On the Provability of Heliocentrism
II. Léon Foucault and the Rotation of the Earth

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Abstract. This paper deals with the experimental provability of heliocentrism from the scientific Renaissance in the beginning of the 17th century, till the Industrial Revolution of the 1850s. Foucault's famous pendulum demonstration is documented. We underline the importance of high accuracy of observations, the interdependence of hypotheses and theories, the impact of technological breakthroughs, the role of serendipity, the importance of fast and accurate publishing, and the need for precise science communication and teaching.

1. Introduction

That the Earth makes one revolution every 24 hours is, intuitively, even more difficult to accept than the annual motion: the daily rotation implies that an observer at average geographical latitude constantly moves with a speed of more than 20 km per minute. The expected consequences of moving at such speeds (considered as impossibly high in Galileo's times) were not felt – in particular the absence of an eternal strong wind blowing in the opposite direction of our motion – and that was a matter of great concern. It was also hard to conceive an experiment to prove this diurnal motion. One remarkable experiment was conducted by Marin Mersenne (1588–1648) in 1638, who fired a cannon ball to the zenith and verified if the motion of the underlying Earth would show up from an analysis of the cannon ball's landing place.[1]

A first quantitative indication that the Earth rotates came from Pierre Louis Moreau de Maupertuis (1698–1759), who measured a geodetic arc south of Lapland, and in 1735 concluded that the Earth was flattened at the poles: the oblate spheroid, under Newton's hypotheses, is an indirect proof of the Earth's rotation.

The real breakthrough in proving that the world turns came through the work of Jean Bernard Léon Foucault (1819–1868) in Paris (Fig. 1). Foucault was a self-taught French 19th-century experimental physicist and a very independent thinker, who systematically pursued extreme accuracy in all his experiments. One of his realisations was the construction of a conical pendulum regulator for the drive of the 38-cm refractor of Paris Observatory. The period T of such a pendulum involves the length l, the local gravitational constant g and the angle θ of the cone, yielding $T = 2\pi\sqrt{\frac{l\cos\theta}{g}}$, a generalisation of Galileo's formula for

[1]This experiment was suggested by Descartes in a 1634 letter to Mersenne.

Figure 1. Léon Foucault. (*Receuil des Travaux Scientifiques de Léon Foucault Publié par Madame Veuve Foucault sa Mère.* 1878, Gauthier-Villars, Paris).

the plane pendulum. As such, Foucault became an expert in pendulums and their isochronism.

Until the middle of the 19th century, the determination of the speed of light (c) was always a matter of astronomers and astronomical observations. Armand Hippolyte Louis Fizeau (1819–1896) and Léon Foucault brought the determination of c to the laboratory: in 1849 Fizeau obtained a "terrestrial" $c =$ 315 300 km s^{-1}, using a toothed-wheel setup with one lens system at his parents' house in Suresnes and the other one 8.6 km away in the vineyards of Montmartre (see Frercks 2000 for a description of the optical and mechanical systems). In 1850 Foucault improved the method using a steam-powered rotating mirror (up to 1000 rotations per second, see Fig. 2) to determine the relative speed of light through air and water, and finally obtained $c = 298\,000 \pm 500$ km s^{-1} in 1862 using an air-powered spinning mirror.[2]

2. Foucault's First Pendulum

In 1848 Léon Foucault happened to watch a long metal rod mounted in a rotating lathe. When twitching the rod, it appeared to oscillate in a plane, in spite of its rotating mounting point, and whatever the orientation of the chuck of the lathe. He then conceived and constructed a 2-meter pendulum[3] with a 5-kilo blob, in the cellar of his house in the Rue d'Assas in Paris (Fig. 3). Just like a vibrating rod "suspended" in the chuck of a rotating lathe oscillated in a fixed plane (with respect to the rotating support structure), his carefully constructed pendulum also oscillates in a fixed plane with respect to its support – the Earth. This precession can be understood as evidence for the Earth's rotation. In 1851, he

[2]The terrestrial determinations of the speed of light led to a definition of the metre by the International Bureau of Weights and Measures as 'the distance travelled by light in absolute vacuum in 1/299,792,458 of a second'.

[3]A very detailed account of Foucault's pendulum work was published by Tobin (2003).

