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What's in a name?

On the latest attempts to revive an Æther

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Abstract The development and evolution of the "Einstein–Æther Theory" (Æ-theory) shows that there is a field in cosmology where the word ether is being used again. It is unclear, however, whether this æther may be regarded *in continuation* with previous ethers, or it is an altogether *new entity*. The main goal of this paper is to understand the nature of this new ether in the context of previous instances of this *scientific object*. In order to do so, we shall first give a brief historical account of the distinct uses the word had assumed in the late nineteenth and early twentieth centuries, before its demise. Then, we shall describe the major attempts to revive the ether over the last century, focusing on the last endeavor: the Æ-theory. In this article, we do not intend to support or reject this new use of the word, but to stress the complexity of establishing a consistent historical narrative of some scientific objects like the ether.

1 Introduction

In a very recent news article in *Nature*, the journalist and popularizer of science Davide Castelvecchi called everyone's attention with his claim that cosmologists might have found hints of "an exotic substance called quintessence" or "ether" that "could be accelerating the Universe's expansion" [10]. The observations he referred to had just been published in *Physical Review Letters* by cosmologists Yuto Minami and Eiichiro Komatsu and consisted on a very tiny deviation "in the measurement of the cosmic birefringence angle" that, if ultimately confirmed by other observations and other teams, might give evidence of parity violation and, in turn "would have a profound implication for fundamental physics" [48]. The latter article, soberly descriptive as research papers tend to be, contrasts with Castelvecchi's use of the words quintessence and ether as a way to trigger curiosity.

Indeed, ether (or æther) is one of those words that recurrently resurface in popular science, among science dilettantes and, only at times, in the ranks of professional physicists. For the latter, the ether is mostly regarded as a curiosity of the past with no place in contemporary physics. And rightly so, if by ether we mean the quasi-mechanical medium that Victorians imagined to account for a number of phenomena in electricity, magnetism, optics and even gravitation. Yet, as a number of historians of science have shown, it is very difficult to attribute a clear, well-defined meaning to a word that has played many roles in the history of science [1,7,53] or [57]. This polysemy is not unique to the ether. Terms consistently used in physics for decades or even centuries such as atom, elementary particle, energy or field, only to name a few, have often times been redefined and their meanings transformed while preserving the name. There is no secret about these diverse fates of words. It is simply proof of the contingency in the development of physics throughout its history.

Perhaps because the ether was at some undetermined time declared dead [52], every attempt to use the word in professional physics has so far always derailed. In this paper we pay attention to one such bid to resuscitate the word ether in the last decades: the so-called Einstein–Æther theory (Æ-theory) in cosmology. Contrary to similar episodes, where proposals often came from the margins of the discipline, reduced to a few papers in second-rate journals, public conferences or folk philosophy, the Æ-Theory has certainly consolidated a school of physicists around it, publishing in major journals, presenting in respected conferences and extending its principles to quite a number of specific problems. As historians of science, what interests us here is to see the extent to which this

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theory might somehow be placed as part of a *long-durée* history of the ether or, on the contrary, the word "æther" in the Einstein–Æther theory is simply a linguistic device to trick the audience.

To do so, we shall start with a brief summary of the history of the ether paying particular attention to the basic uses the word had in the late nineteenth and early twentieth centuries. We shall then list the major attempts to bring back the word ether in professional physics in the last one hundred years. This will give us the background to describe and analyze the meaning of "Æther" in the Einstein–Æther theory. Perhaps we should emphasize that our aim is purely descriptive and historical; we have no vested interest in promoting the use of the word ether or dismissing it altogether in any present or future theory. As historians of science, this is not our role.

2 From the many ethers to the many uses of the one ether

When to start a history, or a *biography*, of the ether? Like with atoms, one could resort to the always available Ancient Greeks and move to include the main medieval scholars in the narrative. Descartes' and Newton's different, almost opposite, ethers to fill the emptiness that the mechanical philosophy of the sixteenth and seventeenth centuries had brought with it, might also be highlights in the story. Yet, for the purposes of this paper, we can easily dismiss those *philosophical ethers* since they were embedded within the tradition of natural philosophy not of the emerging modern physics. Indeed, when Geoffrey Cantor and Jonathan Hodge edited their now classical book on *Conceptions of Ether* [7], they chose the reasonable time-line 1740–1900, which may be regarded as the heyday of modern ether in physics.

