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THE CLASSICAL MICHELSON-MORLEY EXPERIMENTS: A NEW SOLUTION TO AN OLD PROBLEM

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ABSTRACT. The classical "ether-drift" experiments in gaseous media (Michelson-Morley, Miller, Illingworth, Joos, ...) have always shown small, irregular residuals, usually interpreted as typical instrumental artifacts. A recent re-analysis indicates, instead, that these small effects could represent the first experimental indication for the Earth's motion within the Cosmic Background Radiation (CBR). This intriguing possibility, and the overall consistency with the modern experiments with vacuum optical resonators, require to perform a different check with a new generation of dedicated experiments. Without such definite clarification, the classical ether-drift experiments will remain as an enigma for physics and history of science.

1. Premise

The Michelson-Morley experiment (Michelson and Morley 1887) has represented a fundamental breakthrough in the history of physics. Indeed its apparent null result, i.e. too small to meet any classical prediction, was essential to stimulate the first, pioneering formulations of the relativistic length contraction and time dilation effects by FitzGerald (1889), Lorentz (1895a) and Lorentz (1895b), Larmor (1897) and Larmor (1900). These developments later induced Lorentz (1904), and Poincaré (1905), to derive a particular set of transformations of the space-time coordinates (Lorentz Transformations): "Applying one of such transformations amounts to apply 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 (1905) was the precise formalization of the Principle of Relativity, already proposed by him (Giannetto 1995) in La Science et l'Hypothese (Flammarion, Paris 1902) and at the 1904 St. Louis Conference.

This first historical phase and its relation with Special Relativity (Einstein 1905) can be well described by quoting, twice, Einstein's 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

This paper is dedicated to the memory of Prof. Gaetano Giaquinta (1945–2016) 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" (Einstein 1931).

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" (Born 1962).

Thus, summarizing: a) the result of the Michelson-Morley experiment was essential for the first formulation of the relativistic effects within the theory of the electromagnetic ether b) later, by Einstein, relativity was recognized as a doctrine of nature and formulated in an axiomatic form, free of any association with electromagnetism [1].

Such premise is essential to properly frame the Michelson-Morley experiment in the evolution of the scientific thought. 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 Illingworth (1927), Miller (1934b), Joos (1930)... as an old, well understood historical chapter for which there is nothing more to refine or clarify. All emphasis is now on the modern ether-drift experiments, with lasers stabilized by optical cavities (see e.g. the work by Müller *et al.* (2003) for a review), which apparently have improved by orders of magnitude on those original measurements.

However, as we are going to discuss, there is a crucial point which has been overlooked by most authors: the modern experiments are *not* performed in the same physical conditions as the classical ones. Therefore, the small residuals of those original experiments might not be mere instrumental artifact. Rather, in a modern theoretical framework, they are suggestive of the same Earth's motion indicated by the observation of the Cosmic Background Radiation (CBR). As a consequence, there could be substantial implications for both physics and history of science. A definitive check requires a new generation of dedicated laser interferometry experiments.

2. The two versions of relativity

Before re-considering the classical (and modern) Michelson-Morley experiments, it is important to stress, once more, that, in spite of the deep conceptual difference, Einstein's

[1]Over the years, Einstein made different statements about the inception of relativity and the influence of the Michelson-Morley experiment on his views, see e.g. Holton (1969). Our synthesis derives directly from two consistent citations and fits well with the historical evolution of the scientific thought.

view of relativity and the Lorentzian perspective with a preferred reference frame, are equivalent with respect to most experiments where one just compares the relative measurements of a pair of observers. This type of conclusion 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”. One can easily understand this because, independently of all interpretative aspects, the basic quantitative ingredients, namely Lorentz transformations, are the same in both formulations. Their validity will be assumed in the following to discuss the possible existence of a preferred reference frame.

The key ingredient to understand Ehrenfest’s statement is the fundamental property of the *Lorentz Group* for which the relation between two observers S’ and S”, individually related to the preferred reference frame Σ by Lorentz transformations with dimensionless parameters $\beta' = v'/c$ and $\beta'' = v''/c$, is also a Lorentz transformation with relative velocity parameter $\beta_{\rm rel}$ fixed by the relativistic composition rule

$$\beta_{\rm rel} = \frac{\beta' - \beta''}{1 - \beta'\beta''} \quad (1)$$

(for simplicity we restrict to the case of one-dimensional motion). This produces a substantial quantitative equivalence with Einstein’s formulation for most standard experimental tests where one just compares the relative measurements of a pair of observers.

Thus, one may get the impression that the present supremacy of Einstein’s interpretation is precisely due to the null results of the ether-drift experiments where one attempts to measure those absolute velocities v', v''... But, again, this is not true. In a Lorentzian view, 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 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 remain unobservable, yet one could interpret relativity ’a la Lorentz. As emphasized by Bell (1987), this change of perspective could be crucial, for instance, to reconcile faster-than-light signals with causality and thus provide a very different view of the apparent non-local aspects of the quantum theory. Hence the importance of trying to measure v', v''... in ether-drift experiments, admittedly those where $c_\gamma \neq c$.

Notice, here, the radical difference between Einstein’s and Lorentz’ points of views. According to Einstein, the original contraction hypothesis by FitzGerald and Lorentz, to explain the result of the Michelson-Morley experiment, although historically important, was highly unsatisfactory. For him, it was better to rely on the relativity postulate and accept the impossibility-in-principle of discovering absolute motion. For Lorentz, on the other hand, only a conspiracy of effects, associated with the equality $c_\gamma = c$, prevents to detect the motion with respect to the ether. For this reason, in Lorentz’ 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" (Lorentz 1909).

Here, the curiosity of a reader is stimulated by the claims of greatest experts, e.g. Hicks (1902) and Miller (1934b), that over the years have seriously questioned the standard null interpretation of the original experiments by stressing the importance of small residuals which were never entirely negligible as compared to the extraordinary sensitivity of the interferometers. This suggests that, in some alternative framework, these small and irregular effects could acquire a definite physical meaning.

With this in mind, we have undertaken a careful reanalysis of those classical experiments to first check Hicks' and Miller's claims and then compare with quantitative predictions in a modern theoretical framework. The results of our analysis have been presented in (Consoli *et al.* 2013), to which we address the reader for all details. The conclusions of that work are striking: Hicks and Miller were right. The traditional null interpretation of the classical ether-drift experiments in gaseous media (air or helium at atmospheric pressure) is far from obvious. In fact, by using Lorentz transformations to connect the Earth's frame to the hypothetical Σ, the small observed residuals become consistent with the average Earth's velocity of 370 km/s obtained by measuring, with aircraft and satellites, the anisotropy of the Cosmic Background Radiation (CBR).

We emphasize that this conclusion is perfectly consistent with an exact null result of experiments where light propagates in an ideal vacuum for which the velocity of light c_γ coincides with the parameter c of Lorentz transformations. In fact, as we are going to show, all observed effects turn out to be proportional to $(c_\gamma - c)/c$ or, equivalently, to $(\mathcal{N} - 1)$ where $\mathcal{N}$ is the refractive index of the gaseous medium. This type of dependence leads to the natural conclusion (Consoli *et al.* 2016) that the observed residual effects are ultimately due to the tiny temperature angular differences, about ± 0.003 K, associated with the Earth's motion within the CBR. This figure would also be consistent with the typical magnitude of periodic temperature differences in the air of the optical arms, about ± 0.001 K or ± 0.002 K (Joos 1934; Shankland *et al.* 1955), which could explain away the average fringe shift observed by Miller.

One may object that such a non-null interpretation of the classical ether-drift experiments is quite unrelated to the conceptual differences between Lorentzian and special relativity. The CBR is a definite medium with a rest frame where the black-body spectrum looks exactly isotropic. Earth's motion within this medium can be detected and, indeed, has been detected. In this sense, for a critical reader, the idea that one can also detect the same motion with a Michelson-Morley experiment, while certainly unconventional, would not have the revolutionary implications of a *genuine* preferred-frame effect due to the vacuum structure.

However, one should also realize that, according to the standard interpretation, the reference frame where the CBR looks exactly isotropic is precisely the same frame where the matter emitting the CBR was globally at rest. This notion of global rest, which is foreign to special relativity, finds a natural place in the modern picture of the vacuum (Consoli 2014) as a condensate of elementary quanta (Higgs particles, quark-antiquark pairs, gluons...) which produce a macroscopic occupation of the same, zero-momentum, quantum state. This means that the isotropy of the CBR merely *indicates* the existence of this underlying frame that we could conventionally call the "ether". But the CBR itself does *not* coincide with this notion of ether which is rather determined by the vacuum structure. For this reason, the implications of our result for the interpretation of relativity are far from being trivial.

The plan of this article is as follows. In Sects. **3**, 4 and 5 we shall discuss the basics of the ether-drift experiments and point out some subtleties that have always been overlooked in the standard analysis of the data. Then, in Sect. 6, as a definite example, we shall review the original experiment performed by Michelson and Morley in 1887. The intriguing aspects of the most precise version performed by Joos in 1930, can be found in Sect.7. Finally Sect.8 will contain a summary of all classical experiments, as presented by Consoli *et al.* (2013), and the basic scheme of new dedicated experiments which are necessary to definitely confirm (or disproof as a mere coincidence) the remarkable agreement we have found.