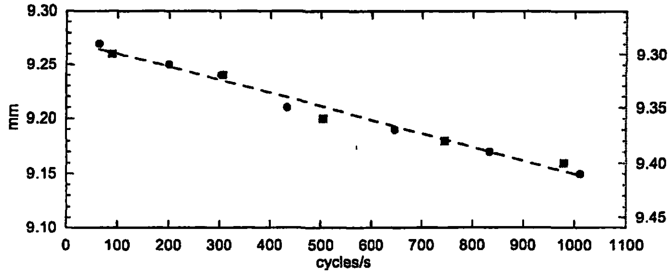

Figure 2. Results of the Foucault rotating mirror experiment. The vertical scales are micrometer readings, the horizontal axis gives the rotation frequency of the mirror in cycles per second. Dots indicate prograde rotation, squares (right axis) are readings from retrograde rotation. The resulting slope (dashed line) is 0.000123 mm per revolution per second.

repeats his experiment with an 11-meter pendulum in the meridian room (salle Cassini) of the Observatoire de Paris.

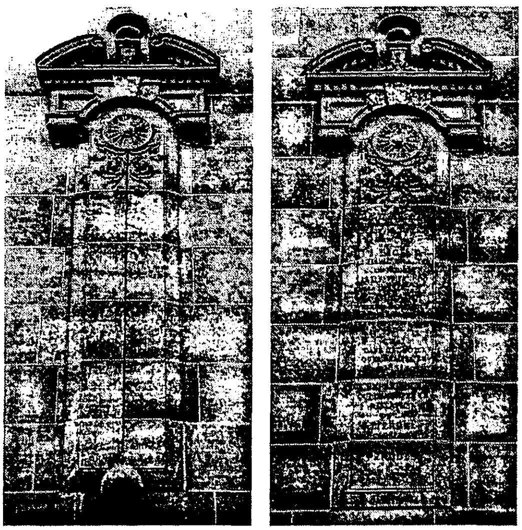

Figure 3. Reliefs commemorating the first Foucault pendulum in the Rue d'Assas in Paris. The text reads: "ICI S'ÉLEVAIT UN HÔTEL OÙ MOURUT LE 11 FÉVRIER 1868 JEAN BERNARD LÉON FOUCAULT. ... C'EST DANS CET HÔTEL QU'IL RÉALISA EN 1851 LA CÉLÈBRE EXPÉRIENCE QUI DÉMONTRE LA ROTATION DE LA TERRE PAR L'OBSERVATION DU PENDULE".

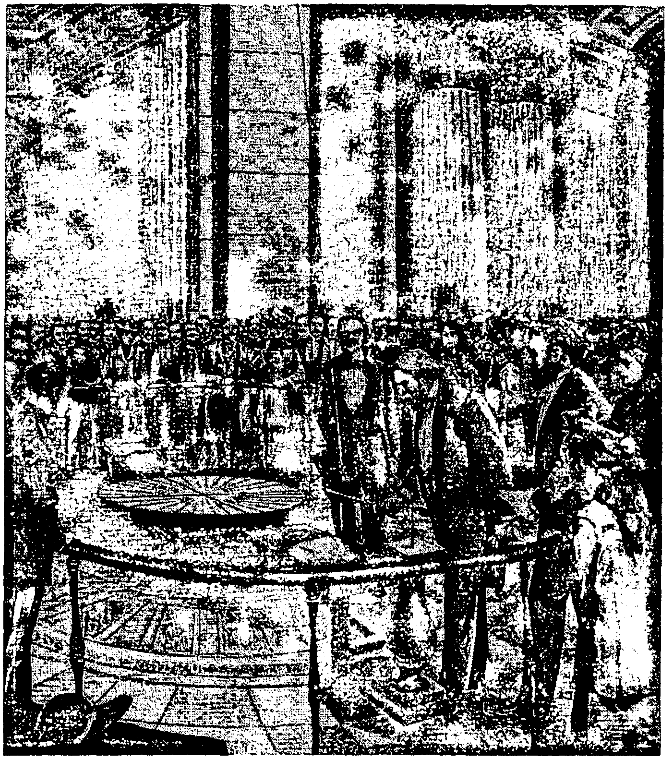

Figure 4. Replica pendulum set up in the Panthéon in 1902. Camille Flammarion (with beard) and Alphonse Berget (with spectacles) observe the then Minister of Public Instruction performing a "hands-free" release of the pendulum blob. Source: front page of the weekly colour supplement of *Le Petit Parisien*, courtesy William Tobin.