This century and a half may, in turn, be divided into two non-equal periods. Until roughly the mid-nineteenth century there was much theorizing about the ether as a solution to different and unconnected problems: from gravitation to heat, from physiology to electricity. It is not that the ether was the mortar that kept all these phenomena together but, on the contrary, there were many theories and models about multiple *imponderable* or *subtle* fluids that had hardly any connection between them. Cantor and Hodge put forward a classification of those models in *five* categories, depending on how any particular ether was modelled to propagate action at a distance: the projectile model (i.e., Descartes and Le Sage), the gradient model (i.e., Newton's Optiks), the interactive atmospheric model (i.e., Franklin's electrostatic action), the hydrodynamical model (i.e., heat flow or Franklin's electrodynamic phenomena), and the vibratory, rotatory or deformable model (i.e., Fresnel theory of light) [7, 29–30].

By mid-nineteenth century, things had changed, partly due to the triumph of the mechanical model tradition, to the establishment of a mathematical and visualizable notion of field in physics, and to the increasing unification of electric and magnetic, and ultimately optical, phenomena. That is why perhaps the most influential definition of the Victorian ether was the one given by James C. Maxwell in his entry to the 9^{th} edition of the *Encyclopedia Britannica*. In the face of the many ethers of previous generations, the physics of his time, after the unification of light, electricity and magnetism, seemed to allow for a single ether with a number of epistemic roles: "The only æther which has survived is that which was invented by Huygens to explain the propagation of light" [45].

Modern physics was finally talking about the ether, in the singular, and not about the many imponderable fluids of post-Newton times [1, 201]. This unified æther—sometimes called *luminiferous æther*—was electrodynamical rather than mechanical. The main roles of the ether were both metaphysical and methodological: to act as the *necessary* medium for the transmission of electromagnetic waves (as well as to fill all the space[1] and define absolute motion); and to serve as an entity to be modelled in order to explain electromagnetic phenomena. On top of that, the ether might also help explain other interactions, especially the always elusive cause of gravitation, or even be the *proto hyle* of all matter [40], thus providing the key element for the long-desired unity of physics.

A few decades later, the moderate hope Maxwell had on a unified physics had reached its peak [46] or [13]. The well-known Electromagnetic view of Nature developed mainly by Hendrik A. Lorentz and which had electric charge and the ether as the only two fundamental entities in physics was the most solid theory at the turn of the century. The ether was here a non-mechanical entity, clearly "described by the concise, elegant equations of the electron theory", and thus, "in marked contrast to ordinary matter, whose complexity was believed incapable of ever being exactly described" ([46, 495], see also [35]). In 1911, Joseph Larmor, another of the main actors of the Electromagnetic view of Nature, was in charge of revising Maxwell's entry about the ether in the 11^{th} edition of the *Encyclopedia Britannica* and he changed it altogether, using a more triumphalist tone. In his words, the whole of "theoretical physics" consisted in "the science of the aether" which, in a way, had turned into the most fundamental substance, "a *plenum*, which places it in a class by itself; and we can thus recognize that it may behave very differently from matter". Atoms became, in this picture, epiphenomena of the ether: manifestations of singularities, asymmetries, or vortices in the ether. An atom "would be identical with the surrounding field of aethereal motion or strain that is inseparably associated with the nucleus" [43]. The dream of the unity of

[1] Maxwell claimed that "whatever difficulties we may have in forming a consistent idea of the constitution of ether, there can be no doubt that the interplanetary and interstellar spaces are not empty" [45].

the physical world hinged on the unicity of the ether which was, in turn, related to the conservation of energy, specifically, the transformation and quantitative equivalence between electric, magnetic, thermal and mechanic energies. This had made “possible the construction of a network of ramifying connections between [the] various departments [of physics]; it thus stimulates the belief that these constitute a single whole” [43]. The science of ether, as Larmor and many others called it, implied that the ether was not only one among the many objects in the physical world, but the fundamental one together with the electron, turning atoms and actions into somewhat epiphenomena of that most basic element.

