ÆTHER THEORIES: A PHYSICS FAIRYTALE RE-TOLD

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Abstract

Physics students are often told a story along the following lines: "During the nineteenth century, all physicists believed in the æther, and wasted much effort trying to study it. In the nick of time, the great heroes Michelson and Morley arrived on the scene, and with their experiment, vanquished the æther. Physics was thus turned away from a dead end, and progress again became possible." Apart from being wrong, this also does scant justice to a prolific and fruitful period in which the foundations of much of modern mathematical physics were laid down. We outline the rise and fall of the æther, and its role, far from encumbrance, as the strand intertwining developments in electrodynamics, optics, and special relativity. The elastic-solid æther is probed in greater detail to allow the importance not of the fairytale's critical experiments, but rather of boundary conditions, to emerge.

Introduction

Physicists, especially physics students, usually make their only acquaintance with the æther through the "æther fairytale." As with all fairytales, each telling is unique, but in general, the æther fairytale runs something like this:

> During the nineteenth century, all physicists believed in the æther, a medium which carried light waves. After Maxwell and his electromagnetic theory, some also believed the æther to carry electromagnetic waves. Towards the end of the century, however, the heroes of the fairytale, two physicists called Michelson and Morley, performed an experiment which would banish the æther forever. They found that the speed of light was the same in directions parallel and perpendicular to the earth's movement. After they published their results, the æther was uniformly believed to be a false medium, and physicists no longer regarded it as the carrier of light waves. Thus, the way was cleared for progress in physics, allowing quantum mechanics and special relativity to be developed, after which the æther was never again mentioned.

A closer examination of the history of this elusive substance reveals the thoroughly make-believe nature of the tale. In the first place, belief in the æther by physicists was not at all uniform: some found it merely a useful construct, while even among those who admitted its existence, dissention was rife. That is, a multiplicity of æther theories exist from Descartes to dark energy. Secondly, light waves were not the only physical phenomena to be explained through the æther's existence. Electricity, gravity, atomic matter, and spiritual life were variously attributed to the properties of an æther. Thirdly, Michelson's experiments aimed to differentiate between only two of the many theories, and were moreover inconclusive. Æther theory thus survived, not to be suppressed by experiment, but to flourish in scientific discourse to the present day. Ultimately, work on æther theories was not wasted on a dead end, but produced classical electrodynamics and the mathematics of special relativity, and drove rapid progress in other fields such as elastodynamics.

As such interrelation between physics disciplines is often unsuspected by students accustomed to compartmentalised courses, this paper deconstructs the æther myth, outlining the critical features of each of several major classes of æther theory. One such class is the elastic-solid æther, which is examined more comprehensively to unmask the critical role, not of mythical experiments, but instead of boundary conditions to differential equations. Finally, the æther is shown to have persisted in the modern scientific discourse, even in the work of such physics heroes as Einstein and Dirac.

Æther Theories

As befits a notion which ran through the heart of classical physics from the time of Descartes (the first to use the term *æther* (Whittaker 1951)), there is no one unified æther theory, but rather a long series of permutations of numerous distinct models. True to the fairytale, however, the propagation of light, or luminiferous æther, is the common thread linking all the important æther theories up to the twentieth century, although many purported to explain a wider range of phenomena. Thus during the æther's heyday, the nineteenth century, the term popularly denoted a substantial medium facilitating light's transmission.

To explain optical effects through æther models, physicists drew in two other major theoretical domains, namely, fluid mechanics and condensed matter. These fields formed the basis of the vortex æther and elastic-solid æther models, respectively. Yet at the same time, interest in the æther provoked detailed study of these seemingly unrelated areas, with developments in one feeding back into the other: an escalation of advances across physics.

