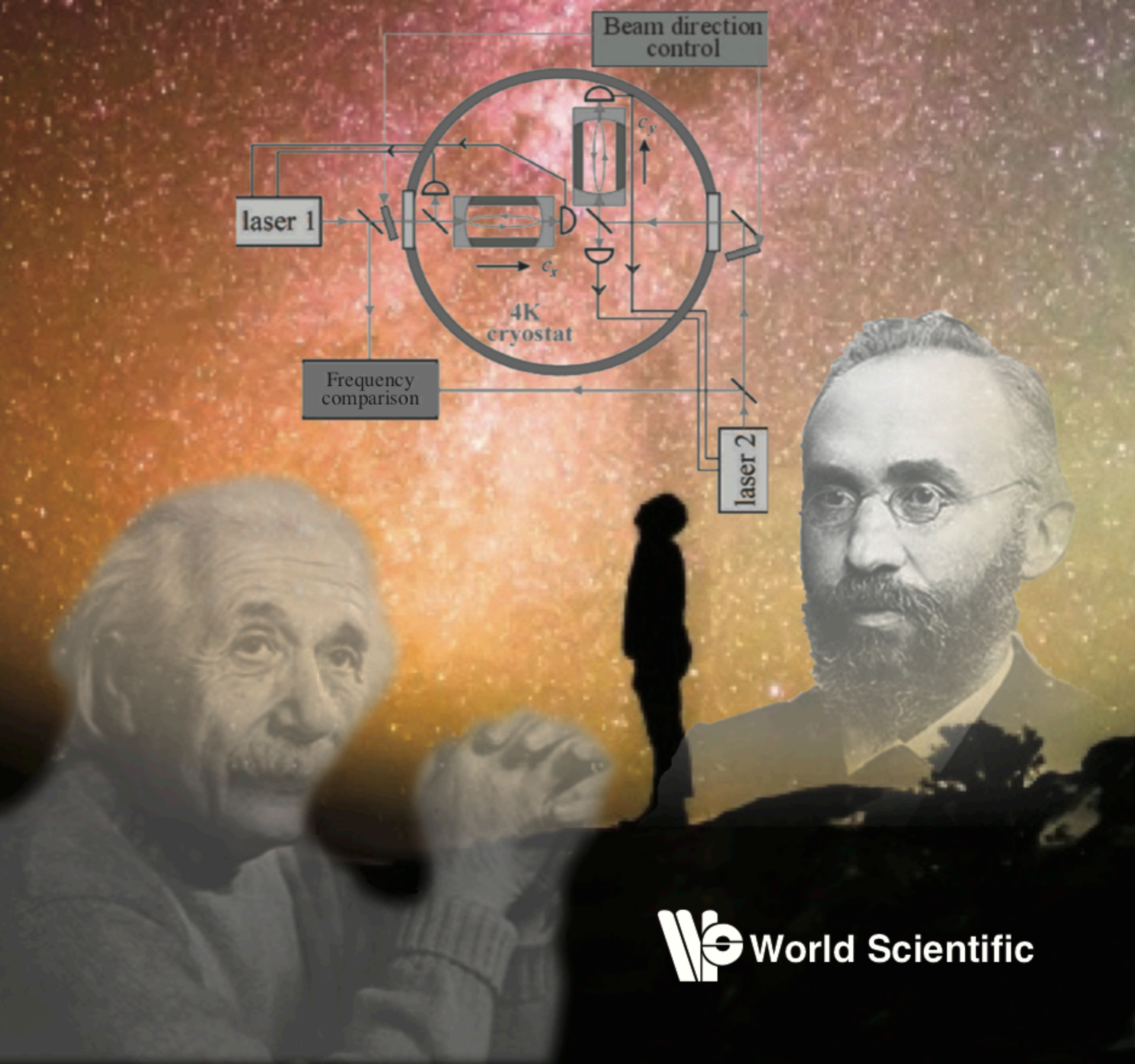
Maurizio Consoli • Alessandro Pluchino

Michelson-Morley Experiments

An Enigma for Physics and the History of Science



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11209_9789813278189_tp.indd 2 16/10/18 3:06 PM

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

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

The cover shows the scheme of the modern Michelson–Morley experiment by H. Müller *et al.* in *Phys. Rev. Lett.* 91 (2003) 020401 with the portraits of Albert Einstein and Hendrik Anton Lorentz.

MICHELSON–MORLEY EXPERIMENTS
An Enigma for Physics and the History of Science

ISBN 978-981-3278-18-9

For any available supplementary material, please visit
https://www.worldscientific.com/worldscibooks/10.1142/11209#t=suppl

Desk Editor: Christopher Teo

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore

Preface

Subtle is the Lord but malicious He is not.

A. EINSTEIN, 1921

The Lord whose oracle is at Delphi
neither reveals nor conceals but gives a sign.

HERACLITUS, V Century B. C.

In 1887 Michelson and Morley tried to detect in laboratory a small difference of the velocity of light propagating in different directions that, according to classical physics, should have revealed the motion of the earth in the ether ("ether drift"). The result of their measurements, however, was much smaller than the classical prediction and considered as a typical instrumental artifact: a "null result". This was crucial to stimulate the first, pioneering formulations of the relativistic effects and, as such, represents a fundamental step in the history of science.

Nowadays, this original experiment and its early repetitions performed at the turn of 19th and 20th centuries (by Miller, Kennedy, Illingworth, Joos...) are considered as a venerable, well understood historical chapter for which, at least from a physical point of view, there is nothing more to refine or clarify. All emphasis is now on the modern versions of these experiments, with lasers stabilized by optical cavities that, apparently, have confirmed the null result by improving by many orders of magnitude on the limits placed by those original measurements.