3. Ether-drift experiments and the velocity of light

In most textbooks, the Michelson-Morley experiment is described as in the old times, by adopting the point of view of an observer at rest in the ether. However, the experiment is performed in the laboratory frame S'. Then, little thought is needed to realize that things become much simpler by adopting the point of view of the S' observer. For this observer, the whole experimental issue consists in testing the isotropy of the two-way velocity of light $\bar{c}_\gamma(\theta)$. This is the only one that can be measured unambiguously and is defined in terms of the one-way velocity $c_\gamma(\theta)$ as

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

Here θ represents the angle between the direction of light propagation and the Earth's velocity with respect to the hypothetical preferred frame Σ. For light propagating in a gaseous medium of refractive index $\mathcal{N} = 1+\varepsilon$ (with $\varepsilon \ll 1$), by defining the anisotropy

$$\Delta\bar{c}_\theta = \bar{c}_\gamma(\pi/2+\theta) - \bar{c}_\gamma(\theta), \tag{3}$$

the time difference for light propagation back and forth at right angles along rods of length D (at rest in the laboratory S' frame) can be expressed as [2]

$$\Delta t(\theta) = \frac{2D}{\bar{c}_\gamma(\theta)} - \frac{2D}{\bar{c}_\gamma(\pi/2+\theta)} \sim \frac{2D}{c}\frac{\Delta\bar{c}_\theta}{c}. \tag{4}$$

In the past, this tiny difference was measured by rotating a Michelson interferometer (see Fig.1) and detecting the fringe shift

$$\frac{\Delta\lambda(\theta)}{\lambda} \sim \frac{c\Delta t(\theta)}{\lambda} \sim \frac{2D}{\lambda}\frac{\Delta\bar{c}_\theta}{c}, \tag{5}$$

[2]Here, we are assuming the validity of Lorentz transformations. Namely, even in the presence of a preferred frame, for the S' observer the length of a rod at rest in S' does not depend on its orientation. However, in principle, one might also consider the more general scenario of an anisotropy of the rod length in the rod rest frame. This would amount to an anisotropy of the underlying molecular forces and, as such, of the basic atomic parameters. This possibility is severely limited experimentally. In fact, in the most recent versions of the original Hughes-Drever experiment (Hughes *et al.* 1960; Drever 1961), where one measures the atomic energy levels as a function of their orientation with respect to the fixed stars, possible deviations from isotropy have been found below the 10^{-20} level (Will 2006). This is incomparably smaller than any other effect on the velocity of light we are going to discuss. Therefore such effects, if present, are completely negligible and, from now on, we shall assume the isotropy of lengths, i.e. $D(\theta) = D =$constant.

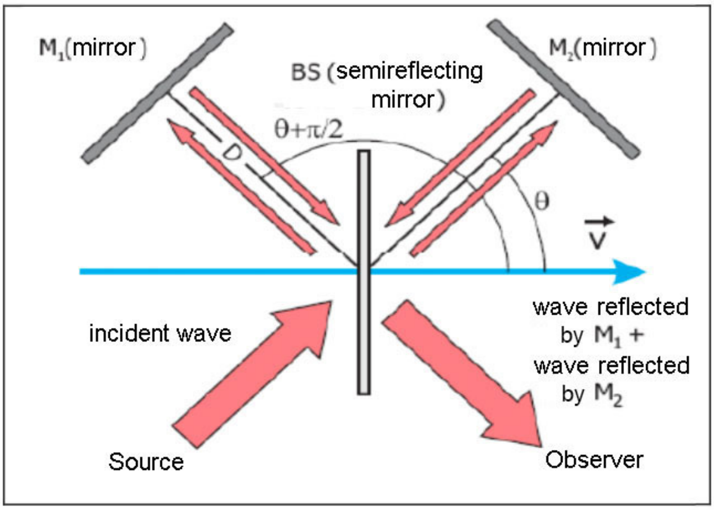

FIGURE 1. The typical scheme of Michelson's interferometer.

λ being the light wavelength.

In modern experiments, instead, light anisotropy is measured from the frequency shift between two rotating optical resonators (Müller *et al.* 2003) through the relation

$$\frac{\Delta\nu(\theta)}{\nu_0} = \frac{\Delta\bar{c}_\theta}{c}, \tag{6}$$

where ν_0 is the reference frequency of the two resonators.

In this context, the most recent result from Nagel *et al.* (2015) amounts to a fractional accuracy $(|\Delta\bar{c}_\theta|/c) \lesssim 10^{-18}$. With this new measurement, by looking at their Fig.1 where all ether-drift experiments are reported, one gets the impression of a steady, substantial improvement over the original 1887 Michelson and Morley (1887) result $(|\Delta\bar{c}_\theta|/c) \lesssim 10^{-9}$.

Though, this first impression might be misleading. The various measurements were performed in different conditions, i.e. with light propagating in gaseous media (as in Michelson and Morley (1887), Illingworth (1927), Joos (1930), and Miller (1934b)) or in a high vacuum (as in Brillet and Hall (1979), Eisele *et al.* (2009), and Herrmann *et al.* (2009)) or inside dielectrics with a large refractive index (as in Shamir and Fox (1969) and Nagel *et al.* (2015)) and there could be physical reasons which prevent such 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.

Another possible objection concerns the traditional analysis of the data. The model assumed so far of slow, periodic time modulations, associated with the Earth's rotation and its orbital revolution, derives from simple spherical trigonometry. Here, there might be a logical gap. The relation between the macroscopic Earth's 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. However, some arguments (for a list of references see Consoli *et al.* (2014)) suggest that the vacuum might rather resemble a turbulent fluid where large-scale and small-scale flows are only indirectly related. In this other perspective, the macroscopic Earth's motion could just give the order of magnitude by fixing the typical boundaries for a microscopic velocity field which is irregular and intrinsically non deterministic. Although it cannot be computed exactly, one could still estimate its statistical properties by numerical simulations (Consoli *et al.* 2013, 2014). To this end, one could assume forms of turbulence or intermittency which, as in most models, become statistically isotropic at small scales. This could easily explain the irregular character of the data because, whatever the macroscopic Earth's motion, the average of all vectorial quantities (such as the Fourier coefficients extracted from a fit to the temporal sequences in modern experiments or the fringe shifts of the old experiments) would tend to zero by increasing more and more the statistics. In this framework, is not surprising that from an instantaneous signal of given magnitude one ends up with smaller and smaller averages. This trend, by itself, might not imply that there is no physical signal. As we shall show in the following, by taking into account these two ingredients, namely a) the specificity of the various media and b) the possibility of a genuine, but irregular, physical signal, there are substantial changes in the interpretation of the experiments.

To derive the relevant relation, we shall follow the same treatment given in Consoli *et al.* (2013) which applies to light propagation in a dielectric medium when the refractive index $\mathcal{N} = 1+\varepsilon$ is extremely close to unity. This is the case of the gaseous systems as air, helium.. which were used in the classical ether-drift experiments (e.g. Michelson-Morley, Miller, Illingworth, Joos,...). For such systems, one can find a simple theoretical framework to analyze the experiments. The standard assumption is that any anisotropy has to vanish when both the observer and the container of the medium are at rest in the hypothetical preferred frame Σ. Therefore, in the physical case where instead both the observer and the container of the medium are at rest in the laboratory S' frame, the anisotropy should vanish identically in the two limits when either $V = 0$ (i.e. $S' \equiv \Sigma$) or $\mathcal{N} = 1$ (i.e. when $c_\gamma \equiv c$). This means that, in a power series expansion in the two small parameters $\beta = V/c$ and $\varepsilon = \mathcal{N} - 1$, any possible anisotropy has to start to $\mathcal{O}(\varepsilon\beta)$ for the one-way velocity $c_\gamma(\theta)$ and to $\mathcal{O}(\varepsilon\beta^2)$ for the two-way velocity $\bar{c}_\gamma(\theta)$ which, by its very definition, is invariant under the replacement $\beta \to -\beta$. At the same time, for any fixed β, $\bar{c}_\gamma(\theta)$ is also invariant under the replacement $\theta \to \pi+\theta$. Therefore, to the lowest non-trivial level $\mathcal{O}(\varepsilon\beta^2)$, one can write down the general expression

$$\bar{c}_\gamma(\theta) = \frac{2c_\gamma(\theta)c_\gamma(\pi+\theta)}{c_\gamma(\theta)+c_\gamma(\pi+\theta)} \sim \frac{c}{\mathcal{N}}\left[1-\varepsilon\,\beta^2\sum_{n=0}^{\infty}\zeta_{2n}P_{2n}(\cos\theta)\right] \tag{7}$$

where, to take into account invariance under $\theta \to \pi+\theta$, the angular dependence is given as an infinite expansion of even-order Legendre polynomials with arbitrary coefficients $\zeta_{2n} = \mathcal{O}(1)$. In Einstein's relativity, where there is no preferred reference frame, these ζ_{2n} coefficients vanish exactly. In a Lorentzian relativity there is no reason why they should vanish *a priori*. Now, one may ask about a dynamical mechanism which produces an anisotropy proportional to $\varepsilon(v/c)^2$ as in Eq. (7). A possible answer is associated with the Earth's motion within the Cosmic Background Radiation (CBR).

4. Earth's motion in the CBR and ether-drift experiments

The discovery of an anisotropy of the Cosmic Background Radiation (CBR) (Mather 2007; Smoot 2007) has introduced an important new element. Indeed, the standard interpretation of its dominant dipole component (the CBR kinematic dipole (Yoon and Huterer 2015)) is in terms of a Doppler effect due to the motion of the solar system with average velocity $v \sim 370$ km/s toward a point in the sky of right ascension $\alpha \sim 168^{\rm o}$ and declination $\delta \sim -7^{\rm o}$. To understand this effect, let us recall that, due to the motion of an observer with velocity $\beta = v/c$, a pure black-body spectrum of temperature T_o becomes Doppler shifted in the various directions θ according to the relation

$$T(\theta) = \frac{T_o\sqrt{1-\beta^2}}{1-\beta\cos\theta}. \tag{8}$$

Therefore, if one sets $T_o \sim 2.7$ K and $\beta \sim 0.0012$ as for $v = 370$ km/s, there is an angular variation

$$\Delta T(\theta) \sim T_o\beta\cos\theta \sim \pm 0.003 \text{ K}. \tag{9}$$

This means that an observer moving through the CBR would see small angular differences in temperature. In principle, this can establish a connection with the ether-drift experiments in gaseous systems. In fact, under a thermal gradient, the elementary constituents of a weakly bound gaseous matter can be easily set in motion and produce a tiny anisotropy of the velocity of light propagating in the gas. For this reason, the small residuals were usually explained away as uninteresting thermal effects (Shankland *et al.* 1955).