Although the ether is often equated with so-called classical physics and the latter strongly shaped by Victorian scientific traditions, the ether was also an intrinsic element in Continental physics. In M. Norton Wise’s [67] description, mid-century German physicists were reluctant to accept a purely mathematical notion of field, in reaction to the speculative excesses of *Naturphilosophie*. As a main example, Wilhelm Weber imagined an ether formed of neutral pairs of positive and negative electricity. After him, Bernhard Riemann moved to an explanation of gravitation and the transmission of light based on the inertia of a space-filling ether: resistance to change in volume would be the source of gravitation; to a change of shape, transmission of light. Finally, Herman von Helmholtz imagined the ether as an electrically and magnetically polarizable medium in which all forces acted successively in contiguous elements of such medium. In any case, as Heaviside once put in a letter to Hertz, “My experience of so-called ‘models’ is that they are harder to understand than the equations of motion!” [31, 105].

Also in mid-century Germany, speculation on the ether was related to a broader interest on the relationship between physics, physiology and psychology. J. R. Mayer, for instance, distinguished between three substances, namely matter, force and *Geist*. The ether would be the seat of an all-pervading force (in opposition to action-at-a-distance forces) and also, by analogy, of mind, soul or *Geist*. Some such ideas were eventually appropriated and transformed by “Energeticists” and “Vitalists”, who thought less in terms of an ether and highlighted the centrality of energy or an *élan vital* as a substance [67, 270–276].

Finally, a consequence rather than a foundation of the ether was its role as the absolute reference framework, as it is clear in the theory of Lorentz. In the early 1880s, the need for global standards in several industries became a priority. Measurements linked to local conditions became useless for global projects in which precision was essential, like in the calibration of apparatus for the telegraph. In this context, the possibility of using the ether as the framework that would provide an absolute reference irrespective of the earth became prominent. As Richard Staley [61] argued, this is the *milieu* of Michelson and Morley’s experiments to measure the speed of the earth in the ether. As it is well known, this property of the ether was the first one that ultimately triggered its demise, a property which will be central in our discussion of the Æ-theory.

3 The many deaths of the ether

Recent scholarship has explored the many ways and times in which the ether lingered, disappeared or attempted to remain on the stage of physics [51]. Certainly, special relativity was at the forefront of the ether’s demise. But wireless technologies, general relativity, quantum physics, energy physics, electrodynamics and precision measurement, among many others, were arenas where the ether was often discussed. Not to mention physiology, aesthetics, spiritualism, politics, religion, etc., where the ether became a recurrent cultural trope. In all cases, however, the tradition initiated with Maxwell’s unification of referring to one ether, not many, meant that discussions about its existence seldom distinguished between the different epistemic roles it played. Recently, Massimiliano Badino and one of us (Jaume Navarro) spoke about “the multiple lives of the ether in the first decades of the last century” [3, 2] suggesting that the ether became a sort of interstitial concept:

> “As an interstitial concept, it was plastic and pliable enough to be adapted to diverse contexts, because it was no longer a specific object, but rather a multidimensional concept able to serve a number of epistemic, symbolical, social, political, emotional, moral, and even scientific functions some of which, in contrast, were perfectly in tune with modernity. But such an extreme flexibility had, of course, a downside. Sitting at the interstices between multiple discourses, the ether was not integral to any of them and was not autonomous. Hence, it had to be sustained by the continuous effort of authoritative figures energetically acting in the public sphere. This, in turn, generated complex dynamics of alliances, negotiations, and strategies reaching out a considerable variety of debates.” [3, 12]

We would like to stress two points, which will be relevant to our ulterior discussion. First, the multidimensionality of the ether, both within the most esoteric circles of physics and the exoteric worlds around it, transformed the ether into a *name* that, because it meant many things and for multiple purposes, could or should be easily dismissed. More so when such uses included anti-Semitism and Nazism [58], spiritualism [55], artistic speculations [30] or a stubborn defense of classical physics [12,61] or [28].