Though, this is not necessarily true. In the original measurements, light was propagating in gaseous systems (air or helium at atmospheric pressure) while now, in modern experiments, light propagates in a high vacuum or inside solid dielectrics. Therefore, in principle, the difference with the modern experiments might not depend on the technological progress only but also on the different media that are tested thus preventing a straightforward comparison.

This is even more true if one takes into account that, in the past, greatest experts (as Hicks and Miller) have seriously questioned the traditional null interpretation of the very early measurements. The observed "fringe shifts", although much smaller than the predictions of classical physics, were often non negligible as compared to the extraordinary sensitivity of the interferometers. Therefore, in some alternative scheme, the small residuals could acquire a definite physical meaning.

By starting from this observation, in the last few years we have formulated a new theoretical framework where these residual effects could represent the first experimental indication for the earth motion within the Cosmic Microwave Background (CMB). In fact, in this alternative scheme, the small observed residuals show surprising correlations with the direct observations of the CMB dipole anisotropy with satellites in space.

The possibility of finally linking the CMB with the existence of a fundamental reference frame for relativity, and the substantial implications for the interpretation of non-locality in the quantum theory, would be of paramount importance. Therefore, we should preliminarily explain at least the key ingredients of our alternative scheme.

First of all, one should not compare the data with the classical predictions but impose that all measurable effects vanish exactly if the velocity of light c_γ propagating in the various interferometers, or more precisely its two-way combination $\bar{c}_\gamma$, coincides with the basic parameter c entering Lorentz transformations. This is the *ideal* vacuum limit of a refractive index $\mathcal{N} = 1$ where no ether drift should be observed. Instead if $\bar{c}_\gamma \neq c$, as for instance in the presence of matter, where light gets absorbed and then re-emitted, nothing would really prevent a non-zero light anisotropy $\Delta\bar{c}_\theta = \bar{c}_\gamma(\pi/2+\theta) - \bar{c}_\gamma(\theta) \neq 0$.

Then, in the infinitesimal region $\mathcal{N} = 1+\epsilon$, which corresponds for instance to gaseous systems, one can expand $\Delta\bar{c}_\theta$ in powers of the two small parameters ϵ and $\beta = v/c$, v being the velocity of the laboratory system with respect to the hypothetical preferred frame. By simple symmetry arguments, this expansion leads to the relation $\frac{|\Delta\bar{c}_\theta|}{c} \sim \epsilon\beta^2$ which is much smaller than the estimate $\frac{|\Delta \bar{c}_\theta|_{\rm class}}{c} \sim \beta^2/2$ of the classical calculation. To have an idea, for experiments in air at room temperature and atmospheric pressure, where $\epsilon \sim 2.8 \cdot 10^{-4}$, and for the typical projection $v \sim 300$ km/s of the earth cosmic motion where $\beta^2 = 10^{-6}$, our estimate would still be about 17 times smaller than the classical prediction for the much smaller traditional orbital value $v = 30$ km/s where $\beta^2 = 10^{-8}$. For helium at room temperature and atmospheric pressure, where $\epsilon \sim 3.3 \cdot 10^{-5}$, our expectation would even be 150 times smaller. This could now explain the order of magnitude of the observed effects.

The other peculiar aspect of our analysis concerns the time dependence of the data. Here, the traditional view is that, for short-time observations of a few days, where there are no sizeable changes in the orbital motion, a genuine physical signal should precisely follow the slow and regular modulations induced by the earth rotation. The fringe shifts instead were showing an irregular behavior indicating sizeably different directions of the drift at the same hour on consecutive days so that statistical averages were much smaller than all individual values. Within the traditional view, this has always represented a strong argument to interpret the measurements as mere instrumental artifacts.

Again, however, there might be a logical gap. The relation between the macroscopic earth motion and the microscopic propagation of light in a laboratory depends on a complicated chain of effects and, ultimately, on the physical nature of the vacuum. By comparing with the motion of a body in a fluid, the standard view corresponds to a form of regular, laminar flow where global and local velocity fields coincide. Instead, some arguments suggest that the *physical vacuum* might rather behave as a stochastic medium which resembles a highly turbulent fluid where large-scale and small-scale flows are only *indirectly* related.

In this different perspective, with forms of turbulence which, as in most models, become statistically isotropic at small scales, the direction of the local drift is a completely random quantity that has no definite limit by combining a large number of observations. Thus, one should first analyze the data in phase and amplitude (which give respectively the instantaneous direction and magnitude of the drift) and then concentrate on the latter which is a positive-definite quantity and remains non-zero under any averaging procedure. In this alternative picture, a non-vanishing amplitude (i.e. definitely larger than the experimental resolution) is the signature to separate an irregular, but genuine, signal from instrumental noise.

By implementing these two ingredients, the classical experiments in gaseous systems can now become consistent with the earth velocity of 370 km/s deduced from the direct CMB observations. In particular, from a fit to Joos's 1930 very precise observations (data collected during all 24 hours to cover the full sidereal day and recorded automatically by photocamera), we have also obtained some information on the angular parameters of the earth motion, namely right ascension $\alpha(\text{fit}-\text{Joos}) = (168\pm30)$ degrees and angular declination $\gamma(\text{fit}-\text{Joos}) = (-13\pm14)$ degrees, to compare with the present values $\alpha(\text{CMB}) \sim 168$ degrees and $\gamma(\text{CMB}) \sim -7$ degrees. This consistency gives good motivations for a new generation of dedicated experiments to reproduce the experimental conditions of those old measurements with today's much greater accuracy.