A more accurate estimate for an ether-drift experiment would first require to replace the value $v = 370$ km/s with its projection in the plane of the interferometer and then evaluate the effects on the observation site. We have not attempted this non-trivial task. However, for Miller's observations this analysis was carried out by Kennedy, Shankland (see p.175 of Shankland *et al.* (1955), in particular the footnote[16]) and Joos (1934). Their conclusion was that periodic temperature variations of about ± 0.001 K or ± 0.002 K in the air of the optical arms could be responsible for Miller's average fringe pattern. Now, on the one hand, these temperature values agree well with Eq. (9). On the other hand, such interpretation of the residual effects would also fit with Miller's conclusion (Miller 1934a) that the needed temperature variations could not be due to a uniform heating (or cooling) of the laboratory but should have been those produced by a directional effect, as it would be with the CBR dipole.

Thus we are lead to a definite dynamical model to understand the small residuals observed in the classical ether-drift experiments: convective currents of the gas molecules associated with the Earth's motion within the CBR. It is remarkable (Consoli *et al.* 2013) (see also Appendix 1 of Consoli (2014)) that such a mechanism would produce exactly the same structure in Eq. (7). Both derivations clearly differentiate gaseous systems from solid and liquid dielectrics (where instead the refractive index $\mathcal{N}$ differs substantially from unity) and, therefore, one can understand the difference with strongly bound matter, as in the Shamir-Fox experiment (Shamir and Fox 1969). Being aware that the classical measurements could be proportional to $\varepsilon(v/c)^2$, they selected a medium where the effect of the refractive index would have been enhanced (i.e. perspex where $\mathcal{N} \sim 1.5$). Since this enhancement was not observed, they concluded that the experimental basis of special relativity was strengthened. However, with a thermal interpretation, one can reconcile the different behaviors because in solid dielectrics 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.

Now, Eq. (7) is exact to the given accuracy. Therefore, by leaving out the first few $\zeta's$ as free parameters in the fits, one could directly compare with the experimental data. Still, there is one more derivation of the $\varepsilon \to 0$ limit with a preferred frame which, on the basis of other symmetry arguments, permits to get rid of the unknown coefficients in (7). To this end, let us consider the transformation matrix, say $A^{\mu}_{\nu}(\varepsilon)$, which connects the space-time metric $\gamma^{\mu\nu}$ for light propagation in Σ to the corresponding $g^{\mu\nu}$ in S'. More precisely, let us define $\gamma^{\mu\nu}$ the space-time metric that the Σ observer uses in the relation $\gamma^{\mu\nu}\pi_\mu\pi_\nu = 0$ to describe light propagation (with 4-momentum π_μ) when the container of the gas is at rest in Σ. Let us also define $g^{\mu\nu}$ the corresponding metric that the S' observer uses in the relation $g^{\mu\nu}p_\mu p_\nu = 0$ to describe light propagation with 4-momentum p_μ when the container of the gas is at rest in S'. Then, the required matrix A^{μ}_{ν} is defined by

$$g^{\mu\nu} = A^{\mu}_{\rho}A^{\nu}_{\sigma}\gamma^{\rho\sigma}. \tag{10}$$

In this context, the previous standard assumptions leading to Eq.(7) amount to impose

$$\gamma^{\mu\nu}(\mathcal{N}) = \text{diag}(\mathcal{N}^2, -1, -1, -1) \tag{11}$$

and

$$g^{\mu\nu}(\mathcal{N}=1) = \gamma^{\mu\nu}(\mathcal{N}=1) = \eta^{\mu\nu} \tag{12}$$

where $\eta^{\mu\nu}$ is the Minkowski tensor. Therefore, by taking into account i) that Eq. (12) can be fulfilled by choosing either $A^{\mu}_{\nu}(\varepsilon=0) = \delta^{\mu}_{\nu}$ or $A^{\mu}_{\nu}(\varepsilon=0) = \Lambda^{\mu}_{\nu}$, where Λ^{μ}_{ν} is the Lorentz transformation matrix from Σ to S', and ii) that δ^{μ}_{ν} and Λ^{μ}_{ν} cannot be related by an infinitesimal transformation, it follows that $A^{\mu}_{\nu}(\varepsilon)$ is a *two-valued* function for $\varepsilon \to 0$. Then, by taking into account this subtlety (see Appendix 2 of Consoli (2014)), there are two solutions: either

$$[g^{\mu\nu}(\mathcal{N})]_1 = \delta^{\mu}_{\rho}\delta^{\nu}_{\sigma}\gamma^{\rho\sigma} = \gamma^{\mu\nu} \sim \eta^{\mu\nu} + 2\varepsilon\delta^{\mu}_{0}\delta^{\nu}_{0} \tag{13}$$

or

$$[g^{\mu\nu}(\mathcal{N})]_2 = \Lambda^{\mu}_{\rho}\Lambda^{\nu}_{\sigma}\gamma^{\rho\sigma} \sim \eta^{\mu\nu} + 2\varepsilon u^{\mu}u^{\nu} \tag{14}$$

where u^μ is the dimensionless S' 4-velocity.

With the second choice Eq. (14) for the metric, from the condition $p_\mu p_\nu g^{\mu\nu} = 0$, by defining $c_\gamma(\theta)$ from the ratio $p_0/|\mathbf{p}|$ and using Eq. (2), one finds a two-way velocity

$$\bar{c}_\gamma(\theta) \sim (c/\mathcal{N})\left[1 - \varepsilon\beta^2\left(2 - \sin^2\theta\right)\right], \tag{15}$$

which corresponds to setting in Eq. (7) $\zeta_0 = 4/3$, $\zeta_2 = 2/3$ and all $\zeta_{2n} = 0$ for $n > 1$. Equation (15) is a definite realization of the general structure in (7) and provides a partial answer to the problem of calculating the $\zeta's$ from first principles. As such, it represents a model to compute the time difference for light propagation back and forth at right angles along rods of length L (at rest in the S' frame). This gives a fringe shift for a Michelson interferometer operating in gaseous systems

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{\rm gas} \sim \frac{2D}{\lambda}\left[\frac{\Delta\bar{c}_\theta}{c}\right]_{\rm gas} \sim \frac{D}{\lambda}\frac{v^2_{\rm obs}}{c^2}\cos(2\theta) \tag{16}$$

in terms of an "observable" velocity

$$v^2_{\rm obs} \sim 2\varepsilon v^2, \tag{17}$$

which is re-scaled by the tiny factor 2ε with respect to the true *kinematical* velocity v^2. The introduction of the observable velocity is convenient because it allows for a direct comparison with the prediction of classical physics (for a careful discussion see Kennedy (1935))

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{\rm class} \sim \frac{D}{\lambda}\frac{v^2}{c^2}\cos(2\theta) \tag{18}$$

Analogously, for modern interferometry experiments with optical resonators filled by a gas we find

$$\left[\frac{\Delta\nu(\theta)}{\nu_0}\right]_{\rm gas} = \left[\frac{\Delta\bar{c}_\theta}{c}\right]_{\rm gas} \sim (\mathcal{N}_{\rm gas}-1)\ (v^2/c^2). \tag{19}$$

In conclusion, in this scheme, the interpretation of the experiments is transparent. According to Special Relativity, there can be no fringe shift upon rotation of the interferometer. In fact, if light propagates in a medium, the frame of isotropic propagation is always assumed to coincide with the laboratory frame S', where the container of the medium is at rest, and thus one has $v = v_{\rm obs} = 0$. On the other hand, one has now definite indications for a non zero effect, namely: i) the fringe shifts should exhibit an angular dependence of the type in Eq. (16) and ii) by using gaseous media with different refractive index one should get consistency with Eq. (17) in such a way that different $v_{\rm obs}$ correspond to the same kinematical v. In any such comparison, one should keep in mind that the expected effects would be proportional to $2\varepsilon(v/c)^2$ and *not* simply to $(v/c)^2$ as in classical physics. Therefore, for instance, for air at atmospheric pressure, where the refractive index $\mathcal{N} \sim 1.00029$, the fringe shifts for the typical $v \sim 300$ km/s of most Earth's cosmic motions would be about 17 times smaller than those classically expected for the much lower $v \sim 30$ km/s. For gaseous helium, where $\mathcal{N} \sim 1.000035$, the effect would be even 140 times smaller.

5. Detecting the Earth's motion in laboratory?

Before addressing the classical experiments, some additional discussion is needed. These experiments were performed in a period when both relativity and quantum theory were not fully developed. Therefore, the theoretical model adopted to compare with the data was the old classical prediction Eq. (18). In this interpretative scheme, the expected effects, although being formally $\mathcal{O}(v^2/c^2)$, were "large", as compared to the extraordinary sensitivity of the Michelson interferometer, and "smooth", because the only time dependence were due to slow effects such as the daily Earth's rotation and its annual orbital revolution.