In keeping with nineteenth-century preoccupations with matter and substance, both models attributed physical properties to the æther, which was held to be as real as any ponderable matter, just more elusive. Under the vortex hypothesis, this slippery substance was composed of "excessively small whirlpools" (Whittaker 1951), a description due to Descartes and Jean Bernoulli. The latter postulated that interspersed between the vortices were even more diminutive corpuscles, which would be forced to oscillate by dilation of the vortices; this oscillation was identified as light waves. A similar model was adopted by Maxwell (1861-2) in the first of his great electrodynamics papers, and thus the æther enmeshed its development with progress in a further branch of classical physics. The vortices and corpuscles which recurred in "On physical lines of force" were identified with magnetic and electric phenomena, respectively. It was thus with the aid of the æther that Maxwell determined the fundamental equations of electromagnetism, even though he did not propose his model as "a mode of connexion [*sic*] existing in nature." (Maxwell 1861-2)

The preceding æther models explain the substance's composition in terms of fluid elements and particles, but what substance forms such vortices? After Helmholtz demonstrated in 1858 that vortices in a perfect fluid are theoretically persistent and indivisible, not only was insubstantial light, but also ponderable matter, identified with an æther; such vortices were considered a prime candidate for atoms by Tait and W. Thomson (Goldman 1983). Pursuing this hypothesis, Thomson showed in 1905 that the vortices were probably unstable; this meant an end to the hypothesis, but an advance for physics in general. The macroscopic vortices were swiftly replaced, however, yielding place to the *vortex sponge*, another perfect fluid, but this time constituted of finely mixed rotational and irrotational fluid portions (Whittaker 1951).

While the vortex æther developed alongside fluid mechanics, the elastic-solid æther was responsible for much of the mathematics and theory of such bodies. Furthermore, both models were also inextricably tied to the great controversy over the nature, particulate or undulatory, of light, aligning themselves on the side of waves. The elastic-solid æther was particularly enmeshed with this question; it was to incorporate polarisation into the wave model, and thus remedy its major flaw, that Fresnel proposed an elastic-solid medium. Polarisation is compatible with a wave theory if the vibrations are taken to be transverse, rather than their more intuitive sound-like longitudinal counterpart. Such transverse waves are clearly manifest in elastic solids.

With this in mind, Fresnel and Stokes asserted the elastic-solid nature of the æther and proceeded to hypothesise its interaction with large moving bodies, notably the earth. It was here that the two physicists disagreed spectacularly, Fresnel advocating free motion through the æther, in contrast to Stokes's drag model (Whittaker 1951). Although their theories offered scant physical insight into the æther, it appeared possible to distinguish experimentally between the two. Such differentiation was the purpose of our fairytale heroes, Michelson and Morley, who, far from banishing the æther, seemed to support Stokes's model over Fresnel's.

Further development of the elastic-solid class of theory occurred not in the realm of experimentation, as the fairytale implies, but through parallel advances in mathematics. Impelled by a desire to uncover the æther's dynamics, the equations and associated mathematical techniques required for modelling elastic solids were developed. Hence, appropriate boundary conditions to the equations of motion became the focus of æther theorists' work, in a particularly surprising departure from the fairytale.

The Elastic-Solid Æther and the Importance of Boundary Conditions

The first step in modelling the elastic-solid æther's dynamics was to determine an equation of motion for small displacements of the solid. Navier accomplished this task for an isotropic medium, including both the density and the elasticity of the æther as coefficients in his differential equation (Whittaker 1951). The equation was then solved in the general case by Poisson (Poisson 1828a; Poisson 1828b), an exercise requiring many complicated substitutions into each of the three coordinate equations. For Poisson, æther theory involved solving sextuple integrals; hardly the stuff of fairytales! Applying the isotropic condition, as well as postulating the propagation of plane waves in the medium, allowed Poisson to simplify considerably his solution (Poisson 1831).