Meanwhile, waiting for this definitive test, we have tried to obtain a different check with modern experiments *in vacuum*. The point is that in the *physical vacuum* the velocity of light may still differ from the parameter c of Lorentz transformations. This might be due to several reasons. For instance, some authors have suggested that the curvature observed in a gravitational field might represent a phenomenon which emerges from a fundamentally flat space-time. This would be in analogy with some condensed-matter systems (such as moving fluids, Bose-Einstein condensates...) at length scales much larger than the size of their elementary constituents. In this picture, one expects a tiny vacuum refractivity $\epsilon_v \sim 10^{-9}$ which accounts for the difference between an apparatus in an ideal freely-falling frame and an apparatus on the earth surface.

Then, if our interpretation of the classical experiments is correct, we would also expect a very small anisotropy $\frac{|\Delta\bar{c}_\theta|_v}{c} \sim \epsilon_v\beta^2 \sim 10^{-15}$ which could be detected by measuring the frequency shift of two vacuum optical resonators. More precisely, in our picture, this is the expected magnitude of the *instantaneous*, irregular signal. Its statistical average $\frac{|\langle\Delta\bar{c}_\theta\rangle_v|}{c}$ after many observations should instead be much smaller, say 10^{-18}, 10^{-19}..., and vanish in the limit of an infinite statistics. As we will illustrate, this expectation is consistent with the most recent room temperature and cryogenic vacuum experiments thus providing further support for our alternative interpretation.

Now, as it is well known, symmetry arguments give often a good description of phenomena independently of the underlying physical mechanisms. As such, our view of the classical experiments in gaseous systems, in terms of a light anisotropy $\frac{|\Delta\bar{c}_\theta|}{c} \sim \epsilon\beta^2$, does not necessarily contradict the standard interpretation of those old measurements as due to thermal disturbances. Indeed, these disturbances are also known to become smaller and smaller when $\epsilon \to 0$.

For this reason, and for the overall consistency of the data, the small temperature variations of a millikelvin in the air of the optical arms assumed by various authors (and never fully understood) to explain Miller's Mt. Wilson observations might have a *non-local* origin somehow associated with an absolute earth velocity v. After all, our motion within the CMB gives the same order of magnitude $[\Delta T(\theta)]_{\mathrm{CMB}} \sim \pm 3$ mK. As we will show, this thermal interpretation could provide a dynamical basis for the *enhancement* found in the gas case (i.e. the observed magnitudes $\frac{|\Delta \bar{c}_\theta|_{\mathrm{air}}}{c} = \mathcal{O}(10^{-10})$ for air and $\frac{|\Delta \bar{c}_\theta|_{\mathrm{helium}}}{c} = \mathcal{O}(10^{-11})$ for gaseous helium vs. the much smaller vacuum value $\frac{|\Delta \bar{c}_\theta|_{v}}{c} \lesssim 10^{-15}$) and, at the same time, could also help to understand the differences and the analogies with the most precise experiment in solid dielectrics where again an *instantaneous* value $\frac{|\Delta \bar{c}_\theta|_{\mathrm{solid}}}{c} \lesssim 10^{-15}$ (as in the vacuum case) is presently observed. In this way, symmetry arguments, on the one hand, would motivate and, on the other hand, would find justification in underlying physical mechanisms, with an overall increase of our understanding.

We emphasize that this book is primarily a monograph about the *physics* of these experiments. However, the *history* of this research is also interesting and sometimes even dramatic for the strong personal commitment of some scientist. For this reason, several historical accounts have been included as a useful supplementary material.

In conclusion, our work should motivate the reader to sharpen his own understanding of both classical and modern Michelson-Morley experiments. Then, it will become evident that their standard null interpretation, presented in all textbooks and specialized reviews as the most evident scientific truth, is very far from obvious and most probably wrong. This is why these experiments represent an enigma for physics and the history of science. In view of their fundamental importance, we hope that our book will induce to refine substantially the experimental tests and the analysis of the data thus contributing to reach a higher level of collective awareness.

Acknowledgments

We thank our friends and colleagues Evelina Costanzo, Caroline Matheson, Angelo Pagano, Lorenzo Pappalardo and Andrea Rapisarda for many useful discussions and their precious collaboration.

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Contents

Chapter 1

You, my honored Herr Michelson began this work when I was only a small boy, not even a meter high. It was you who led the physicists into new paths, and through your marvelous experimental labors prepared for the development of the relativity theory. You uncovered a dangerous weakness in the ether theory of light as it then existed, and stimulated the thoughts of H. A. Lorentz and Fitzgerald from which the special theory of relativity emerged.

A. EINSTEIN, Speech in honor of Michelson, Pasadena,15 January 1931.

1.1 Premise

The Michelson-Morley experiment [1] was designed to check Maxwell's classical prediction [2] that if the earth drifts in the ether with a velocity v there should be an anisotropy $\frac{|\Delta \bar{c}_\theta|}{c} \sim \frac{v^2}{c^2}$ of the two-way velocity of light in the earth frame[1]. Michelson's idea was to detect this tiny effect by observing the interference fringes of two light rays propagating back and forth along perpendicular directions.

To introduce the argument, let us consider the two-way velocity of light $\bar{c}_\gamma(\theta)$. This is the only one that can be measured unambiguously and is

[1]Actually, Maxwell's estimate is larger by a factor of two than the standard classical prediction $\frac{|\Delta \bar{c}_\theta|}{c} \sim \frac{v^2}{2c^2}$, see Chapt.3.