The other point to underline is the role of figures with public authority in preserving or rejecting some sort of ether in physics. In Britain, popular figures like Oliver Lodge[2] and Arthur Eddington[3] both icons of modern science in the early twentieth century, strongly defended the preservation of an ether. Their use of the word ether could not be more different. Lodge wanted to preserve a classical ether similar to Maxwell's [50,64], while Eddington campaigned to re-signify the word ether to describe the space-time tensor of General Relativity [53]. Elsewhere, Lorentz and Michelson also did not give up talking about the ether and continued to base their theoretical work on this *epistemic object*[4].

Of course, the authority of Einstein was central in debates about the ether (see [38] and Renn's criticism of the book [56]). As it has often been explained, the irrelevance of the ether in his 1905 theories on special relativity and the quantum of light—both as medium for the propagation of light and as universal reference framework—seemed to be later appeased in his famous 1920 Leiden conference [19]. There, he argued that special relativity had proven the idea of an ether *qua* absolute space inconsistent, but he left space to the existence of a medium. Thus, Einstein's authority on the ether supported both its abandonment and its re-signification *a la* Eddington.

By the end of the 1930s, appeals to the Maxwellian ether had largely disappeared from mainstream professional physics and any ulterior attempt at resurrecting the name had to come side with a clear transformation of the concept associated with this *epistemic object*.

4 Ether revivals

In the short preface to the second edition of his *A History of the Theories of Aether and Electricity*, issued in 1951, Edmund Whittaker explained why he decided to preserve the old title. First published in 1910, this book was intended as an encyclopedic account of the evolution of physics since the days of Descartes. The word *aether* had fallen "out of favour", he said, and it had become "customary to refer to the interplanetary spaces as *vacuous*". But, his argument continued, with the formulation of quantum electrodynamics "the vacuum has come to be regarded as the seat of the *zero-point fluctuations* of electric charge and current, and of a *polarisation* corresponding to a dielectric constant different from unity". Whittaker's suggestion was that "it seems absurd to retain the name *vacuum* for an entity so rich in physical properties, and the historical word *aether* may fitly be retained"[5] [63, preface].

With the complexities to formulate a consistent theory of quantum field theory, the suggestion to establish a continuity between the quantum vacuum and the old ether has often surfaced. At any rate, as well stressed by Kragh and Overduin, tempting as it may be to consider the *classical æther* as an anticipation of *modern vacuum energy*, it is important to realize that it is at best an analogy and that the historical connection between the two *concepts* is much more complicated: "Vacuum energy is a quantum phenomenon and to find its historical origin we need to look at the early development of quantum theory" [41, 11]. A different thing would be to discuss, as Whittaker was doing in the preface, whether the *name* could be recycled. Because that is what some attempted comebacks of the ether have actually done: to re-use the word for its analogy with some Victorian, Cartesian, Medieval or Ancient ether, rather than to resurrect the old ether with all its conceptual scaffolding of classical physics or natural philosophy.

One of the earliest such attempts was the so-called neo-Lorentzian interpretation of the theory of special relativity. In this modernized version of Lorentz's ether theory, some scientists such as the industrial physicist Herbert E. Ives re-proposed Lorentz's concept of ether, stating that the result of the famous Ives-Stilwell experiment[6] could be explained assuming a *fixed luminiferous ether* [42].

Another attempt, maybe the best-known one, to re-use the word ether was brought by Paul Dirac's famous 1951 notes in *Nature* where, with the catchy title "Is there an Æther?", he tried to raise awareness about the troublesome state of quantum electrodynamics and to promote his own solution [16,17]. His main criticism to the current state of affairs was his rejection of the existence of infinities that had to be circumvented. On this, he was not alone, since many tried to reformulate quantum electrodynamics in different ways [59]. Thus, the responses to Dirac's theory did not normally make any references to the ether but to its actual technical points [39, 189–204], [68]. So, why mention the ether, let alone in its ancient spelling *Æther*? Dirac seldom sent letters to *Nature* and, when he did, it tended to be with provocative titles to capture the attention of the reader. This led Aaron Wright

[2] Oliver Lodge is known for his role in the development of wireless technologies.