To see this, let us first introduce the instantaneous direction $\theta_0(t)$ and the projection $v(t)$ of the Earth's velocity in the plane of the interferometer and re-write the basic Eq. (16) as

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{\rm gas} \sim \frac{2D\varepsilon}{\lambda}\frac{v^2(t)}{c^2}\cos 2(\theta-\theta_0(t)) \equiv 2C(t)\cos 2\theta + 2S(t)\sin 2\theta \qquad (20)$$

where (x-y denotes the plane of the interferometer)

$$C(t) = \frac{D\varepsilon}{\lambda}\frac{v^2(t)}{c^2}\cos 2\theta_0(t) = \frac{D\varepsilon}{\lambda}\,\frac{v_x^2(t)-v_y^2(t)}{c^2}, \qquad (21a)$$

$$S(t) = \frac{D\varepsilon}{\lambda}\frac{v^2(t)}{c^2}\sin 2\theta_0(t) = \frac{D\varepsilon}{\lambda}\,\frac{2v_x(t)v_y(t)}{c^2}. \qquad (21b)$$

Then, the standard classical assumption is to consider a cosmic Earth's velocity with well defined magnitude V, right ascension α and angular declination γ that can be considered constant for short-time observations of a few days where there are no appreciable changes due to the Earth's orbital velocity around the Sun. In this framework, where the only time dependence is due to the Earth's rotation, one identifies $v(t) \equiv \tilde{v}(t)$ and $\theta_0(t) \equiv \tilde{\theta}_0(t)$ where $\tilde{v}(t)$ and $\tilde{\theta}_0(t)$ derive from the simple application of spherical trigonometry

$$\cos z(t) = \sin\gamma\sin\phi + \cos\gamma\cos\phi\cos(\tau-\alpha), \qquad (22a)$$

$$\frac{\tilde{v}_x(t)}{V} \equiv \sin z(t)\cos\tilde{\theta}_0(t) = \sin\gamma\cos\phi - \cos\gamma\sin\phi\cos(\tau-\alpha), \qquad (22b)$$

$$\frac{\tilde{v}_y(t)}{V} \equiv \sin z(t)\sin\tilde{\theta}_0(t) = \cos\gamma\sin(\tau-\alpha), \qquad (22c)$$

$$\tilde{v}(t) \equiv \sqrt{\tilde{v}_x^2(t)+\tilde{v}_y^2(t)} = V\sin z(t). \qquad (22d)$$

Here $z = z(t)$ is the zenithal distance of $\mathbf{V}$, ϕ is the latitude of the observatory, $\tau = \omega_{\rm sid}t$ is the sidereal time of the observation in degrees ($\omega_{\rm sid} \sim \frac{2\pi}{23^h56'}$) and the angle θ_0 is counted conventionally from North through East so that North is $\theta_0 = 0$ and East is $\theta_0 = 90^{\rm o}$. In this way, one finds

$$S(t) \equiv \tilde{S}(t) = S_{s1}\sin\tau + S_{c1}\cos\tau + S_{s2}\sin(2\tau) + S_{c2}\cos(2\tau), \qquad (23a)$$

$$C(t) \equiv \tilde{C}(t) = C_0 + C_{s1}\sin\tau + C_{c1}\cos\tau + C_{s2}\sin(2\tau) + C_{c2}\cos(2\tau) \qquad (23b)$$

In this picture, the C_k and S_k Fourier coefficients depend on the three parameters (V,α,γ) (see Consoli *et al.* (2013)) and, to very good approximations, should be time-independent for short-time observations.

As it is well known, this simple theoretical framework did *not* fit with the observations. In fact, the experimental data, even though slightly larger than the experimental resolution, were always much smaller than the classically expected values. Also the observed pattern was highly irregular because observations performed at the same time on consecutive days could differ sizeably. This has always represented a strong argument to interpret the data as pure instrumental effects, i.e. "null results".

As anticipated, by comparing the Earth's cosmic motion with that of a body in a fluid, the standard picture Eqs. (22a)–(23b) amounts to the condition of a pure laminar flow where global and local velocity fields coincide. However, the relation between the macroscopic Earth's motion and an ether-drift experiment in laboratory depends on a complicated chain of effects. For instance, in our model, on the temperature gradient due to the Earth's motion within the CBR which induces convective currents of the gas molecules and, in the end, produces an angular dependence of the velocity of light in the gas. Therefore, as compared to a direct measurement of the CBR in space with satellites there are a few more intermediate steps. For this reason, as anticipated, the real situation could be more similar to that of a turbulent fluid where the large-scale flow exhibits well definite directional properties but these get lost at small scales. In this case, due to the typical irregular behaviour, vectorial quantities (such as the fringe shifts) might easily average to zero. But, now, this does not mean that there is no ether-drift. In fact, by adopting the different model of a turbulent flow, the local velocity field $(v_x(t), v_y(t))$ in Eqs. (20)–(21b) no longer coincides with the smooth, global quantities $(\tilde{v}_x(t), \tilde{v}_y(t))$ which describe the cosmic Earth's motion. These latter parameters are only used to fix the limiting boundaries (Fung *et al.* 1992) for a microscopic velocity field which has instead an intrinsic stochastic nature. Although it cannot be predicted exactly, its statistical properties could be estimated by numerical simulations.

The simplest choice, which represents a zeroth-order approximation, corresponds to a turbulence which, at small scales, appears statistically isotropic and homogeneous [3]. In spite of its simplicity, it is a useful example to illustrate basic phenomenological features associated with an underlying stochastic vacuum. The perspective is that of an observer moving in the turbulent fluid who wants to simulate the two components of the velocity in his x-y plane at a given fixed location in his laboratory. For homogeneous turbulence, one finds the general expressions

$$v_x(t) = \sum_{n=1}^{\infty} \left[x_n(1) \cos \omega_n t + x_n(2) \sin \omega_n t \right], \tag{24a}$$

$$v_y(t) = \sum_{n=1}^{\infty} \left[y_n(1) \cos \omega_n t + y_n(2) \sin \omega_n t \right], \tag{24b}$$

where $\omega_n = 2n\pi/T$, T being a time scale which represents a common period of all stochastic components. For our simulations, we have adopted the typical value $T = T_{\text{day}}$= 24 hours. However, we have also checked with a few runs that the statistical distributions of the various quantities do not change substantially by varying T in the rather wide range $0.1\ T_{\text{day}} \leq T \leq 10\ T_{\text{day}}$.

The coefficients $x_n\ (i = 1,2)$ and $y_n\ (i = 1,2)$ are random variables with zero mean and have the physical dimension of a velocity. By assuming statistical isotropy, we shall denote by $[-\tilde{v}, \tilde{v}]$ the common interval for these four parameters. In terms of $\tilde{v}$ the statistical average of the quadratic values can be expressed as

$$\langle x_n^2(i=1,2) \rangle_{\text{stat}} = \langle y_n^2(i=1,2) \rangle_{\text{stat}} = \frac{\tilde{v}^2}{3\ n^{2\eta}} \tag{25}$$

for the uniform probability model (within the interval $[-\tilde{v}, \tilde{v}]$) which we have chosen for our simulations. Finally, the exponent η controls the power spectrum of the fluctuating components. For the simulations, between the two values $\eta = 5/6$ and $\eta = 1$ reported in

[3] This picture reflects the basic Kolmogorov theory (Kolmogorov 1940; Landau and Lifshitz 1959) of a fluid with vanishingly small viscosity.

ref.Fung *et al.* 1992, we have chosen $\eta = 1$ which corresponds to the point of view of an observer moving in the fluid.

We observe that one could further improve the stochastic model by introducing time modulations and/or slight deviations from isotropy. For instance, $\tilde{v}$ could become a function of time $\tilde{v} = \tilde{v}(t)$. By still retaining statistical isotropy, this could be used to simulate the possible modulations of the projection of the Earth's velocity in the plane of the interferometer. Or, one could fix a range, say $[-\tilde{v}_x, \tilde{v}_x]$, for the two random parameters $x_n(1)$ and $x_n(2)$, which is different from the range $[-\tilde{v}_y, \tilde{v}_y]$ for the other two parameters $y_n(1)$ and $y_n(2)$. Finally, $\tilde{v}_x$ and $\tilde{v}_y$ could also become given functions of time, for instance $\tilde{v}_x(t) \equiv \tilde{v}(t)\cos\tilde{\theta}_0(t)$ and $\tilde{v}_y(t) \equiv \tilde{v}(t)\sin\tilde{\theta}_0(t)$, $\tilde{v}(t)$ and $\tilde{\theta}_0(t)$ being defined in Eqs. (22a)−(22d). In this way, for each time t, Eqs.(25) now become

$$\langle x_n^2(i=1,2)\rangle_{\text{stat}} = \frac{\tilde{v}_x^2(t)}{3\,n^2\eta}, \qquad \langle y_n^2(i=1,2)\rangle_{\text{stat}} = \frac{\tilde{v}_y^2(t)}{3\,n^2\eta}. \tag{26}$$

For most classical experiments, these further refinements are unnecessary. In fact in most cases only observations at few selected hours were performed so that, in view of the strong fluctuations of the data, one can just extract the average magnitude of the observed velocity and, within the errors, a macroscopic kinematical velocity. A notable exception is Joos' 1930 experiment (Joos 1930). Its accuracy was incomparable among the classical experiments since the observations were performed each hour to cover the whole sidereal day and the data were recorded by photocamera. As we shall see in the following, Joos' data are sensitive to the details of the Earth's cosmic motion and require to adopt the most refined framework Eqs. (26).

6. Michelson-Morley 1887 experiment

Michelson and Morley performed their six observations in 1887, on July 8th, 9th, 11th and 12th, at noon and in the evening, in the basement of the Case Western University of Cleveland (Michelson and Morley 1887). As well summarized by Miller in 1933 Miller 1934b, "The brief series of observations was sufficient to show clearly that the effect did not have the anticipated magnitude. However, and this fact must be emphasized, *the indicated effect was not zero*". The same conclusion had already been obtained by Hicks in 1902 Hicks 1902: "..the data published by Michelson and Morley, instead of giving a null result, show distinct evidence for an effect of the kind to be expected". Quantitatively, the situation can be summarized in Fig. 2, taken from Miller Miller 1934b, where the values of the effective velocity measured in various ether-drift experiments are reported and compared with a smooth curve fitted by Miller to his own results as function of the sidereal time.