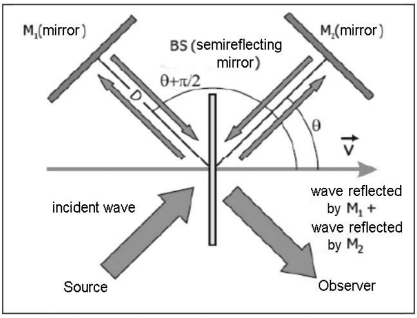

Fig. 1.1 *The typical scheme of Michelson's interferometer.*

defined in terms of the one-way velocity $c_\gamma(\theta)$ as

$$\bar{c}_\gamma(\theta) = \frac{2\ c_\gamma(\theta) c_\gamma(\pi+\theta)}{c_\gamma(\theta) + c_\gamma(\pi+\theta)} \tag{1.1}$$

where θ represents the angle between the direction of light propagation and the earth velocity with respect to the hypothetical preferred frame Σ.

By introducing the anisotropy

$$\Delta\bar{c}_\theta = \bar{c}_\gamma(\pi/2+\theta) - \bar{c}_\gamma(\theta) \tag{1.2}$$

there is a simple relation with the time difference $\Delta t(\theta)$ for light propagation back and forth along perpendicular rods of length D (see Fig.1.1)

$$\Delta t(\theta) = \frac{2D}{\bar{c}_\gamma(\theta)} - \frac{2D}{\bar{c}_\gamma(\pi/2+\theta)} \sim \frac{2D}{c}\ \frac{\Delta\bar{c}_\theta}{c} \tag{1.3}$$

(where, in the last relation, we have assumed that light propagates in a medium of refractive index $\mathcal{N} = 1+\epsilon$, with $\epsilon \ll 1$). This gives the fringe patterns (λ is the light wavelength)

$$\frac{\Delta\lambda(\theta)}{\lambda} \sim \frac{2D}{\lambda}\ \frac{\Delta\bar{c}_\theta}{c} \tag{1.4}$$

and could be measured, in principle, by rotating the apparatus.

The classical prediction (see e.g. [3] for a simple derivation) was

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{\rm class} \sim \frac{D}{\lambda}\frac{v^2}{c^2}\cos 2\theta \tag{1.5}$$

and, for the Michelson-Morley apparatus, the relevant value was $(D/\lambda) \sim 2\cdot 10^7$. Therefore, for $v = 30$ km/s (the earth orbital velocity about the sun, and consequently the minimum anticipated drift velocity) where $v^2/c^2 = 10^{-8}$, under a 90 degree rotation, one was expecting a shift

$$\left[\frac{\Delta\lambda(0)}{\lambda} - \frac{\Delta\lambda(\pi/2)}{\lambda}\right]_{\text{class}} \sim \frac{2D}{\lambda}\frac{v^2}{c^2} \sim 0.4 \qquad (1.6)$$

that would have been about *hundred times larger* than the extraordinary sensitivity of the apparatus, about ± 0.004 [1, 4, 5].

Instead, in the various experimental sessions, the observed shifts were about $10 \div 20$ times smaller than expected [6, 7]. By using Eq.(1.5), these values were indicating earth velocities of about $6 \div 10$ km/s which have no obvious interpretation. In addition, the observed pattern was irregular because observations performed at the same hour on consecutive days were showing sizeable differences. The simultaneous presence of these two aspects gave a strong argument to consider the data as typical instrumental effects, i.e. a "null" result.

The acceptance of this view, indicating a failure of the classical ideas and/or the non-existence of the ether, had a strong impact on the scientific ambiance and was crucial to stimulate the first, pioneering formulations of the relativistic length contraction and time dilation effects, by Fitzgerald in 1889 [8], Lorentz in 1895 [9] and 1899 [10], Larmor in 1897 [11] and 1900 [12]. These original developments of the theory of the electromagnetic ether induced Lorentz in 1904 [13] and Poincaré in 1905 [14] to derive a particular set of transformations of the space-time coordinates (Lorentz Transformations) : "Applying one of such transformations amounts to an overall translation to the whole system. Then two frames, one at rest in the ether and one in uniform translation, become the perfect images of each other". This statement of Poincaré in 1905 was the precise formalization of the Principle of Relativity, already proposed by him in La Science et l'Hypothese (Flammarion, Paris 1902) and at the 1904 St. Louis Conference [15][2].

[2] Poincaré's precise words to formulate this principle in his 1904 address are: "The principle of relativity, according to which the laws of physical phenomena should be the same, whether for an observer fixed, or for an observer carried along in a uniform movement of translation; so that we have not and could not have any means of discerning whether or not we are carried along in such a motion" [16]. In the same address, Poincaré was also concluding that "From all these results, if they are confirmed, would arise an entirely new mechanics, which would be, above all, characterized by this fact, that no velocity could surpass that of light, any more than any temperature could fall below the zero absolute, because bodies would oppose an increasing inertia to the causes, which would tend to accelerate their motion; and this inertia would become infinite when one approached the velocity of light" [16].

This first historical phase and its relation with special relativity [17] can be well described by quoting, twice, Einstein himself. The first quotation is from his address to Michelson during a social gathering of scientists at the California Institute of Technology in mid-January 1931: "You, my honored Herr Michelson began this work when I was only a small boy, not even a meter high. It was you who led the physicists into new paths, and through your marvelous experimental labors prepared for the development of the relativity theory. You uncovered a dangerous weakness in the ether theory of light as it then existed, and stimulated the thoughts of H. A. Lorentz and Fitzgerald from which the special theory of relativity emerged" [18].