3. Public Demonstration

Next came a public demonstration in the Panthéon, the so-called *Temple de la Nation*, in the former Sainte-Geneviève church in Paris. The pendulum had a blob of 28 kilo (17 cm diameter) with a wire of 67 meter length, and the suspension fixture was made in a most careful way (Fig. 6). The oscillation period was 16 seconds, and the plane of oscillation appeared to turn leftward with a period of 31 hours 52 minutes, indicating the rotation of the Earth "under" the pendulum, as the invitation[4] *"Vous êtes invités à venir voir tourner la terre"* promised. The demonstration was a gigantic success, and the experiment was repeated over and over in all France's provinces and in many other countries.[5]

[4]You are invited to come and see the Earth rotate.

[5]A Foucault pendulum was also set up in the *Aula* building of the Ghent University.

4. The Theoretical Framework

The first astonishing element about this experiment, is that there was no physical theory supporting it. Moreover, intuitive expectations would rather anticipate a 24-hour veering period than anything else. Foucault, mainly using his intuition, and without using mathematical deductions, introduced the so-called sine factor for explaining the speed of veering: the rotation period of the oscillating plane corresponds to 24 hours divided by the sine of the geographical latitude. At the latitude of Paris (48°50′), the resulting rotation period is close to 32 hours. The oscillation plane of a pendulum at one of the poles will thus rotate in one (sidereal) day, and a pendulum on the equator will thus not rotate at all.

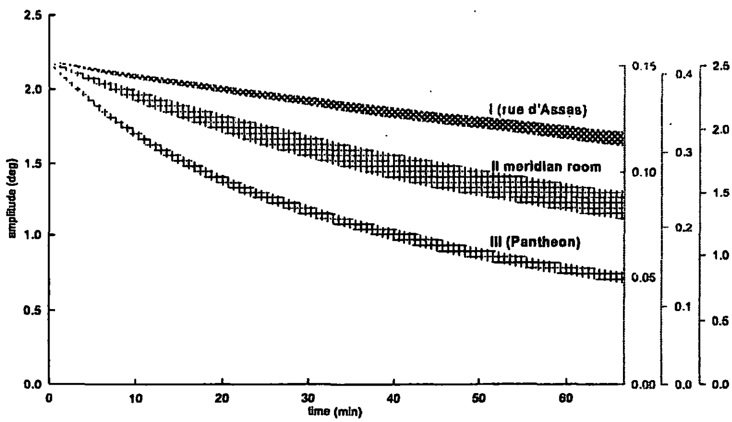

Figure 5. Calculated damping for Foucault's 1851 pendulums. The widths of the traces indicate the ranges expected due to different factors. Based on Fig. 9.26 in Tobin (2003).

Several members of the Academy put forward an explanation for the sine factor: Jacques Binet, Joseph Liouville, Louis Poinsot, and so on, but none could give a satisfactory theoretical explanation.[6] In addition, the mathematicians were not very pleased with the fact that someone not trained in mathematics could produce a 'universal' formula out of the observation of a phenomenon from just one single location.

The underlying physical principle of the the Foucault pendulum is the force proposed by Gaspard Gustave de Coriolis (1792–1843) in his 1835 work *Sur les equations du movement relative des systems des corps.* This is a fictitious force affecting bodies in rotation, acting sideways on the body, in a direction perpendicular to its direction of motion. A complete mathematical and physical treatment was offered by Heike Kamerlingh Onnes (1853–1929) in his PhD thesis,[7] where he gave theoretical as well as experimental proof that Foucault's

[6] See Tobin (2003) and also Aczel (2003, 2004) for details.

[7] NIEUWE BEWIJZEN VOOR DE ASWENTELING DER AARDE. Groningen, 1879.

pendulum experiment is a special case of a group of phenomena which can be used to prove the rotation of the Earth.