[3] Arthur Eddington is known for his astronomical work in the famous eclipse expeditions of 1919.

[4] Here we use epistemic object in the sense given by Hasok Chang in [11].

[5] On this he may have been following the suggestion, not very popular at that time, that Walther Nernst had made as early as 1916 [41, 29–37].

[6] This experiment, which is usually interpreted as the first direct confirmation of the time dilation formula of special relativity, was part of an extended research program with the aim of challenging the acceptance of relativity theories. It was regarded by Ives as proof of what he called the Larmor-Lorentz theory.

to suggest that Dirac's 1951 *Æther* was "an example of a strongly rhetorical use of the aether", since "among scientists in 1951 the aether was an anachronism. Anachronisms—whether obsolete words or horse-drawn carriages in contemporary cities—draw attention" [68, 231].

But what did Dirac's æther refer to? It was a formal entity, the electromagnetic potential, that represented a velocity at each point in space, which in turn would cause charges to move:

> "Its [the æther velocity's] physical significance in the theory is that if there is any electric charge it must flow with this velocity, and in regions where there is no charge it is the velocity with which a small charge would have to flow if it were introduced. We have now the [æther] velocity at all points of space-time, playing a fundamental part in electrodynamics. It is natural to regard it as the velocity of some real physical thing. Thus with the new theory of electrodynamics we are rather forced to have an æther." [16, 906–907]

We shall discuss the possible connections between the neo-Lorentzian ether, Dirac's æther and contemporary ethers in the next sections. At any rate, it is undeniable that, in spite of the *ether effect*, these theories did not find much support, neither were they further developed. Similar fate suffered the scattered mentions to the ether randomly appearing in the non-technical literature written by physicists, some major examples of which may be Robert Dicke in 1959 [15], Paul Davies in 1982 [14] or Frank Wilczek in 1999 [65], as mentioned in [41, 11].

With all this in mind, our first goal was to systematically explore the times and venues where the attempts to revive the ether debate have taken place since Dirac's 1951 paper. Using the *Web of Science* search engine, and specifically aiming only at indexed physics (broadly understood) journals, we found 235 papers mentioning the ether, many of which we considered irrelevant, either because they referred to past theories, because they were sideline speculations, or because their use of ether did not have responses in the scientific press. Yet, one third of the papers seemed to form a unified cluster of papers devoted to the same topic, with references and cross-references. It was the so-called Einstein–Æther theory and, as we already said in the introduction, we thought it interesting to explore the potential connection of this cosmological theory and its ether with the previous historical episodes we have mentioned.

5 Einstein–Æther theory

In another recent paper in *New Scientist*, the science writer Brendan Foster shouts from the rooftops that "a shadowy substance killed by Einstein may be making a comeback" [25, 32]. He first describes state-of-the-art theoretical physics by focusing on the conceptual problems of a theory of unification to later turn up with a possible solution, although probably a too ambitious one: "More than a century after its banishment from the realm of respectable science, the aether could be the very thing we need to help make sense of the universe." [25, 35].

In his paper, Foster alludes to the "Einstein–Æther Theory", first proposed with this name by Ted Jacobson and David Mattingly in the year 2001 [33]. Jacobson is an American theoretical physicist, specialized in gravity and thermodynamics. In 2004, he wrote an extended review of the Æ-theory [22] in collaboration with David Mattingly and Christopher Eling, two PhD researchers at the University of Maryland, who have later followed this line of investigation each on their own. Although they were the ones who baptized the theory, the word æther has been widely used since then among researches in this discipline. It should be noted that, even if it began as a rather esoteric field—its main nuclei being in only a handful of universities—the theory spread globally by 2010, making Æ-Theory an international and decentralized field of knowledge.

But, why ether? *Dirac's æther* can be understood to serve as inspiration for the "Einstein–Æther Theory", as he proposed the *non-gravitational* part of the theory in his "new classical theory of electrons" [17], in which the unit timelike vector played the dual role of gauge-fixed vector potential and flow vector of a stream of charged dust. The evolution of Lorentz's ether could also be another motivation: whether or not the word ether was actually used, neo-Lorentzian proposals introduce length contraction and time dilation for all phenomena in a *preferred frame of reference*, which plays the role of Lorentz's stationary ether (for the discussion on the Neo-Lorentzian interpretation of special relativity, see [4]).