The second quotation is from an Einstein's interview delivered in 1955, a few months before his death. When asked, once more, about his original view and the relation with previous work he said: " There is no doubt that the theory of relativity, if we regard its development in retrospect, was ripe for discovery in 1905. Lorentz had already observed that the transformations which later were known by his name were essential for the analysis of Maxwell equations and Poincaré had even penetrated deeper into these connections. Concerning myself, I knew only Lorentz' important work of 1895 but not his later work nor the consecutive investigations by Poincaré. In this sense my work of 1905 was independent. The new feature of it was the realization that the bearing of Lorentz transformations transcended its connection with Maxwell equations and was concerned with the nature of space and time in general. The new result was that Lorentz invariance was the general condition for any physical theory" [19].

Thus, one could summarize as follows: (i) the Michelson-Morley experiment was crucial for the first formulation of the relativistic effects within the theory of the electromagnetic ether (ii) later on, by Einstein, relativity was recognized as a doctrine of nature and formulated in an axiomatic form, free of any association with ether and electromagnetism[3].

[3]Over the years, Einstein made different statements about the inception of relativity and the possible influence that the Michelson-Morley experiment had on his views. For instance, Holton [5] reports the following sentence: "In my own development Michelson's result has not had a considerable influence. I even do not remember if I knew of it at all when I wrote my first paper on the subject (1905). The explanation is that I was, for general reasons, firmly convinced that there does not exist absolute motion and my problem was only how this could be reconciled with our knowledge of electrodynamics. One can therefore understand why in my personal struggle Michelson's experiment played no role or at least no decisive role". At the same time, this other statement is reported by van Dongen [20]: "As a young man I was interested, as a physicist, in the question what is the nature of light, and, in particular, what is the nature of light with respect to bodies. That is, as a child I was already taught that light is subordinate to the oscillations of the

Such premise is essential to properly frame the Michelson-Morley experiment in the history of physics. At the same time, nowadays, there is the tendency to consider this fundamental experiment, and its classical repetitions at the beginning of 20th century by Miller [7], Illingworth [21], Joos [22] ... as an old, well understood historical chapter for which there is nothing more to refine or clarify. All emphasis is now on the modern versions of these experiments, with lasers stabilized by optical cavities (see e.g. [23] for a review), which apparently have improved by orders of magnitude on those original measurements [24].

However, a basic aspect has been overlooked by most authors. The various measurements were performed in different conditions, i.e. with light propagating in gaseous media (as in [1,7,21,22]) or in a high vacuum (as in [25–27]) or inside dielectrics with a large refractive index (as in [24, 30]) and there could be physical reasons which prevent a straightforward comparison. In this case, the difference between old experiments (in gases) and modern experiments (in vacuum or solid dielectrics) might not depend on the technological progress only but also on the different media that were tested. Then, if the small residuals of those original experiments were not mere instrumental artifacts, there would be substantial implications for both physics and history of science.

1.2 Lorentz vs. Einstein

Before going deeper into the analysis of the experiments, we want to add some general comment about Lorentz' and Einstein's views of relativity. Apart from all historical aspects, the basic difference could simply be phrased as follows. In a "Lorentzian" approach, the relativistic effects originate from the *individual* motion of each observer S', S"...with respect to some preferred reference frame Σ, a convenient redefinition of Lorentz' ether. Instead, according to Einstein, eliminating the concept of the ether as a preferred frame leads to interpret the same effects as consequences of the *relative* motion of each pair of observers S' and S".

light ether. If that is the case, then one should be able to detect it, and thus I thought about whether it would be possible to perceive through some experiment that the earth moves in the ether. But when I was a student, I saw that experiments of this kind had already been made, in particular by your compatriot, Michelson. He proved that one does not notice anything on earth that it moves, but that everything takes place on earth as if the earth is in a state of rest". In spite of these contradictions, we trust in our synthesis (points i) and ii) above) which derives from two consistent Einstein's citations and fits well with the historical evolution of the scientific ideas.

In spite of this difference, it is generally assumed that there is a substantial phenomenological equivalence between the two formulations. This point of view was, for instance, already clearly expressed by Ehrenfest in his lecture 'On the crisis of the light ether hypothesis' (Leyden, December 1912) as follows: "So, we see that the ether-less theory of Einstein demands exactly the same here as the ether theory of Lorentz. It is, in fact, because of this circumstance, that according to Einstein's theory an observer must observe exactly the same contractions, changes of rate, etc. in the measuring rods, clocks, etc. moving with respect to him as in the Lorentzian theory. And let it be said here right away and in all generality. As a matter of principle, there is no experimentum crucis between the two theories". In fact, independently of all interpretative aspects, the basic quantitative ingredients, namely Lorentz transformations, are the same in both formulations.

Then, one may get the impression that the present supremacy of Einstein's interpretation depends on the null interpretation of the ether-drift experiments where one attempts to measure the "absolute" earth velocity with respect to the hypothetical Σ. Though, this is not true. In a Lorentzian perspective, if the velocity of light c_γ propagating in the various interferometers coincides with the basic parameter c entering Lorentz transformations, relativistic effects conspire to make undetectable the individual velocity parameter of each observer. For this reason, a null result of the ether-drift experiments should *not* automatically be interpreted as a confirmation of special relativity. The motion with respect to Σ might well remain unobservable, yet one could interpret relativity 'á la Lorentz'. As emphasized by Bell [31], see also [32, 33], this change of perspective, which may be useful for pedagogical reasons, could also be crucial to reconcile faster-than-light signals with causality [34, 35] and thus provide a very different view of the apparent non-local aspects of the quantum theory [36].