Two sets of waves, propagating at different velocities, were then revealed to be able to exist in the æther. These Poisson classified according to the medium's dilation during passage of the wave. In mathematical terms, the dilation corresponds to the divergence of the molecular displacement in the æther. In the first case, the dilation was non-zero, from which Poisson inferred that "the speed of the molecules [of the æther] is perpendicular to the wave surface." (Poisson 1831, p. 601) The wave surface is today known as the wave front; Poisson's conclusion thus corresponds to the propagation of longitudinal waves. For the second type of wave, Poisson found that "as [...] the component of the velocity at [the arbitrary] point M in the ray direction [is equal to zero], it results that M's velocity is perpendicular to this ray." (Poisson 1831, p. 601) Furthermore, propagation of this class of wave causes no change in the density of the medium in the propagation direction; combined with the previous result, these waves are clearly transverse. Poisson established equations of motion for both sets of waves (Poisson 1831); however, Fresnel's polarisation explanation required only transverse waves to represent light. What then was the identity of the longitudinal waves? Poisson did not specify, and while Cauchy initially thought they might correspond to heat (Whittaker 1951), calculations involving purely luminiferous phenomena should cause them to disappear.

Some test of Navier's and Poisson's theories was therefore required in order to verify their applicability to optical phenomena. Success would be measured by the appearance of transverse waves only in the final solution. By implicit consent, derivation of the Fresnel coefficients for reflection at a dielectric interface was the chosen gauge. It is here that boundary conditions play their singular role in the tale of the æther; applying appropriate boundary conditions at the interface was crucial to matching the experimentally known coefficients. The tests would also provide valuable insight into the æther's dynamics, by answering two critical questions: is the vibration of the æther perpendicular or parallel to the plane of polarisation of the light wave, and is the variation in refractive index between materials due to a changing æther density (inertia), a differing elasticity, or a combination of both?

One of the first such tests was made by Cauchy, who chose to examine molecular vibrations perpendicular to the plane of incidence. Assuming a constant æther density and varying elasticity, he successfully obtained the Fresnel sine law coefficient, which corresponds to reflection of light polarised in the plane of incidence. Hence, molecular motion perpendicular to the incident plane yielded a polarisation parallel to that plane, in other words, the æther vibrates perpendicular to the plane of polarisation (Whittaker 1951). Cauchy thus answered one of the key questions for the elastic-solid model. Equating Cauchy's descriptions with modern theory, vibrations of the æther may be identified with the electric field. Moreover, Cauchy's boundary conditions are analogous to continuity of normal $\mathbf{B}$ (for the sine law) and of normal $\mathbf{D}$ and tangential $\mathbf{E}$ (for the tan law). Unfortunately, although Cauchy avoided longitudinal waves, he did so "for the simple reason that he assumes the boundary conditions to be only four in number; and that these can all be satisfied without the necessity for introducing any but transverse vibrations." (Whittaker 1951, p. 137) His approach thus evaded the physical question, as his choice of boundary conditions ensured in advance that he would pass the test. It would be up to Green and MacCullagh to propose meaningful behaviour of the elastic-solid æther.

The End of the Æther, and its Survival

The demise of the æther as the 'problem of the age' began as early as Maxwell's definitive paper on electromagnetic theory, in which he rejected knowledge of the interior structure of the æther as unnecessary. He proved his point by re-deriving the electrodynamics equations without the aid of his mechanical æther model. Larmor later echoed these sentiments, suggesting that it was enough to have determined the differential equations which govern electromagnetism; there was no need to seek further physical properties behind this formulation (Whittaker 1951).

Meanwhile, Lorentz, Larmor, and Poincaré, among others, established the mathematical foundations of special relativity in a successful attempt to account for the electrodynamics of moving media, making the æther not only unnecessary, but also undetectable. In 1905, Einstein showed that the same end result could be reached without assuming the existence of any such physical medium (Einstein 1905). Finally, it was commonly argued that the æther's velocity would establish a preferred direction in the light-cone in a perfect vacuum, a finding incompatible with special relativity (Dirac 1951b).

Neither redundancy nor contradiction fully removed the æther from the scientific discourse, with such heroes of modern physics as Einstein and Dirac re-postulating its existence many years after the fairytale's expiry date. Dirac stated in 1951 that, thanks to quantum mechanics, the æther was no longer incompatible with relativity because its wave function could result in a relativistically (Lorentz-wise) isotropic probability distribution in velocity (Dirac 1951b). Not mere speculation, Dirac's assertion was a consequence of his modified theory of classical electrodynamics published in the same year (Dirac 1951a). One fundamental constituent of the theory was a velocity, that of the "flow" of electric charge, from which Dirac concluded: "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." (Dirac 1951b, p. 907) Far from the fairytale's implication that the æther had to disappear before quantum mechanics could be developed, the substance was seen as the "new hope for the future" (Dirac 1954, p. 146) of quantum field theory, with the potential to render renormalisation unnecessary.

