Michelson-Morley Experiments

An Enigma for Physics and the History of Science

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World Scientific

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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.

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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 $\alpha(\text{fit} - \text{Joos}) = (168 \pm 30)$ degrees and angular declination $\gamma(\text{fit} - \text{Joos}) = (-13 \pm 14)$ 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 $[\Delta T(\theta)]_{\rm CMB} \sim \pm 3$ 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 $\frac{|\Delta \bar{c}_\theta|_{\rm air}}{c} = \mathcal{O}(10^{-10})$ for air and $\frac{|\Delta \bar{c}_\theta|_{\rm helium}}{c} = \mathcal{O}(10^{-11})$ 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 $\frac{|\Delta \bar{c}_\theta|_{\rm solid}}{c} \lesssim 10^{-15}$ (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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