In the framework of Eq. (16), the fringe shift is a second-harmonic effect, i.e. periodic in the range $[0,\pi]$, whose amplitude A_2 is predicted differently by using the classical formulas or Lorentz transformations (16)

$$A_2^{\text{class}} = \frac{D}{\lambda}\frac{v^2}{c^2}, \qquad A_2^{\text{rel}} = \frac{D}{\lambda}\frac{{v_{\text{obs}}}^2}{c^2} \sim 2\varepsilon A_2^{\text{class}}. \tag{27}$$

Now, for the Michelson-Morley interferometer the whole effective optical path was $D = 11$ meters, or about $2\cdot 10^7$ in units of light wavelengths, so for a velocity $v \sim 30$ km/s (the Earth's orbital velocity about the Sun, and consequently the minimum anticipated drift

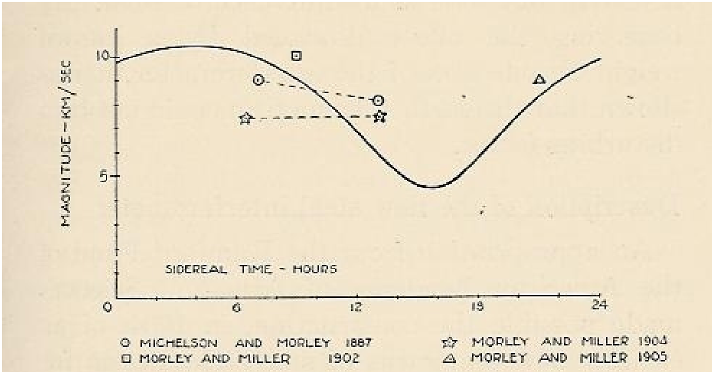

FIG. 4. Velocity of ether drift observed by Michelson and Morley in 1887, and by Morley and Miller in 1902, 1904 and 1905, compared with the velocity obtained by Miller in 1925.

FIGURE 2. The magnitude of the observable velocity measured in various experiments as reported by Miller (1934b).

velocity) the expected classical 2nd-harmonic amplitude was $A_2^{\rm class} \sim 0.2$. This value can thus be used as a reference point to obtain an observable velocity, in the plane of the interferometer, from the actual measured value of A_2 through the relation

$$v_{\rm obs} \sim 30 \sqrt{\frac{A_2}{0.2}} \;\; {\rm km/s}. \tag{28}$$

For the Michelson-Morley experiment, the average observable velocity reported by Miller is about 8.4 km/s. Comparing with the classical prediction for a velocity of 30 km/s, this means an experimental 2nd- harmonic amplitude

$$A_2^{\rm EXP} \sim 0.2 \left(\frac{8.4}{30}\right)^2 \sim 0.016 \tag{29}$$

which is about twelve times smaller than the expected result.

Neither Hicks nor Miller reported an estimate of the error on the 2nd harmonic extracted from the Michelson-Morley data. To understand the precision of their readings, we can look at the original paper (Michelson and Morley 1887) where one finds the following statement : "The readings are divisions of the screw-heads. The width of the fringes varied from 40 to 60 divisions, the mean value being near 50, so that one division means 0.02 wavelength". Now, in their tables Michelson and Morley reported the readings with an accuracy of 1/10 of a division (example 44.7, 44.0, 43.5,..). This means that the nominal accuracy of the readings was ± 0.002 wavelengths. In fact, in units of wavelengths, they reported values such as 0.862, 0.832, 0.824,.. Furthermore, this estimate of the error agrees well with Born's book (Born 1962). In fact, Born, when discussing the classically expected fractional fringe shift upon rotation of the apparatus by $90^{\rm o}$, about 0.37, reports explicitly: "Michelson was certain that the one-hundredth part of this displacement would still be observable" (i.e.

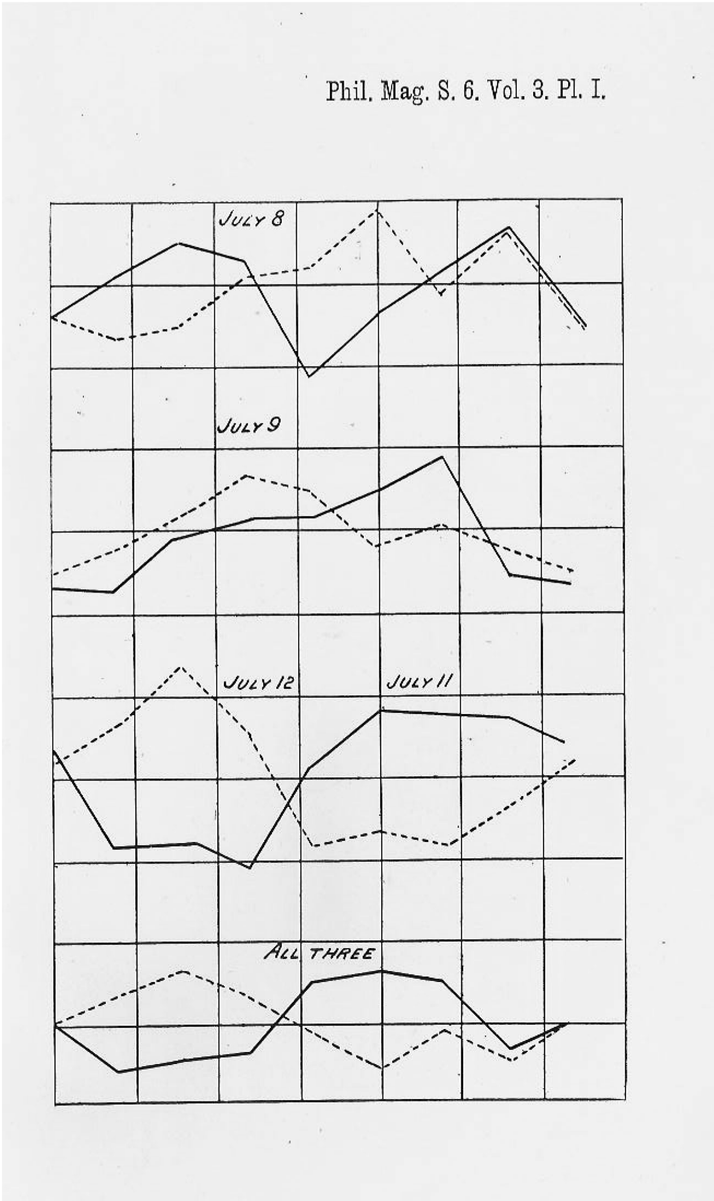

FIGURE 3. The Michelson-Morley fringe shifts as reported by Hicks (1902). Solid and dashed lines refer respectively to noon and evening observations.

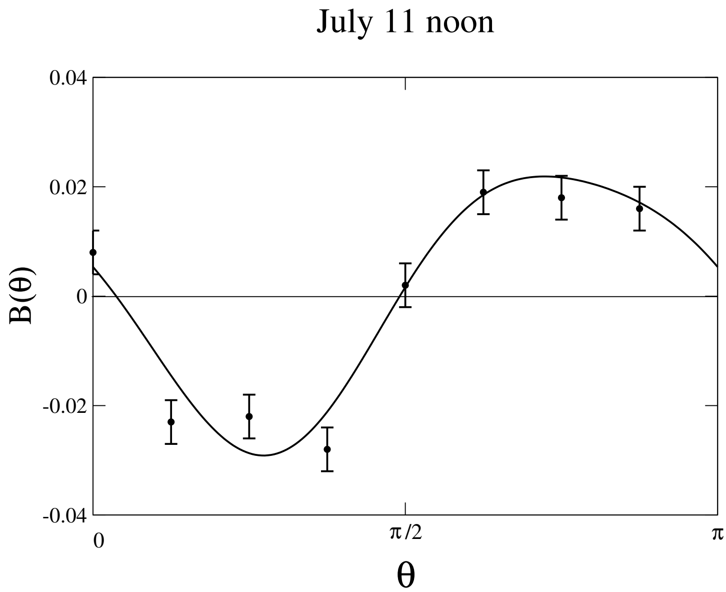

FIGURE 4. A fit to the even combination $B(\theta)$ Eq. (30). The second harmonic amplitude is $A_2^{\mathrm{EXP}} = 0.025 \pm 0.005$ and the fourth harmonic is $A_4^{\mathrm{EXP}} = 0.004 \pm 0.005$. The figure is taken from Consoli and Costanzo (2004b). Compare the data with the solid curve of July 11th shown in Fig. 3.

TABLE 1. *The amplitude of the fitted second-harmonic component* A_2^{EXP} *for the six experimental sessions of the Michelson-Morley experiment.*

SESSION	A_2^{EXP}
July 8 (noon)	0.010 ± 0.005
July 9 (noon)	0.015 ± 0.005
July 11 (noon)	0.025 ± 0.005
July 8 (evening)	0.014 ± 0.005
July 9 (evening)	0.011 ± 0.005
July 12 (evening)	0.024 ± 0.005

0.0037). Therefore, to be consistent with both the original Michelson-Morley article and Born's quotation of Michelson's thought, the estimate ± 0.004 for the error was adopted by Consoli and Costanzo (2004b) and Consoli *et al.* (2013). In these papers, many other details and all numerical values for the fringe shifts are reported.

The fringe shifts are given as a periodic function, with vanishing mean, in the range $0 \leq \theta \leq 2\pi$, so that they can be reproduced in a Fourier expansion. One can thus extract the amplitude and the phase of the 2nd-harmonic component by fitting the even combination of fringe shifts

$$B(\theta) = \frac{\Delta\lambda(\theta) + \Delta\lambda(\pi + \theta)}{2\lambda} \tag{30}$$

(see Fig.4). This is essential to cancel the 1st-harmonic contribution originally pointed out by Hicks Hicks 1902. Its theoretical interpretation is in terms of the arrangements of the mirrors and, as such, this effect has to show up in the outcome of real experiments. The 2nd-harmonic amplitudes from the six individual sessions are reported in Table 1. One can then compute the mean and variance of the six determinations by obtaining $A_2^{\mathrm{EXP}} \sim 0.016 \pm 0.006$. This figure is consistent with an observable velocity $v_{\mathrm{obs}} \sim 8.4^{+1.5}_{-1.7}$ km/s. Then, by using Eq. (17), which connects the observable velocity to the projection of the kinematical velocity in the plane of the interferometer through the refractive index of the medium where light propagation takes place (in our case air where $\mathcal{N} \sim 1.00029$ and thus $\varepsilon \sim 2.9 \cdot 10^{-4}$), we deduce the average value

$$v \sim 349^{+62}_{-70} \text{ km/s} \tag{31}$$

While the individual values of A_2 show a reasonable consistency, there are substantial changes in the apparent direction θ_0 of the ether-drift effect in the plane of the interferometer. This is the reason for the strong cancelations obtained when fitting together all noon sessions or all evening sessions (Handschy 1982). According to the usual interpretation, the large spread of the azimuths is taken as indication that any non-zero fringe shift is due to pure instrumental effects. However, as anticipated, this type of discrepancy could also indicate an unconventional form of ether-drift where there are substantial deviations from Eq. (16) and/or from the smooth trend in Eqs. (22a)–(22d). For instance, in agreement with the general structure Eq. (7), and differently from July 11 noon, which represents a very clean indication, there are sizeable 4th- harmonic contributions (here $A_4^{\mathrm{EXP}} = 0.019 \pm 0.005$ and $A_4^{\mathrm{EXP}} = 0.008 \pm 0.005$ for the noon sessions of July 8 and July 9 respectively). In any case, the observed strong variations of θ_0 are in qualitative agreement with the analogous values reported by Miller. To this end, compare with Fig. 22 of Miller (1934b) and in particular with the large scatter of the data taken around August 1st, as this represents the epoch of the year which is closer to the period of July when the Michelson-Morley observations were actually performed. Thus one could also conclude that individual experimental sessions indicate a definite non-zero ether-drift but the azimuth does not exhibit the smooth trend expected from the conventional picture Eqs. (22a)–(22d).