4.1. Hidden Problems

The *Times*, in 1851, wrote "the experiment is so simple that the least scientific of your readers can try it" (quoted by Tobin 2003). Anyone who ever tried to construct a Foucault pendulum knows that this is not exactly true: the Coriolis force is subtle, and the least disturbance will alter and even destroy the veering effect. One of the main practical difficulties is damping, as is illustrated in Fig. 5, which gives the calculated amplitude decay for Foucault's 1851 pendulums, assuming they were swung with the same initial amplitude.[8] Another effect is looping: the deterioration of the straight-line motion in elliptical loops, produced by asymmetries in the construction of the pendulum blob and in the design of the suspension fixture. The initial conditions at startup are also very critical, see Fig. 6 which shows how Foucault tried to minimize disturbances introduced by the "operator" at startup. The operational requirements for a Foucault pendulum thus are: free rotation at the suspension point, a blob with isotrope mass distribution, minimal damping, a long wire, and a start-up procedure without any kind of interference. For an in-depth description of all disturbing effects, see Tobin (2003) and van Delft (2005), and also Kamerlingh Onnes (1879) for a rigorous mathematical treatment.

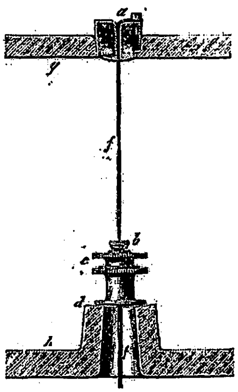

Figure 6. Elimination of disturbances. *Left:* suspension of the wire of the 1851 Panthéon pendulum (*Receuil des Travaux Scientifiques de Léon Foucault*). *Right:* Detail of Fig. 4.

5. The Two Aspects of Heliocentrism

Foucault's famous demonstration with the pendulum, and his even more assuring experiments with the gyroscope, were convincing "proofs" in their own right

[8]Based on Fig. 9.26 in Tobin (2003).

that the Earth rotates and thus causes the diurnal motion of the heavens. Our own "experiments" of daily life – transatlantic travel, satellite-supported communication and the exploration of space – continuously confirm the validity of the heliocentric worldview.[9]

Galileo's and Rømer's work, on the other hand, was not as solidly conclusive as was Foucault's, simply because no measurable parallax could be produced – though more than one claim was published. But observational persistence, together with an ever increasing accuracy of measuring apparatus and solid methodology of procedures of analysis, made the body of growing evidence for the annual motion of the Earth more and more compelling.

James Bradley (1693–1762), using a very accurate zenith telescope, discovered the phenomenon of *stellar aberration* in December 1725. Aberration supports the heliocentric doctrine in much the same way as does the light-time effect: one theory goes in tandem with the other, but both phenomena are by no means explicable by the competing geocentric worldview[10]. So, Bradley (1738) concludes:

> *" it must be granted that the parallax of the fixed stars is much smaller than hath been hitherto supposed by those who have pretended to deduce it from their observations ... I am of the opinion, that if it were 1″, I should have perceived it ... "*

This is the first published statement supporting the view that the failure of measuring parallax is not to be ascribed to the underlying scientific model, but is entirely due to inadequate observational results. That conclusion seems to have stopped the quest for parallax for almost one century.

It was Friedrich Wilhelm Bessel (1784–1846), Thomas Henderson (1789–1844) and Friedrich Wilhelm Struve (1793–1864) who finally undertook to measure the parallax of stars with high proper motion. Bessel (1838) showed that 61 Cygni has a parallax of $0\overset{''}{.}3136 \pm 0\overset{''}{.}0202$, leading to a distance of 657 700 astronomical units.[11] These findings led to the inevitable conclusion that the Sun occupies a central place (in our planetary system), but also that the nearest stars are at fabulous distances. The discovery of parallax not only proved heliocentrism, it also yielded the first realistic estimate of the size of the solar neighborhood.

6. The Lessons of the Quest for the Proof of Heliocentrism

Finding sufficient experimental evidence for establishing the validity of the heliocentric doctrine took more than 300 years after Copernicus' proposition of the model. The quest for evidence supporting heliocentrism through creativity and

[9]Not in the literal medieval sense that the Sun is the center of the universe, but that the Sun is the dominant body in the solar system.

[10]The new data led Bradley (1727) to a new estimate of the velocity of light: 301 000 km s^{-1}.

[11]In fact, Henderson obtained the first parallax (to α Centauri: $0\overset{''}{.}9128 \pm 0\overset{''}{.}0640$), but he did not immediately publish it, Bessel was the first to publish an accurate parallax measurement.

technology contains many school examples of the hidden dangers and difficulties of scientific experimentation in the broadest sense.