As we have mentioned before, few researchers followed up on Dirac's theory or the neo-Lorentzian interpretation of Einstein's theory, but the idea of a preferred frame of reference moved from *electrodynamics* to *gravity*, where it slowly evolved creating a new line of investigation in cosmology. Although it has been constantly transforming until its consolidation as Æ-theory, we have been able to find its traces in different papers of the second half of the twentieth century (see [27,54,66,70] or [37]). All these articles show an effort to develop a theory where Lorentz invariance is *violated* at very short distance scales. These attempts gained popularity gradually, but it was not until the beginning of the twenty first century that they reached their peak under Æ-theory, making the discussion expand in all directions, involving top-quality physicists all over the world.

But, again, why ether? What does Einstein–Æther Theory truly account for? As well described by Eling, Jacobson and Mattingly [22, 1], Æ-theory describes a generally covariant theory of gravity coupled to a dynamical, unit timelike vector field—the æther (u^a)—that breaks local Lorentz symmetry. The Æ-theory provides a simple, dynamical mechanism for breaking this symmetry within a generally covariant context. As of today, the theory that best describes the universe we live in is General Relativity (GR), which is based on *general covariance*. According to that fundamental principle, the formulation of physical laws should be expressed in such a way so as to be coordinate independent: there are *no preferred observers*. Lorentz transformations provide us with a useful mechanism to jump between equivalent (geodesic) frames, and local Lorentz invariance is a fundamental space-time symmetry in GR. So, what Æ-theory actually suggests is to modify GR at short length scales by introducing a *preferred rest frame* at each space-time point in order to make room for a potential theory of quantum gravity.

The main reason to doubt about *exact Lorentz invariance* is that "it leads to divergences in quantum field theory associated with states of arbitrarily high energy momentum" [33, 1]. Æ-theory seeks to solve this problem by incorporating the preferred frame while preserving *general covariance*. In order to do so, the preferred frame cannot be a fixed external structure, but it has to be *dynamical*. If we go deeper, Einstein Æther Theory is described by the *action principle* considering a derivative expansion of the action for the metric g_{ab} and æther u^a. The most general action that is diffeomorphism-invariant and quadratic in derivatives is [22, 3]:

$$S = \frac{-1}{16\pi G} \int d^4 \sqrt{-g}(R + K^{ab}_{mn} \nabla_a u^m \nabla_b u^n + \lambda(u^a u_a - 1)), \tag{1}$$

where

$$K^{ab}_{mn} = c_1 g^{ab} g_{mn} + c_2 \delta^a_m \delta^b_n + c_3 \delta^a_n \delta^b_m + c_4 u^a u^b g_{mn}. \tag{2}$$

The coefficients $c_{1,2,3,4}$ are dimensionless constants, R is the Ricci scalar, and λ is a Lagrange multiplier that enforces the unit constraint. The metric signature is $(+---)$ and units are chosen such that the speed of light defined by the metric g_{ab} is unity ($c = 1$). The constant G is related to the Newton constant G_N by a c_i-dependent rescaling (see [22, 9–10] for a further understanding of the Newtonian limit).

Leaving simple rescalings out, there is a *one-parameter family* of metrics that can be constructed from a metric and a unit vector field. The action changes when it is expressed in terms of a different metric in this family, but only insofar as the values of the c_i in equation 2 are concerned. Many publications have contributed in determining the theoretical and observational constraints on the parameters c_i.

What makes exact Lorentz invariance so difficult to test is that the boost parameter is unbounded: the Lorentz group is *noncompact* [33, 1]. In the next subsections, we have divided the *theoretical* and *observational* progress in the "Einstein–Æther Theory". There are two reasons for this separation: on the one hand, we wanted to further understand the actual status and different fields of investigation of the Æ-theory. On the other hand, we aimed to stress the repercussion that this theory has had in recent years, both among theoretical and experimental physicists.