In our context of the ether-drift experiments, we want to add one more remark about Einstein's and Lorentz' points of views. According to Einstein, the original hypothesis of a real, physical length contraction along the direction of motion, to compensate the difference of the light velocity and thus explain the failure of the classical relation (1.5), was important from a historical point of view but highly unsatisfactory as ultimate explanation. For him, it was preferable to build the theory by postulating the impossibility-in-principle of discovering an absolute state of motion, or equivalently of assigning "a velocity vector to a point in empty space where electromagnetic processes take place" [17]. For Lorentz, on the other hand, only a conspiracy of effects, associated with the equality $c_\gamma = c$, was preventing to detect the motion with respect to the ether which, however different might be from ordinary matter, is nevertheless endowed with a certain degree of substantiality. For this reason, in his view, "it seems natural not to assume at starting that it can never make any difference whether a body moves through the ether or not" [37].

Adopting such a "Lorentzian" open mind was for us an important motivation to undertake a re-analysis [38] of the early ether-drift experiments in gaseous media and check the claims of those experts [6,7] that over the years have seriously questioned the standard null interpretation. In their opinion, in fact, the fringe shifts were much smaller than the classical predictions but not always negligible as compared to the extraordinary sensitivity of the interferometers. This means that, in some alternative model, the small residuals can acquire a definite physical meaning.

1.3 Classical ether-drift experiments: Just null results?

For our analysis of the ether-drift experiments, we shall rely on two basic assumptions, namely (i) the existence of a preferred frame Σ where light propagation is seen isotropic and (ii) the validity of Lorentz transformations. This means that any anisotropy in the earth frame S' should vanish identically either when the earth velocity $v = 0$ (i.e. $S' \equiv \Sigma$) or when $\mathcal{N} = 1$, i.e. when $c_\gamma \equiv c$[4]. The reason for the substantial suppression of the fringe shifts can then be understood by exploring the possible functional forms for the two-way velocity of light in the limit of refractive index $\mathcal{N} = 1 + \epsilon$. With our premise, in fact, for $\epsilon \ll 1$, one can expand in powers of ϵ and $\beta = v/c$ and it is elementary to show, see [38, 40] and the following Chap.6, that the leading term for a possible anisotropy of the two-way velocity of light is

$$\frac{\Delta\bar{c}_\theta}{c} \sim \epsilon\beta^2 \cos 2\theta. \tag{1.7}$$

Therefore, the fringe shifts are now predicted

$$\frac{\Delta\lambda(\theta)}{\lambda} \sim \frac{D}{\lambda}\,\frac{2\epsilon v^2}{c^2} \cos 2\theta \tag{1.8}$$

and are suppressed by the tiny factor 2ϵ with respect to Eq.(1.5). As such, this basic difference can be reabsorbed into an *observable* velocity

$$v^2_{\rm obs} \sim 2\epsilon v^2 \tag{1.9}$$

[4]Actually, De Abreu and Guerra have shown [39] that the null result of a Michelson-Morley experiment in an ideal vacuum can be deduced without using Lorentz transformations, but only from general assumptions on the choice of the admissible clocks.

which depends on the refractive index and is the one traditionally reported in the classical analysis of the data.

More precisely, one can *define* the observable velocity $v_{\rm obs}$ through the relation

$$\frac{\Delta\lambda(\theta)}{\lambda} \sim \frac{D}{\lambda}\,\frac{v^2_{\rm obs}}{c^2}\cos 2\theta \tag{1.10}$$

to make clear that this is the velocity extracted from the fringe shifts. In classical physics one has $v_{\rm obs} = v$, where v is the *kinematical* velocity. However, in other contexts the two quantities are different.

In any case, due to the formal properties of the two way velocity of light, the fringe shifts should represent a 2nd-harmonic effect, i.e. periodic in θ in the range $[0, \pi]$, with amplitude

$$A_2 \sim \frac{D}{\lambda}\,\frac{v^2_{\rm obs}}{c^2}. \tag{1.11}$$

Notice also that in the classical experiments, where one was always assuming the identity $v_{\rm obs} = v$, it was customary to formulate predictions for the orbital earth velocity $v = 30$ km/s. For this reason, we will often refer to the classical expected amplitude

$$A^{\rm class}_2 \sim \frac{D}{\lambda}\,\frac{(30\ {\rm km/s})^2}{c^2} \tag{1.12}$$

as a convenient reference value to compute the observable velocity from the experimental amplitude $A^{\rm EXP}_2$ through the relation

$$v_{\rm obs} \sim 30\ {\rm km/s}\,\sqrt{\frac{A^{\rm EXP}_2}{A^{\rm class}_2}}. \tag{1.13}$$

The main conclusion of this discussion is that those small *observable* velocities obtained from the measured fringe shifts, typically $v_{\rm obs} = 6 \div 10$ km/s for experiments in air (where ϵ is about $2.8 \cdot 10^{-4}$) and $v_{\rm obs} = 2 \div 3$ km/s for experiments in helium (where ϵ is about $3.3 \cdot 10^{-5}$), can now become consistent with the average *kinematical* earth velocity $v \sim 370$ km/s obtained by studying, with aircraft and satellites, the Cosmic Microwave Background (CMB).

Apart from the order of magnitude of the fringe shifts, another important aspect concerns the time dependence of the data. Traditionally, it has been always assumed that, for short-time observations of a few days, where there are no sizeable changes in the earth orbital velocity, the time dependence of a genuine physical signal should reproduce the slow and regular modulations induced by the earth rotation. The data instead, for both classical and modern experiments, have always shown a very irregular behavior. As a consequence, all statistical averages are much smaller than the instantaneous values. This difference, between individual measurements and statistical averages, has always represented a strong argument to interpret the data as mere instrumental artifacts.