If the labels 'unnecessary' and 'contradicts special relativity' couldn't vanquish the æther, it appears surprising that another familiar fairytale character, blackbody radiation, was its most effective enemy. Essentially, if the æther were a truly continuous physical medium, pervading all space, it would support fluctuations at all size scales. In thermodynamic equilibrium, fluctuations at all size scales must have equal energy, which means that the total thermal energy per unit volume of the æther would be infinite at any temperature above absolute zero. This corresponds to an æther with infinite heat capacity, and would result in all matter very rapidly cooling to the æther temperature (Jeans 1905; Jeans 1922). Such a result is exactly the ultraviolet catastrophe, expressed in terms of fluctuations of a medium rather than fluctuations of a classical electromagnetic field. Yet even ultraviolet catastrophe could not banish the æther forever; it continues to appear on the fringes of scientific discourse, linked most recently to dark energy (Sidharth 2004).

Conclusion

Undone, the æther fairytale is revealed to be nothing but a tall story, useful perhaps for promoting interferometers. The story of the æther is seen to be far more complex, containing many elements unexpected by today's physics student. Yet, because of the fairytale, this history is but a shadow in their minds, the elusive fluid slipping once again from firm grasp. Not a wasted opportunity by a century of physicists, æther should be portrayed as a central notion which was inherently linked to the development of physics throughout the nineteenth century. Moreover, for all its attributed insubstantiality, the æther has survived into modern physics discourse. For students to understand the multi-faceted history of the æther is to touch upon the ideas which shaped the optics, electromagnetics, and elastic solid theory which they learn today, not to mention its involvement with fluid mechanics, quantum physics and relativity. From pervading all space, æther can now be seen as pervading all physics.

Refererences

Dirac, P.A.M. (1951a). A new classical theory of electrons. *Proceedings of the Royal Society of London A* **209**, 291-6.

Dirac, P.A.M. (1951b). Is there an æther? *Nature* **168**, 906-7.

Dirac, P.A.M. (1954). Quantum mechanics and the aether. *The Scientific Monthly* **78**, 142-6.

Einstein, A. (1905). Zur Elektrodynamik bewegter Körper. *Annalen der Physik* **17**, 890-921.

Goldman, M. (1983). The demon in the æther: The story of James Clerk Maxwell. Paul Harris Publishing, Edinburgh.

Jeans, J.H. (1905). On the application of statistical mechanics to the general dynamics of matter and ether. *Proceedings of the Royal Society of London A* **76**, 296-311.

Jeans, J.H. (1922). The present position of the radiation problem. *Proceedings of the Physical Society* **35**, 222-24.

Maxwell, J.C. (1861-2). On physical lines of force. *Philosophical Magazine* **21**, 161-75, 281-91, 338-48; **23**, 12-24, 85-95.

Poisson, S.-D. (1828a). Mémoire sur l'équilibre et le mouvement de corps élastiques. *Mémoires de l'Académie Royale des Sciences de l'Institut de France* **8**, 357-570.

Poisson, S.-D. (1828b). Addition au mémoire sur l'équilibre et le mouvement de corps élastiques, inséré dans ce volume. *Mémoires de l'Académie Royale des Sciences de l'Institut de France* **8**, 623-7.

Poisson, S.-D. (1831). Mémoire sur la propagation du mouvement dans les milieux élastiques. *Mémoires de l'Académie Royale des Sciences de l'Institut de France* **10**, 549-606.

Sidharth, B.G. (2004). The mysterious dark energy. arXiv:physics/0402007.

Whittaker, E. (1951). A history of the theories of æther and electricity. Vol. 1: The classical theories. Thomas Nelson and Sons, London.