Publication of scientific results. Galileo, Rømer and Foucault taught us a very important lesson on the necessity of *fast* and *accurate* communication of scientific results – to the scientific world as well as to the public.

Galileo published fast (in a tempo that is unthinkable even today), using clear and direct language, except when he was reluctant to reveal his newest discoveries. His anagram letter to Kepler announcing the important observation that Venus shows phases: "Haec immatura a me iam frustra leguntur o y", rendered as *Cynthiae figuras aemulatur mater amorum*[12], is one of the history of science's finest examples of retaining credit by revealing a discovery in a "covered" way. But also Fizeau and Foucault used a method with quite similar effect under the form of the so-called "Pli cacheté", or sealed document. The practice of sealing submissions under this form had been established by the Paris Academy in the 17th century, when it was granted royal authority to issue patents for new inventions in all of France. Such a submission, which would be sealed in the presence of the entire membership, was then placed in safekeeping with the academy's secretary until the inventor would recall it (Cohen 1983).[13] Bessel published accurately and fast, Henderson, on the other hand, waited too long to make his data public, and missed the credit being the first to measure parallax. He should, perhaps, have considered the anagram or Pli cacheté method, though it is very likely that he considered that he had not yet brought his experiment[14] to a close. Rømer used a fast communication channel for publishing his findings, unfortunately he failed to safeguard his data for posteriority. A lot can be said about the publishing business, but there is a considerable truth in the words of Kennedy (1997)[15]

> *"All the thinking, all the textual analysis, all the experiments and the datagathering aren't anything until we write them up. In the world of scholarship, we are what we write."*

Communication of scientific results to the public. Foucault vividly demonstrated that disclosing a discovery to the community at large not only is something that is necessary, but also very rewarding in terms of moral and financial support. He was also fully aware that some degree of *dramatisation* in the exposition to the public and to the political and scientific peers is very lucrative. As such, the Foucault pendulum became a standard demonstration in schools, universities and science museums around the world. It is a matter of deep regret that science teaching in schools – and the history of science teaching in universities – is quite often done in a rather sloppy way. The last diagram of Paper I

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[12] Venus (the mother of love) imitates the shape (phases) of Cynthia (the Moon).

[13] These sealed documents and boxes are now real treasure troves for historians of science. The Pli cacheté custom lost its power when some authors began to submit two Plis at the same time, requesting later that only one of the two should be published.

[14] The observations were conducted by Thomas Maclear (1794–1879).

[15] Rector emeritus of Stanford University.

is but one example. From my own school days I recall that we were taught that it was Rømer who was the first to measure the velocity of light. Later even I learned that water going down the drain does this in clockwise sense in the southern hemisphere, although the Coriolis force is so subtle that local disturbances (e.g. the shape of the tub) completely dominate the phenomenon.

Science and politics. It is very widely known that Galileo ran into severe problems because of his teachings on the mobility of the Earth. It is much less known that Foucault's work invoked a very opposite political reaction. Prince Charles Louis-Napoléon Bonaparte (1808–1873), President of the French Republic from 1848 to 1851 (who later became Emperor Napoléon III, till 1870), had a keen interest in physics, and he even read the reports of the meetings of the Academy. So it was Louis-Napoléon who ordered the 67-m pendulum being set up and demonstrated in his beloved domed temple on the Mont Sainte Geneviève in the *Quartier Latin* (Aczel 2003). The building had switched back and forth from church to secular temple several times, and exhibiting this final proof of heliocentrism in an ex-church was a very strong demonstration of the future emperor's secular powers.

The universal character of explanations of experimental results. Proving heliocentrism through astronomical observations was never total: the proof always depended on the finitness of the speed of light (and vice versa). But Cassini was fully right requiring that any scientific hypothesis or explanation should be universal, and not just "prove" one single case.

The role of serendipity in scientific discovery. Galileo's visual discoveries can hardly be termed serendipitous: he had made a good-quality telescope and simply turned it to the heavens. Rømer 's discovery relied on a high degree of serendipity in the sense that he was given access to a long time baseline of eclipse timings, and that he could afford a prediction at the moment when the deviating effect was greatest (see Fig. 13 in Paper I). Bradley's discovery of aberration was a byproduct of his search for parallax, and his good fortune was that the displacement he found for the star γ Draconis was – at that time of the year – not in the direction expected for a shift by parallax. And Foucault, in Paris, was lucky too: we can only guess what he would have concluded if he had devised his experiment in Quito or in Singapore.