However, again, could there be an alternative interpretative scheme? A possibility, would be to characterize the signal as in the standard simulations adopted to model turbulent flows. This idea derives from realizing that, at the most fundamental level, light propagation (e.g. inside an optical cavity) takes place in that substratum which we could call *physical vacuum*[5]. This is dragged along the earth motion but, so to speak, is not rigidly connected with the solid parts of the apparatus as fixed in the laboratory. Therefore, if one would try to characterize its local state of motion, say $v_\mu(t)$, this does not necessarily coincide with the projection of the global earth motion, say $\tilde{v}_\mu(t)$, at the observation site. The latter is a smooth function while the former, $v_\mu(t)$, in principle is unknown. By comparing with the motion of a body in a fluid, the equality $v_\mu(t) = \tilde{v}_\mu(t)$ amounts to assume a form of regular, laminar flow where global and local velocity fields coincide.

Though, this is not necessarily true. For instance, it would be natural to compare the physical vacuum to a fluid with vanishing viscosity (or infinite Reynolds number for any flow velocity). But, within the framework of the Navier-Stokes equation, the picture of a laminar flow is by no means obvious due to the subtlety of the zero-viscosity limit, see for instance the discussion given by Feynman in Sec. 41.5, Vol.II of his Lectures [41]. The reason is that the velocity field of such a hypothetical fluid cannot be a differentiable function [42]. Instead, one should think in terms of a continuous, nowhere differentiable function[6], similar to an ideal Brownian path [43]. This leads to the idea of the vacuum as a fundamental stochastic medium, somehow similar to a highly turbulent fluid, consistently with some basic foundational aspects of both quantum physics and relativity [45].

For these reasons, it becomes conceivable that, as in turbulent flows, the local $v_\mu(t)$ exhibits random fluctuations while the global $\tilde{v}_\mu(t)$ just determines its typical limiting boundaries. Although the random $v_\mu(t)$ cannot

[5]Maxwell's original argument in favor of an ether was indeed considering this basic aspect of light propagation [2].

[6]Onsager's argument relies on the impossibility, in the zero-viscosity limit, to satisfy the inequality $|\mathbf{v}(\mathbf{x}+\mathbf{l}) - \mathbf{v}(\mathbf{x})| < (\text{const.})l^n$, with $n > 1/3$. Kolmogorov's theory [44] corresponds to $n = 1/3$.

be computed exactly, one could still estimate its statistical properties by numerical simulations [38, 45]. To this end, one could start by assuming forms of turbulence or intermittency which, as it is generally accepted in the limit of zero viscosity, become statistically isotropic at small scales. In this way, see the following Chap.6, one could easily explain the irregular character of the data because, whatever the macroscopic earth motion, the average of all vectorial quantities (such as the fringe shifts at the various angles) would tend to zero by increasing more and more the statistics. In this framework, is not surprising that from instantaneous measurements of given magnitude one ends up with smaller and smaller statistical averages. This trend, by itself, might not imply that there is no physical signal.

1.4 A universal thermal gradient, the CMB and the vacuum structure

Now, it is well known that symmetry arguments, of the type used to derive Eq.(1.7), can provide a successful description of phenomena *independently* of the particular dynamics. Still, one may wonder about the underlying physical mechanisms. Namely, when considering light propagation in a gas, why there should be an anisotropy in the earth laboratory where (the container of) the gas is at rest?

For instance, a possibility is that the electromagnetic field of the incoming radiation produces different polarizations in different directions depending on the state of motion of the medium. Such mechanism should act in both weakly bound gaseous matter and strongly bound solid dielectrics with the final conclusion that light anisotropy would increase proportionally to the refractivity of the medium. This is in contrast with the result of the Shamir-Fox [30] experiment in perspex where no particular enhancement was observed (with respect to the Michelson-Morley experiment in air).

As an alternative possibility, it was noted in [38, 40] (see also Chap.6) that the trend in Eq.(1.7) is just a special case of a more general structure where light anisotropy originates from convective currents of the gas molecules, along the optical paths, associated with an absolute velocity v. Therefore, on the basis of the traditional thermal interpretation[7] of the residuals, and of the consistency of the kinematical velocities obtained

[7] The idea that temperature differences along the optical paths could be crucial dates back to Helmholtz, already at the time of the first 1881 Michelson [46] experiment in Potsdam. The same emphasis on temperature differences is also found in the critical reanalysis of Miller's observations performed by Shankland et al. [47].

from measurements in different laboratories and different conditions, it becomes conceivable that such universal effect in gaseous systems reflects the existence of a *non-local* thermal gradient.

At the beginning, the ultimate explanation for the sought non-local thermal gradient was searched for [38, 40] in the fundamental energy flow which, on the basis of general arguments, is expected in a quantum vacuum which is not exactly Lorentz invariant and thus sets a fundamental preferred reference frame (see Chap.6).

Later on, however, it was argued [48] that the required physical mechanism could perhaps be related to the temperature variations associated with the CMB *kinematic dipole* [49–51] . This is interpreted as a Doppler effect due to a motion of the solar system with average velocity $v \sim 370$ km/s toward a point in the sky of right ascension $\alpha \sim 168^o$ and declination $\gamma \sim -7^o$ and produces angular variations of a few millikelvin which would fit well with the typical magnitude of the periodic temperature differences in the air of the optical arms, about $(1 \div 2)$ mK [47, 52], which in principle could explain away the typical fringe shifts observed by Miller at Mount Wilson[8].

To check this interpretation, a new generation of dedicated experiments is needed to reproduce the experimental conditions of those early measurements with today's much greater accuracy. The essential ingredient is that the optical resonators which nowadays are coupled to the lasers should be filled by gaseous media. Such experiments would be along the lines of ref. [53] where just the use of optical cavities filled with different forms of matter was considered as a useful complementary tool to study deviations from exact Lorentz invariance.