We emphasize that the large spread of the θ_0-values might also reflect a particular systematic effect pointed out by Hicks (1902). As described by Miller (1934b), " before beginning observations the end mirror on the telescope arm is very carefully adjusted to secure vertical fringes of suitable width. There are two adjustments of the angle of this mirror which will give fringes of the same width but which produce opposite displacements of the fringes for the same change in one of the light-paths". Since the relevant shifts are extremely small, "...the adjustments of the mirrors can easily change from one type to the other on consecutive days. It follows that averaging the results of different days in the usual manner is not allowable unless the types are all the same. If this is not attended to, the average displacement may be expected to come out zero—at least if a large number are averaged" (Hicks 1902).

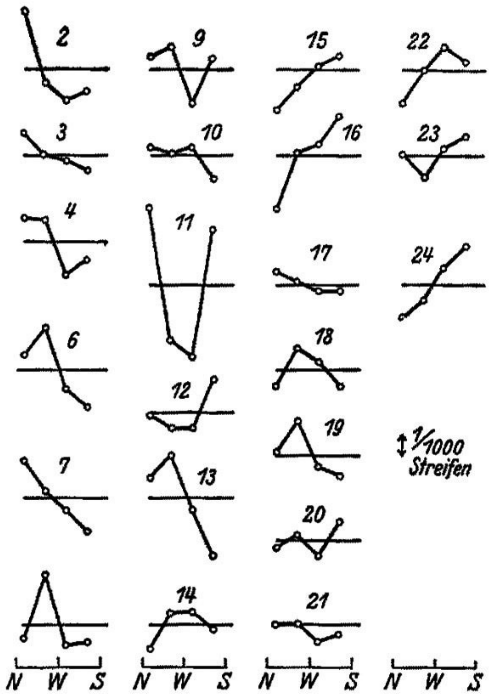

FIGURE 5. The selected set of data reported by Joos Joos 1930. The yardstick corresponds to 1/1000 of a wavelength so that the experimental dots have a size of about $0.4 \cdot 10^{-3}$. This corresponds to an uncertainty $\pm 0.2 \cdot 10^{-3}$ in the extraction of the fringe shifts.

Therefore averaging the fringe shifts from various sessions represents a delicate issue and can introduce uncontrolled errors. In fact, an overall change of sign of the fringe shifts at all θ-values is equivalent to replacing the azimuth $\theta_0 \to \theta_0 \pm \pi/2$. However, this relative sign does not affect the values of A_2 and this is why averaging the 2nd-harmonic amplitudes in Table 1, as we have done, is a safer procedure. From these amplitudes one obtains the average kinematical velocity Eq. (31) which is completely consistent with the average value 369 km/s associated with the Earth's motion with respect to the CMB.

7. Joos 1930 experiment

Joos' optical system (Joos 1930) was enclosed in a hermetic housing and, traditionally, it was always assumed that the fringe shifts were recorded in a partial vacuum. On the other hand, Swenson (1970) explicitly reports that fringe shifts were finally recorded with optical paths placed in a helium bath. In spite of the fact that this important aspect is never mentioned in Joos' papers, we have followed Swenson by assuming that during the measurements the interferometer was filled by gaseous helium at atmospheric pressure.

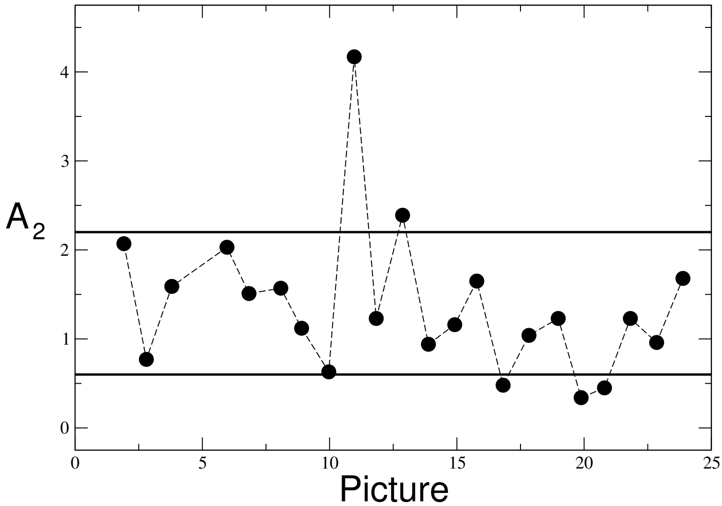

FIGURE 6. Joos' 2nd-harmonic amplitudes, in units 10^{-3}. The vertical band between the two lines corresponds to the range $(1.4 \pm 0.8) \cdot 10^{-3}$. The figure is taken from Consoli *et al.* (2013).

The observations were performed in Jena in 1930 starting at 2 P.M. of May 10th and ending at 1 P.M. of May 11th. Two measurements, the 1st and the 5th, were finally deleted by Joos with the motivation that there were spurious disturbances. The data were combined symmetrically, in order to eliminate the presence of odd harmonics, and the magnitude of the fringe shifts was typically of the order of a few thousandths of a wavelength. To this end, one can look at Joos' picture (reported here as our Fig. 5) and compare with the shown size of 1/1000 of a wavelength. From this picture, Joos decided to adopt 1/1000 of a wavelength as an upper limit and deduced an observable velocity $v_{\text{obs}} \lesssim 1.5$ km/s. To derive this value, he used the fact that, for his apparatus, an observable velocity of 30 km/s would have produced a 2nd-harmonic amplitude of 0.375 wavelengths.

Still, since it is apparent from Fig. 5 that some fringe displacements were definitely larger than 1/1000 of a wavelength, the values of the 2nd-harmonic amplitude A_2 were extracted Consoli *et al.* 2013 from the 22 pictures. Differently from the values of the azimuth, this can be done unambiguously. The point is that, due to the camera effect, it is not clear how to fix the reference angular values θ_k in Fig. 5 for the fringe shifts. In addition, there is a small misalignment angle, between the dots of Joos' fringe shifts and the N, W, and S marks, which cannot be deduced from the articles. Since clearly there is only one correct choice for the reference angles θ_k, we have preferred not to quote theoretical uncertainties on the azimuth and just concentrate on the amplitudes whose values, instead, do not depend on the angles θ_k and thus can be extracted unambiguously. Their values are reported in Fig. 6. The accuracy of each determination is about $\pm 0.2 \cdot 10^{-3}$ as given by the size of Joos' experimental dots in Fig.5. This uncertainty is about one order of magnitude better than for Michelson-Morley and a factor of 3 better than the 1/1500 reading error in the Illingworth experiment (Illingworth 1927).

By computing mean and variance of the individual values, we obtain an average 2nd-harmonic amplitude

$$\langle A_2^{\rm joos} \rangle = (1.4 \pm 0.8) \cdot 10^{-3} \quad (32)$$

and a corresponding observable velocity $v_{\rm obs} \sim 1.8^{+0.5}_{-0.6}$ km/s. By correcting with the helium refractive index, Eq.(17) would then imply a true kinematical velocity $v \sim 217^{+66}_{-79}$ km/s.

However, this is only a first and very partial view of Joos' experiment. In fact, we have compared Joos' amplitudes with theoretical models of cosmic motion. To this end, after transforming the civil times of Joos' measurements into sidereal times, by using Eqs. (22a) and (22d), one can compare Joos' amplitudes with theoretical predictions which, for the given latitude $\phi = 50.94$ degrees of Jena, depend on the right ascension α and the angular declination γ. To this end, it is convenient to first re-write the theoretical forms as

$$A_2(t)\cos 2\theta_0(t) = 2C(t) = \frac{2D(\mathcal{N}-1)}{\lambda}\,\frac{v_x^2(t)-v_y^2(t)}{c^2} \sim 2.6\cdot 10^{-3}\,\frac{v_x^2(t)-v_y^2(t)}{(300\ {\rm km/s})^2}, \quad (33)$$

and

$$A_2(t)\sin 2\theta_0(t) = 2S(t) = \frac{2D(\mathcal{N}-1)}{\lambda}\,\frac{2v_x(t)\,v_y(t)}{c^2} \sim 2.6\cdot 10^{-3}\,\frac{2v_x(t)\,v_y(t)}{(300\ {\rm km/s})^2}, \quad (34)$$

where we have used the numerical relation for Joos's experiment $\frac{D}{\lambda}\,\frac{(30{\rm km/s})^2}{c^2} \sim 0.375$ and the value of the helium refractive index $\mathcal{N} \sim 1.000035$. Then, by approximating $v_x(t) \sim \tilde{v}_x(t)$, $v_y(t) \sim \tilde{v}_y(t)$ and using Eq. (22d) for the scalar combination $\tilde{v}(t) \equiv \sqrt{\tilde{v}_x^2(t)+\tilde{v}_y^2(t)}$, we have fitted the data of Fig. 6 to the smooth form

$$A_2^{\rm smooth}(t) = {\rm const}\cdot \sin^2 z(t), \quad (35)$$

where $\cos z(t)$ is defined in Eq. (22a). The results of the fit

$$\alpha = 168^{\rm o} \pm 30^{\rm o} \qquad \gamma = -13^{\rm o} \pm 14^{\rm o} \quad (36)$$

confirm that, as found in connection with the Michelson-Morley experiment, the Earth's motion with respect to the CMB (which has $\alpha \sim 168^{\rm o}$ and $\gamma \sim -6^{\rm o}$) could serve as a useful model to describe the ether-drift data.