5.1 Theoretical progress

Many physicists have contributed to the theoretical progress of Æ-theory determining the theoretical constraints on the parameters c_i. As a sample of this progress, it is worth mentioning a useful way to analyze the stability of the theory. The spectrum of linearized waves[7] around a flat space-time background was first estimated for the "Einstein–Æther Theory" by Jacobson and Mattingly in 2004 [34]. This was later used to confine the theory a priori, as the values of the parameters c_i for which there are exponentially growing modes are discarded. Even harder conditions for the stability of theories in which Lorentz invariance is spontaneously broken by an æther field have been discussed by different authors in the same decade (see, for example, [9] or [18]).

Another useful mechanism to constrain the theory has been the positive energy theorem. The usual positive energy theorem for GR assumes the dominant energy condition holds for the matter stress tensor, and proves that the total energy-momentum 4-vector of the space-time is future timelike. The æther stress tensor does not appear to satisfy the dominant energy condition, so the proof does not go through as usual. Nevertheless, the energy of the linearized theory is positive for certain ranges of c_i. This was further studied by Eling in [20] or Garfinkle and Jacobson in [26].

Einstein–Æther theory has also improved the status of other alternative gravitational theories among the scientific community. For instance, the theoretical hurdles of modified Newtonian dynamics (MOND) were only overcome using the framework of Æ-theory: due to the absence of a consistent covariant action formulation of the theory, most scientists did not regard MOND as a viable theory. Bekenstein gave a deep, theoretical explanation of the solution in 2004 [5], which was two years later complemented by the study of Zlosnik, Ferreira and Starkman in [71].

[7] Coupled metric-æther modes.

Before considering the general theory, many physicists aimed to better understand the basis of the theory by investigating the simplified models. These toy models have already been used as a starting point for further investigations into semiclassical or fully quantum models of quantum gravity with a dynamical preferred frame. Eling, Jacobson and Mattingly have contributed to this endeavour by reviewing the Maxwell-like simplified theory in [22, 5–7] by taking $c_1 + c_3 = 0$ and $c_2 = c_4 = 0$; where Æ-theory in a flat space-time is almost equivalent to Einstein–Maxwell theory in a gauge with $u^2 = 1$. Eling and Jacobson [21] have also explored the classical behaviour of Æ-theory in $1 + 1$ dimensions.

It is worth stressing that one might also consider the theory where the restriction on the norm of u^a is enforced not rigidly by a constraint but rather by a potential energy term $V(u^a u_a)$ in the action. This approach was discussed by Bjorken [6], Moffat [49] and Gripaios [29]. Or more recently by Wei, Yan and Zhou [62], where the cosmological evolution of Einstein–Æther models is studied with power-law-like potential, by using the method of dynamical system.

5.2 Experimental progress

Cosmology has undergone a precision revolution during the 21^{st} century. A large amount of data have been obtained from observations in the cosmic microwave background (CMB), large scale structure and supernovae. This data have been the best ally to work on past, present and future experiments that could provide us with observable phenomena to constrain Æ-theory or even with a direct detection of an æther field. The effect of Lorentz violation on cosmology as parametrized by the Einstein–æther model is compatible with current cosmological data [73], and there is a wide variety of papers focused on the phenomenological work of the possible æther. As a sample of this spectrum, we shall here present the work many authors have done in relation to stars, black holes, dark matter and dark energy.

The primordial effect of the cosmological æther is to renormalize the gravitational constant and to add a perfect fluid that renormalizes the spatial curvature contribution to the field equations. Carroll and Lim [8] note that, since this is not the same as G_N, the expansion rate of the universe differs from what would have been expected in GR with the same matter content. They assume the positive energy and stability constraints mentioned above, which imply $G_{\text{cosmo}} < G < G_N$. So, although it has not been observed for now, the universe would have been expanding more slowly than in GR [22, 15–16].