Experimental errors, and the theory of the apparatus. Rømer had expert knowledge about his telescopes and measuring devices. So had Flamsteed, Bradley, Struve, Bessel, Fizeau. And certainly Foucault: see, for example Fig. 2, where the results of prograde and retrograde mirror rotation are combined to produce one single result: both experiments yield different precision, but combined they render a higher accuracy. Experimental sloppiness was fatal in the quest for parallax: many observers rushed to print too fast, often contributing only junk data (parallaxes up to almost 3 arcseconds were reported).

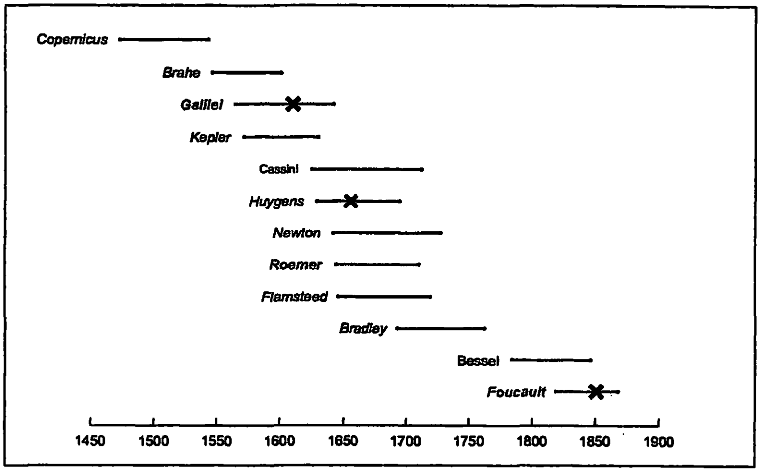

Figure 7. Heliocentrism timeline: *dramatis personae* are Galilei, Rømer and Foucault. The × symbols indicate the moments of technological breakthroughs driving the experiments: invention of the telescope in 1610, the pendulum clock in 1654, and the many discoveries of the 19th century industrial revolution (high-precision equipment, steam engine, etc.).

7. Postscript

Provability (or demonstrability) is the capability of being demonstrated or logically proved. But it is not appropriate to speak of an *absolute proof* of a scientific theory: a theorical model is never final, and is always open to revision and falsification. As Charles Darwin[16] stated:

> *"...for with the exception of the Coral Reefs, I cannot remember a single first-formed hypothesis which had not after a time to be given up or greatly modified."*

Fuller (2004) reflects on the epistemic[17] demotion of scientific theories by casting them as flexible rhetorics that can be deployed to suit the occasion. The relativistic viewpoint that scientific truths and facts are pure intellectual constructions solely depending on the individuals holding them, is not supported by the experimental justification of heliocentrism. What is important with both "experiments" – Rømer's and Foucault's – is that they were carried out without the help of any theory telling them which data to look for. In other words:

[16]One should not forget that the final breakthrough in proving heliocentrism occurred almost simultaneously with the emergence of darwinism in 1859 with the publication of Darwin's *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.*

[17]Epistemology refers to the study of the nature of knowledge, especially with reference to the relationship between knowledge of the world and the realist world.

there was no theoretical framework driving them or leading them by the nose. Foucault carried through his demonstrations after careful observation of a mechanical analogy, and the theories came later: Foucault's was a true "discovery-motivated" project. Rømer did not attempt to prove any theory, he was just timing eclipses for plain surveying purposes, and solved the enigma of the finite character of the speed of light – and received support for the heliocentric doctrine for free.

The process of proving heliocentrism was driven by the fusion of the tools for exploring with the unique personality of each of these three main actors, in tandem with the surrounding social and cultural influences. Figure 7 shows a timeline for heliocentrism with the *dramatis personae* Galilei, Rømer and Foucault, and the moments of technological breakthroughs that drove their crucial experiments. But all actors listed in Fig. 7 – experimenters as well as theorists – possessed one common distinguishing quality: extreme consideration for cutting-edge scientific accuracy in measurement, theory and report.

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