Still, in spite of the good agreement with the CMB α- and γ-values obtained from the fit Eq. (36), the nature of the strong fluctuations in Fig. 6 remains unclear. Apart from this, there is also a sizeable discrepancy in the absolute normalization of the amplitude. In fact, by assuming the standard picture of smooth time modulations, the mean amplitude over all sidereal times can trivially be obtained from the mean squared velocity Eq. (22d)

$$\langle \tilde{v}^2(t) \rangle = V^2 \left(1 - \sin^2\gamma \sin^2\phi - \frac{1}{2}\cos^2\gamma\cos^2\phi\right). \quad (37)$$

For the CMB and Jena, this gives $\sqrt{\langle \tilde{v}^2 \rangle} \sim 330$ km/s so that one would naively predict from Eqs.(33), (34)

$$\langle A_2^{\rm smooth}(t) \rangle \sim 2.6\cdot 10^{-3}\,\frac{\langle \tilde{v}^2(t)\rangle}{(300\ {\rm km/s})^2} \sim 3.2\cdot 10^{-3} \quad (38)$$

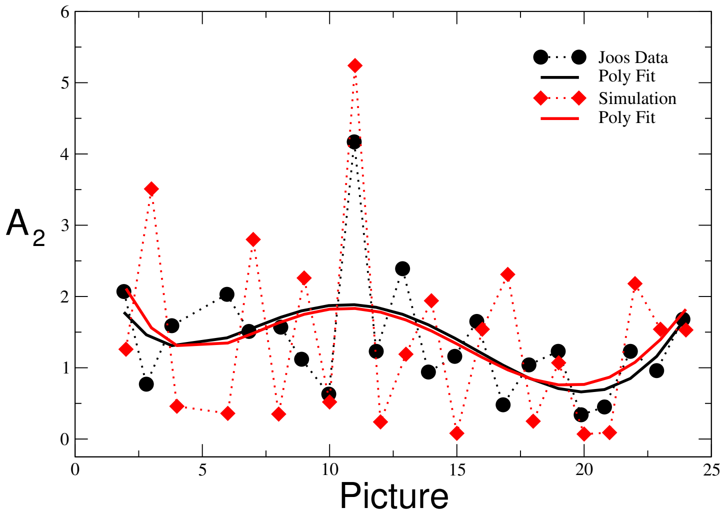

FIGURE 7. Joos' experimental amplitudes in Fig. 6 are compared with a single simulation of 22 instantaneous measurements. By changing the random sequence, the typical variation of each simulated entry is $(1 \div 4) \cdot 10^{-3}$ depending on the sidereal time. The stochastic velocity components are controlled by the kinematical parameters $(V, \alpha, \gamma)_{\rm CMB}$ as explained in the text. We also show two 5th-order polynomial fits to the two different sets of values. The figure is taken from Consoli *et al.* (2013).

to be compared with Joos' mean value $\langle A_2^{\rm joos} \rangle = (1.4 \pm 0.8) \cdot 10^{-3}$. In the standard picture, this experimental value leads to the previous estimate $\sqrt{\langle \tilde{v}^2 \rangle} \sim 217$ km/s and *not* to $\sqrt{\langle \tilde{v}^2 \rangle} \sim$ 330 km/s so that it is necessary to change the theoretical model to try to make Joos' experiment completely consistent with the Earth's motion with respect to the CMB.

To try to solve this problem, and understand the origin of the observed strong fluctuations, we have used the model Eqs.(24a), (24b) of Sect.6, to simulate stochastic variations of the velocity field. As anticipated, due to the high accuracy of the Joos experiment, the two random parameters $x_n(1)$ and $x_n(2)$ were allowed to vary in the range $[-\tilde{v}_x(t), \tilde{v}_x(t)]$ and the other two parameters $y_n(1)$ and $y_n(2)$ to vary in the different range $[-\tilde{v}_y(t), \tilde{v}_y(t)]$, where $\tilde{v}_x(t)$ and $\tilde{v}_y(t)$ are defined in Eqs. (22a)–(22c). Also the quadratic values were fixed as in Eqs.(26). It is understood that the latitude corresponds to Joos' experiment while V, α and γ describe the Earth's motion with respect to the CMB.

In this model, there will be a substantial reduction of the amplitude with respect to its smooth prediction. To estimate the order of magnitude of the reduction, one can perform a full statistical average (as for an infinite number of measurements) and use Eqs. (26) in Eqs. (33), (34) for our case $\eta = 1$. This gives

$$\langle A_2(t) \rangle_{\rm stat} \sim 2.6 \cdot 10^{-3} \, \frac{\tilde{v}^2(t)}{(300 \text{ km/s})^2} \, \frac{1}{3} \sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{18} \, A_2^{\rm smooth}(t). \qquad (39)$$

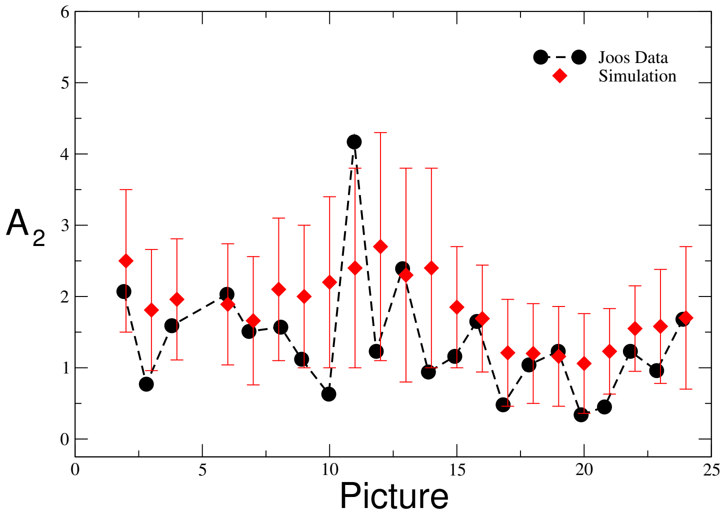

FIGURE 8. Joos' experimental amplitudes in Fig.6 are compared with the result of simulating the averaging process over 10 measurements performed, at each Joos' time, on 10 consecutive days. The stochastic velocity components are controlled by the kinematical parameters $(V,\alpha,\gamma)_{\rm CMB}$ as explained in the text. The effect of varying the random sequence has been approximated into a central value and a symmetric error. The figure is taken from Consoli *et al.* (2013).

By also averaging over all sidereal times, for the CMB and Jena, one would now predict a mean amplitude of about $1.7\cdot 10^{-3}$ and not of $3.2\cdot 10^{-3}$.

To have an idea of the agreement between Joos' 22 amplitude data and a *single* numerical simulation of instantaneous measurements, we show a graphical comparison in Fig.7. We emphasize that one should not compare each individual entry with the corresponding data since, by changing the random sequence, the simulated instantaneous entries vary typically of about $(1\div 4)\cdot 10^{-3}$ depending on the sidereal time. Instead, one should compare the overall trend of data and simulation. To this end, we show two 5th-order polynomial fits to the two different sets of values.

A more conventional comparison with the data consists in quoting for the various 22 entries simulated average values and uncertainties. To this end, we have considered the mean amplitudes $\langle A_2^{\rm simul}(t_i)\rangle$ defined by averaging, for each Joos' time t_i, over 10 hypothetical measurements performed on 10 consecutive days. For each t_i, the observed effect of varying the random sequence has been summarized into a central value and a symmetric error. The simulated values and the comparison with Joos' amplitudes is shown in Fig.8.

The spread of the various entries is larger at the sidereal times where the projection at Jena of the cosmic Earth's velocity becomes larger. The tendency of Joos' data to lie in the lower part of the simulated range mostly depends on our use of symmetric errors. In fact, by comparing in some case with the histograms of the basic generated configurations $A_2^{\rm simul}(t_i)$, we have seen that our sampling method of $\langle A_2^{\rm simul}(t_i)\rangle$ typically underestimates the weight of the low-amplitude region in a prediction at the 70% C.L. For this reason, one could improve the evaluation of the probability content. However, in view of the good agreement already found in Fig. 8 ($\chi^2 = 13/22$), we did not attempt to carry out this more refined analysis.

In conclusion, after the first indication obtained from the fit Eq. (36), the link between Joos' data and the Earth's motion with respect to the CMB gets reinforced by our simulations. In fact, by inspection of Figs. 7 and 8, the values of the amplitudes and the characteristic scatter of the data are correctly reproduced. From this agreement, we then deduce that the previous kinematical value $v \sim 217^{+66}_{-79}$ km/s has to be considerably increased if one allows for stochastic variations of the velocity field. In fact, the magnitude of the fluctuations in v_x and v_y is controlled by the same scalar parameter $\tilde{v}(t) \equiv \sqrt{\tilde{v}_x^2(t) + \tilde{v}_y^2(t)}$ of Eq. (22d). We thus conclude that Joos' data are consistent with a range of kinematical velocity $v = 330^{+40}_{-70}$ km/s which corresponds to Eq. (22d) for $\phi = 50.94^{\text{o}}$, $V = 370$ km/s, $\alpha = 168^{\text{o}}$ and $\gamma = -6^{\text{o}}$.

