Ballot's results (1845)

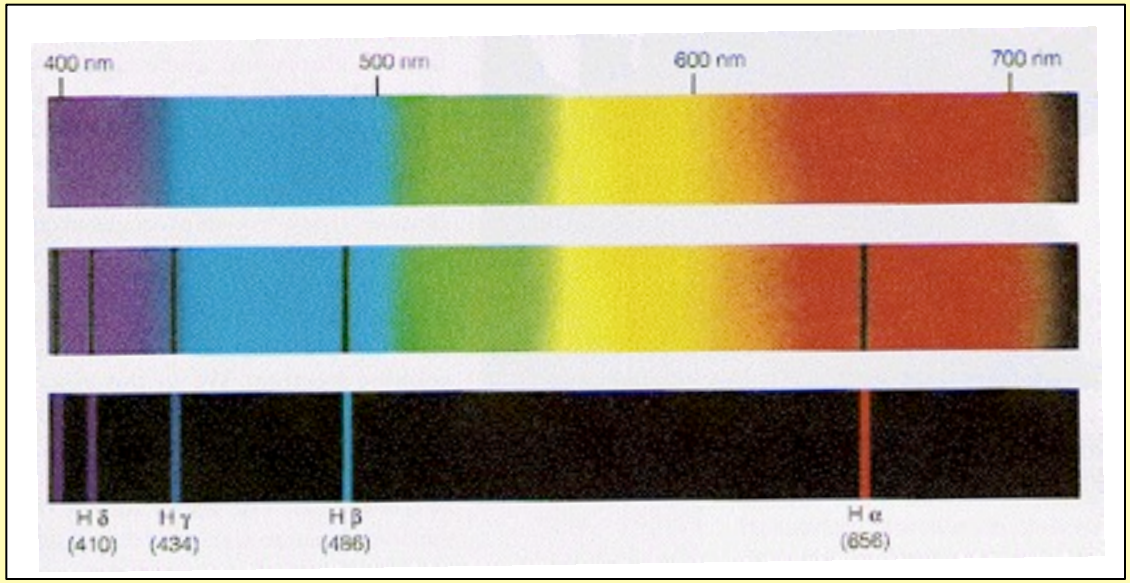




Emission spectrum

Absorption spectrum

Hydrogen spectrum



absorption spectrum

emission spectrum

Just before the beginning of the total eclipse a part of the solar atmosphere is visible as a very thin bright crescent. Its spectrum consists of lines in the form of crescents of different colours (so-called **flash spectrum**)

Spectra