In these modern ether-drift experiments one looks for a possible anisotropy of the two-way velocity of light through the relative frequency shift $\Delta\nu(\theta)$ of two orthogonal optical resonators (for a review see e.g. [23]). In units of their natural frequency ν_0, we thus predict a frequency shift

$$\left[\frac{\Delta\nu(\theta)}{\nu_0}\right]_{\rm gas} \sim \left[\frac{\Delta\bar{c}_\theta}{c}\right]_{\rm gas} \sim (\mathcal{N}_{\rm gas}-1)\ (v^2/c^2)\cos 2\theta. \tag{1.14}$$

[8]We emphasize that our interpretation of light anisotropy $\frac{\Delta\bar{c}_\theta}{c} \sim \epsilon v^2/c^2$ in gaseous systems, as originating from a non-local thermal gradient, applies to *all* classical ether-drift experiments and not just to Miller's Mount Wilson measurements. This is an important difference with the standard point of view, deriving from the article of the Shankland team [47], which tends to distinguish sharply Miller's observations from all other experiments. These aspects will be discussed in great detail in the following Chaps.5, 6 and 7.

This type of thermal interpretation would also explain why the same trend $\frac{\Delta \bar{c}_\theta}{c} \sim (\mathcal{N}-1)v^2/c^2$ does *not* extend to experiments in solid dielectrics, where the refractivity $\mathcal{N}-1$ is of order unity, as with the mentioned Shamir-Fox [30] experiment in perspex ($\mathcal{N}=1.5$). In this case, in fact, a small temperature gradient would mainly dissipate by heat conduction without generating any appreciable particle motion or light anisotropy in the rest frame of the apparatus. Hence, the non-trivial physical difference between classical experiments (in gaseous systems) and modern experiments (in a very high vacuum or in solid dielectrics).

Now, conceptually, explaining the residuals of the classical ether-drift experiments as non-local thermal effects, eventually related to the CMB temperature dipole, is different from introducing a preferred frame through a Lorentz-non-invariant vacuum state. To try to disentangle the two mechanisms, we have thus started to look at experiments where optical cavities are maintained in an extremely high vacuum, both at room temperature and in the cryogenic regime. The reason is that, in this limit, where any residual gaseous matter is totally negligible, a temperature gradient of a millikelvin cannot produce any observable light anisotropy. Therefore, if some infinitesimal effect still persists, the idea of a fundamental preferred frame would find additional support.

As a definite scenario to analyze these experiments, one can again consider the same scheme where $\bar{c}_\gamma \neq c$ so that the ideal equality $\mathcal{N}=1$ does not hold exactly in the *physical* vacuum. As a possible motivation, it was proposed [57] that an effective vacuum value $\mathcal{N}_v = 1+\epsilon_v$, with $\epsilon_v \sim 10^{-9}$, could reveal the different refractivity between an apparatus in an ideal freely-falling frame and an apparatus on the earth surface. This difference is expected if the curvature observed in a gravitational field is an emergent phenomenon from a fundamentally flat space-time. Then, the existence of a preferred frame would imply in our picture a definite, instantaneous $\frac{|\Delta \bar{c}_\theta|}{c} \sim \epsilon_v \beta^2 \sim 10^{-15}$ which coexists with a much smaller statistical average $|\langle \frac{\Delta \bar{c}_\theta}{c} \rangle| \ll 10^{-15}$. By assuming the same form of cosmic motion as for the classical experiments, in the following Chap.7, this expectation will be shown to be consistent with our numerical simulations of the most recent room temperature and cryogenic vacuum experiments.

Likewise, the existence of a fundamental 10^{-15} instantaneous signal, with very precise measurements, should also show up in solid dielectrics where, as anticipated, there should be no particular enhancement with respect to the vacuum case. This expectation is consistent with the cryogenic experiment of ref. [24] where most electromagnetic energy propagates in a solid with a refractive index $\mathcal{N} \sim 3$ (at microwave frequencies) but again a 10^{-15} instantaneous signal is observed.

To conclude this introductive chapter, we emphasize that, apart from its relevance for our view of relativity and for the history of science, a check of our predictions could have other non-trivial implications. In fact, suppose some future experiment would confirm the unambiguous detection of a universal signal in gaseous systems as in Eq.(1.14). In our interpretation, this would mean that light propagation in gaseous systems is modified due to a non-local temperature gradient, somehow associated with our motion within the CMB. But, of course, all physical systems on the moving earth would also be exposed to the same energy flow. This is very weak today but was substantially larger in the past when the temperature of the CMB was much higher. For this reason, one may speculate [58] on the role that this gradient might have played for the chemistry of liquid water. More in general, it is known [59, 60] that an external energy flow can induce forms of spontaneous self-organization in matter. In this sense, a universal thermal gradient could increase the efficiency of physical systems and provide a microscopic, dynamical mechanism to produce those macroscopic aspects (self-organized criticality, large-scale fluctuations, fat-tailed probability density functions...) which characterize the behavior of many complex systems, see e.g. [61–65] .

In the following, we will start in Chap.2 with some historical accounts on the ether conceptions that finally, at the end of XIX century, gave the motivation for the ether-drift experiments.

In Chap.3, we will concentrate on Michelson, on his early attempts to measure an ether-drift and on the original Michelson-Morley experiment.

In Chap.4, we will briefly comment on the inception of relativity and on its implications for the analysis of the experiments.

In Chap.5 we will report on the early repetitions of the Michelson-Morley experiment and on their traditional interpretation.

In Chap.6, we will re-consider the whole issue from scratch by introducing a modern formalism to re-interpret both the classical ether-drift experiments and the modern versions with optical resonators.

Finally, in Chap.7, we will extend our analysis to the present experiments in vacuum and solid dielectrics by discussing in more detail the various aspects briefly illustrated above.