8. Summary and conclusions

Traditionally, the classical ether-drift experiments were analyzed by using classical, pre-relativistic physics. In addition, the interpretation of the data was based on a theoretical model where all type of signals that are not synchronous with the Earth's rotation tend to be considered as spurious instrumental noise. As we have explained, in this strategy there are two logical gaps. First, one should take into account consistently that, according to both special and Lorentzian relativity, any effect should vanish identically if the velocity of light c_γ, propagating in the various interferometers, coincides with the basic parameter c entering Lorentz transformations. At the same time, the relation between the macroscopic Earth's motion and the microscopic measurements of the velocity of light in a laboratory depends on a complicated chain of effects and, ultimately, on the physical nature of the vacuum. As such, the observed signal could be more subtle than naively expected. The point of view adopted so far corresponds to assume the Earth's motion as in a fluid in a state of regular, laminar motion where global and local properties of the flow coincide. Instead, the physical situation might be more similar to that of a turbulent fluid where the macroscopic motion would only fix the typical boundaries for a microscopic flow which has an intrinsic stochastic nature. In this case, there could be forms of random signals that have a genuine physical origin.

To explore this idea, we have re-considered from scratch the classical experiments. These were performed in gaseous media where the refractive index $\mathcal{N}$ is extremely close to unity. In this case, if there were a preferred reference frame, by expanding around $\mathcal{N} = 1$ and to leading order in v/c, one formally finds the same classical formulas with the only replacement

$$v^2 \to 2(\mathcal{N} - 1)v^2 \equiv v^2_{\text{obs}}. \tag{40}$$

Testing this scheme is very simple: one should just check the consistency of the true kinematical v's obtained in different experiments. In this alternative interpretation, the indications of the various experiments are summarized in our Table 2 which is taken from Consoli *et al.* (2013) (to which we address the reader for many details). Here, we just emphasize the following points:

TABLE 2. *The average velocity observed (or the limits placed) by the classical ether-drift experiments in the alternative interpretation of Eqs. (15), (16), (17). The table is taken from Consoli* et al. *(2013).*

Experiment	gas in the interferometer	v_{obs}(km/s)	v (km/s)
Michelson-Morley(1887)	air	$8.4^{+1.5}_{-1.7}$	349^{+62}_{-70}
Morley-Miller(1902-1905)	air	8.5 ± 1.5	353 ± 62
Kennedy(1926)	helium	< 5	< 600
Illingworth(1927)	helium	3.1 ± 1.0	370 ± 120
Miller(1925-1926)	air	$8.4^{+1.9}_{-2.5}$	349^{+79}_{-104}
Michelson-Pease-Pearson(1929)	air	$4.5 \pm \ldots$	$185 \pm \ldots$
Joos(1930)	helium	$1.8^{+0.5}_{-0.6}$	330^{+40}_{-70}

i) an analysis of the individual sessions of the original Michelson-Morley experiment, in agreement with Hicks (1902) and Miller (1934b) (see our Figs. 2 and 3), gives no justification to its standard null interpretation. As discussed in Sect.5, this type of analysis is more reliable. In fact, averaging directly the fringe displacements of different sessions requires two additional assumptions, on the nature of the ether-drift as a smooth periodic effect and on the absence of systematic errors introduced by the re-adjustment of the mirrors on consecutive days, that in the end may turn out to be wrong.

ii) from the Michelson-Morley, Morley-Miller, Miller and Illingworth-Kennedy experiments one gets average kinematical velocities which are well consistent with the value 370 km/s which today is obtained from the CBR anisotropy. In view of this consistency, the standard interpretation of Miller's observations in terms of a temperature gradient (Shankland *et al.* 1955) is only acceptable provided this gradient represents a *non-local* effect as in the picture of (Consoli *et al.* 2016) where the ether-drift is the consequence the CBR temperature gradient. This conclusions would also fit well with the estimates of periodic temperature differences in the air of the optical arms of about ± 0.001 K or ± 0.002 K, by Joos, Kennedy and Shankland, and the observed gradient ± 0.003 K which is due to the Earth's motion within the CBR.

iii) some discrepancy is found with the experiment performed by Michelson, Pease and Pearson (MPP). At the same time, as emphasized by Consoli *et al.* (2013), the uncertainty cannot be easily estimated since only one basic MPP observation is explicitly reported in the literature. Therefore, since Miller's extensive observations (see Fig. 22 of Miller (1934b)), within their errors, gave fluctuations of the observable velocity in the wide range 4–14 km/s, a single observation giving $v_{\mathrm{obs}} \sim 4$ km/s cannot be interpreted as a refutation. This becomes even more true by noticing that the single MPP session explicitly reported, within a period of several months, was chosen to represent an example of extremely small ether-drift effect.

iv) Joos' experiment is particularly important since the data were collected at steps of 1 hour to cover the full sidereal day and were recorded by photocamera. For this reason, it is not comparable with other experiments (e.g. Michelson-Morley, Illingworth) where only observations at few selected hours were performed and for which, in view of the strong fluctuations of the data, one can just quote the average magnitude of the observed velocity.

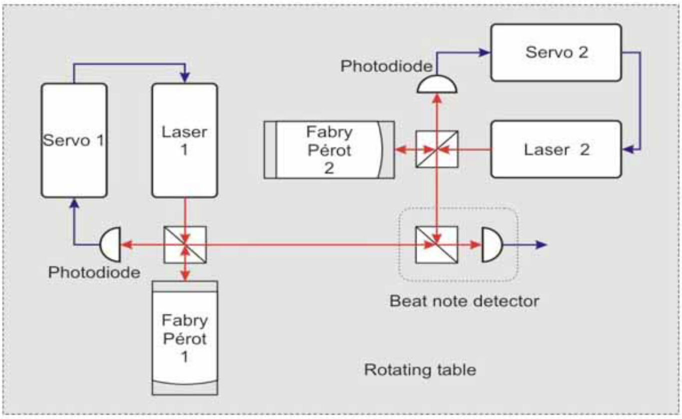

FIGURE 9. The scheme of a modern ether-drift experiment. The light frequencies are first stabilized by coupling the lasers to Fabry-Perot optical resonators. The frequencies ν_1 and ν_2 of the signals from the resonators are then compared in the beat note detector which provides the frequency shift $\Delta\nu = \nu_1 - \nu_2$. In present experiments a very high vacuum is maintained within the resonators.

In fact, by fitting the experimental amplitudes in Fig. 6 to various forms of cosmic motion (see Eq. (36)) we have obtained angular parameters which are very close to those describing the CBR anisotropy (right ascension $\alpha_{\rm CBR} \sim 168^{\rm o}$ and angular declination $\gamma_{\rm CBR} \sim -6^o$). Still, to get a complete agreement, one should explain the absolute normalization of the amplitudes and the strong fluctuations of the data. Thus we have sharpened our analysis by performing various numerical simulations where the velocity components $v_x(t)$ and $v_y(t)$ are not smooth functions but are represented as turbulent fluctuations. Their Fourier components in Eqs. (24a) and (24b) vary within time-dependent ranges Eqs. (22b)–(22c), $[-\tilde{v}_x(t), \tilde{v}_x(t)]$ and $[-\tilde{v}_y(t), \tilde{v}_y(t)]$ respectively, controlled by the macroscopic parameters $(V, \alpha, \gamma)_{\rm CMB}$. Taking into account these stochastic fluctuations of the velocity field tends to increase the fitted average Earth's velocity, see Eq.(39), and can reproduce correctly Joos' 2nd-harmonic amplitudes and the characteristic scatter of the data, see Figs. 7 and 8.

These results give a strong motivation to repeat these crucial measurements with today's much greater accuracy. To this end, let us now briefly consider the modern ether-drift experiments. In this case, as anticipated, the test of the isotropy of the velocity of light consists in measuring the relative frequency shift $\Delta\nu$ of two orthogonal optical resonators (Müller *et al.* 2003). Here, the analog of Eq. (16) is

$$\left[\frac{\Delta\nu(\theta)}{\nu_0}\right]_{\rm gas} = \frac{\bar{c}_\gamma(\pi/2+\theta) - \bar{c}_\gamma(\theta)}{c} \sim (\mathcal{N}_{\rm gas} - 1)\frac{v^2}{c^2}\cos 2(\theta - \theta_0), \tag{41}$$

where the pair (v, θ_0) describes the magnitude and the direction of the ether-drift in the plane of the interferometer and $\mathcal{N}_{\rm gas}$ the refractive index of the gaseous medium filling the optical resonators. Testing this prediction, requires replacing the high vacuum usually adopted within the optical resonators with a gaseous medium and studying the substantially larger frequency shift introduced with respect to the vacuum experiments, see Fig. 9.

As a rough check, a comparison was made (Consoli and Costanzo 2004a; Consoli *et al.* 2016) with the results obtained by Jaseja *et al.* (1964) in 1963 when looking at the frequency shift of two orthogonal He-Ne masers placed on a rotating platform. To this end, one has to preliminarily subtract a large systematic effect that was present in the data and interpreted by the authors as probably due to magnetostriction in the Invar spacers induced by the Earth's magnetic field. As suggested by the same authors, this spurious effect, which was only affecting the normalization of the experimental $\Delta\nu$, can be subtracted by looking at the variations of the data. As discussed by Consoli and Costanzo (2004a) and Consoli *et al.* (2016), the measured variations of a few kHz are roughly consistent with the refractive index $\mathcal{N}_{\text{He}-\text{Ne}} \sim 1.00004$ and the typical variations of an Earth's velocity as in Eq. (31).

More recent experiments (Brillet and Hall 1979; Eisele *et al.* 2009; Herrmann *et al.* 2009) have always been performed in a very high vacuum where, as emphasized in the Introduction, the differences between Special Relativity and the Lorentzian interpretation are at the limit of visibility. In fact, in a perfect vacuum by definition $\mathcal{N}_{\text{vacuum}} = 1$ so that any effect would vanish. Thus one should switch to the new generation of dedicated ether-drift experiments in gaseous systems. Our conclusion is that these new experiments should just confirm Joos' remarkable observations of eighty years ago.

In Memoriam

This article is dedicated to the memory of Prof. Gaetano Giaquinta. He was a brilliant scientist with an analytical mind, ready to find the logical solution to the problems, though not necessarily a solution that would find an immediate acceptance. For this reason, he had to fight many times before his ideas could find proper acknowledgment. He was also a dear friend and we really miss him.

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