The most ambitious field where this new theory about the æther has tried to fit is in the *dark side of cosmology*. The cosmological standard model, Lambda cold dark matter (ΛCDM), is based on GR and requires only about 5% of the energy budget of the universe to be in known baryonic form. The rest is divided into cold dark matter and dark energy. Although their phenomenology as fluids has been shown to agree with observations to a very good degree, their actual nature is left to speculation as no such particles have been observed so far. Taking advantage of this blind spot and arguing that GR cannot explain neither the full dynamics of our universe or its structures, many theoretical physicists have implemented the Einstein–Æther theory as an alternative to the ΛCDM model. In other words, they have seen room for an alternative theory of gravity in which, instead of adding unknown sources of gravity (i.e., cold dark matter and dark energy), they alter the response of gravity to the known matter sources by adding a new degree of freedom, the æther, in the form of a vector field that is coupled with the space-time metric. This line of investigation has been deeply analyzed in [72] by Zlosnik, Ferreira and Starkman or in [47] by Meng and Du, to mention a few.

Binary pulsars [69], neutron stars [23] and black holes [36] are another source to test the foundations of GR, such as Lorentz symmetry, which requires that experiments produce the same results in all inertial frames. By testing the predictions made by this studies against observations, they have already placed very stringent constraints on gravitational Lorentz violation. And a new generation of gravitational antennas could ultimately conclude in the direct observation of the æther field.

The spectrum of linearized waves can also be used to place empirical constraints on the c_i parameters. For example, Æ-theory was constrained by the observation of ultra-high energy cosmic rays which implies the absence of energy loss via Cherenkov type processes, as Elliot, Moore and Stoica explained in 2005 [24]. In that direction, as a further source of constraints, the primordial perturbation spectrum has also been widely studied by different authors such as Eugene A. Lim [44], from the University of Chicago; Cristian Armendariz-Picon, Noela Fariña and Jaume Garriga [2], from the University of Barcelona; Ted Jacobson [32], from the University of Maryland; or Adam R. Solomon and John D. Barrow [60], from the University of Cambridge.

6 Discussion and conclusions

Although the echo of what once was the *æther* has never been muted, not many physicists in the second half of the twentieth century kept using this word. However, the nucleus of the discussion has always been at the root of modern physics. Is the universe really *empty*? What are the features of that "emptiness"? Could there exist a *preferred frame* of reference? Could *Lorentz symmetry* be violated, even if only locally?

These are the questions that some physicists have tried to answer with the recent development of the "Einstein–Æther Theory" in the field of cosmology. The preferred frame is inherent and unavoidable in Æ-theory. But, is it *sensible* to use such a plastic word to refer to a field that would modify the response of the metric to the presence of matter?

We have seen that it could be somehow "justified" by bearing on Dirac's æther, or even going back to Lorentz's ether theory. Æ-theory can be said to take the idea of a preferred frame of reference from the neo-Lorentzian interpretation of special relativity, and the idea of a unit timelike vector describing the ether from Dirac's theory. Indeed, we have asked Jacobson the reasons for his choice of the expression "Einstein–æther" and he argues that it was not intended to be a linguistic device to trick the audience, but it was meant to give continuity to the concept of ether. Because in his theory the unit timelike vector field determines a local preferred rest frame at each point of space-time, and he believes this is a key property of what was historically referred as ether. It is worth mentioning, however, that Æ-theory is the first theory of such scope to take this feature into the field of cosmology and to propose modifications to the theory of general relativity by breaking local Lorentz symmetry.

In any case, we do not aim here to evaluate the validity of this justification, but to *understand* the possible explanation future scientists may offer to the continuity of the ether if Æ-theory turns out to succeed. Although it is easy to see a *disruption* (or many) in the history of the ether due to the different uses the word has been put to, it is not hard either to imagine the *continuity* of the "essence" of the discussion from a *whiggish* point of view. If the Einstein–Æther Theory progresses, a completely coherent and continuous account of the concept focusing on the preferred frame of reference will probably be given, highlighting this aspect in any theory of the many historical ethers. This is one of the biggest problems with any *history* of the æther; that physicists and historians of physics may end up creating a historical scientific object that may have not existed in a continuous way, except perhaps for the preservation of the name. Maybe the question itself is badly formulated: it may not be about discerning the existence of a well defined entity, but about trying to shape its meaning and investigate its nature as a complex scientific object.

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