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Physics as a Calling, Science for Society

Studies in Honour of A.J. Kox

Edited by

Ad Maas and Henriëtte Schatz

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2 The drag coefficient from Fresnel to Laue¹

Michel Janssen

Snell's law of refraction, $\sin i = n \sin r$, was Lorentz invariant *avant la lettre*. After all, it can be derived directly from Maxwell's equations. This a-historical observation provides a convenient way of introducing the issue that I will discuss in a historically more respectable fashion in this essay. The luminiferous ether, the 19th-century medium for the propagation of light, was believed by many physicists at the time to be completely immobile, i.e., to be at rest with respect to something like the fixed stars.² That means that experiments on earth are always carried out in a frame of reference in motion through the ether. Snell's law holds in the frame of ether. As long as (what are now called) Galilean transformations are used to relate two frames in uniform relative motion with respect to one another, it follows that the law does not hold in the frame of the earth. In refraction experiments on earth, one would expect deviations from Snell's law of order v/c , where v is the velocity of the earth with respect to the ether and c is the velocity of light. If the velocity of the earth with respect to the sun is used as an estimate of v , this ratio is about 10^{-4} . In the early-19th century, optical experiments were already accurate enough to detect effects this small. Yet no deviations from Snell's law were ever seen in experiments on refraction. To account for the discrepancy, Fresnel introduced the ether drag coefficient named after him. Initially, the drag coefficient was seen as a peculiar dynamical effect rendering the motion of the ether invisible at least to first order in v/c . However, it was not until the 1890s that Lorentz (1892) proposed a satisfactory dynamical model for the drag coefficient based on his microscopic elaboration of Maxwell's electromagnetic theory. In the intervening decades, a number of physicists had already suggested that one should give up on finding a dynamical model for the Fresnel drag effect altogether and just accept the drag coefficient as part of some general principle of relativity for optics.³ Only three years after introducing his electromagnetic model for the effect, Lorentz himself, in effect, showed that the drag effect is a kinematical effect in the sense that it is independent of the details of the dynamics. In a book known in the historical literature as the *Versuch*, Lorentz (1895) showed that the drag coefficient follows immediately from the Lorentz-invariance (to first order v/c) of the source-free Maxwell equations, a

result he himself called the ‘theorem of corresponding states’. Lorentz did not appreciate at the time that this new derivation of the drag coefficient suggested a reappraisal of its status as a dynamical effect peculiar to the interaction of light and charged particles in matter in motion through the ether. It was left to Laue (1907) to show once and for all that the Fresnel drag effect is a kinematical effect, not just in the broad sense of being independent of the details of the dynamics, but in the narrow sense of being a direct manifestation of the underlying space-time kinematics. He showed that the Fresnel drag coefficient is a direct consequence of the way velocities are added in special relativity. In this essay, I will briefly tell the story of how the Fresnel drag effect went from being classified as dynamical to being classified as kinematical, first in the broad and then in the narrow sense.

Aberration, refraction, and the Fresnel drag coefficient

Physicists in the 19th century took it to be completely self-evident that light waves, like all other waves, need a medium for their propagation. Since light can reach us from the farthest recesses of the universe, this medium, the luminiferous ether, had to be omnipresent. In 1804, Young pointed out that the phenomenon of stellar aberration, discovered by Bradley in the 1720s, indicated that this universal ether must be immobile, i.e., that the earth and other ponderable matter move through it without disturbing it in the least. Fig. 1 illustrates stellar aberration for a star directly overhead. The situation is drawn from the point of view of the ether.

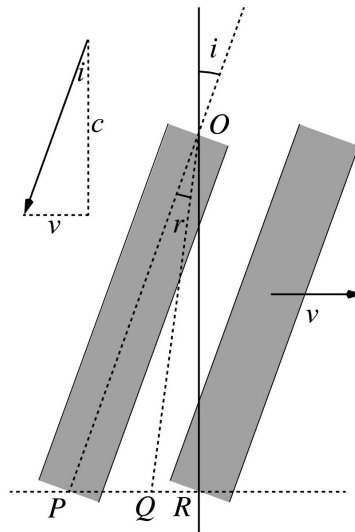


Fig. 1 – Stellar aberration

The solid vertical line through O and R – ignore the dashed lines for the moment – represents a light ray, or more accurately the normal to a plane wave front, travelling from the star to the earth at velocity c . The shaded rectangles represent two snapshots of a telescope moving with the earth at velocity v , the first as the light enters at O , the second as it exits at R . For the telescope to collect the light of this star, it must be tilted at an angle, called the aberration angle and labeled i in the figure. This means that an observer on earth will see the star in the direction indicated by the dashed line through O and P . Drawing a vector diagram for the two components of the velocity of the light with respect to a terrestrial observer, one sees that the aberration angle is given by $\tan i = v/c$ (since $v/c \approx 10^{-4}$, the angle i is actually much smaller than the drawing in Fig. 1 suggests). Any currents in the ether would add more components to the velocity of light and change the aberration angle. Young thus concluded that the universal ether had to be immobile.

In 1818, however, Fresnel argued that in some situations ether is dragged along by matter. In the early part of the 19th century, wave theorists assumed that the index of refraction n was proportional to the square root of the ether density ρ . Moving transparent substances, Fresnel assumed, would not affect the universal ether in the space they travelled through but would carry excess ether along with them to preserve the ether density inside. The weighted average of the velocities of these two types of ether, the unaffected and the dragged-along, is a fraction $\rho_{\text{excess}}/\rho_{\text{total}}$ of the velocity with which the substance is moving through the ether. Since $\rho_{\text{excess}} = \rho_{\text{total}} - \rho_{\text{vacuum}}$ and $\rho_{\text{total}}/\rho_{\text{vacuum}} = n^2$, this fraction is equal to $1 - 1/n^2$. This expression became known as the Fresnel drag coefficient. Stokes later suggested an alternative mechanism in which transparent media moving through the ether drags along all ether inside of it with this fraction.

No matter how one envisions this ether drag, Fresnel showed that the component it adds to the velocity of light is necessary to explain why the presumed motion of the earth with respect to the universal ether does not affect the outcome of refraction experiments. This extra velocity component ensures that, to first order in v/c – and greater experimental accuracy was not attainable until much later in the century – refraction at the surface of a body moving through the ether will follow Snell's law, $\sin i = n \sin r$ (where i is the angle of incidence and r is the angle of refraction), *from the point of view of someone moving with the refracting body*. A lens in a telescope is an example of a refracting body in motion through the ether. In the simple derivation of the formula for the aberration angle above, it was tacitly assumed that the observer moving with the telescope can appeal to Snell's laws to describe the refraction in the lenses of the telescope. That assumption, Fresnel showed, is not as innocuous as it may sound. It would not be true without the extra velocity component resulting from the Fresnel drag effect. With this extra component, however, no first-order refraction experiment can ever reveal

the earth's motion through the ether. In 1871, for instance, Airy found that filling the tube of his telescope with water did not affect the aberration angle.

A more primitive version of Airy's experiment can be used to derive Fresnel's result for the special case in which the angle of incidence is 0° for the observer moving with the refracting body. Imagine that the shaded rectangles in Fig. 1 represent two snapshots of a piece of glass with flat surfaces at the top and the bottom. From the point of view of the ether, the light ray striking the surface at O makes an angle i with the normal, the dashed line through O and P . If Snell's law were to hold from the ether's perspective, as would be the case if no ether drag were assumed, the refracted ray would follow the dashed line segment OQ at an angle $r < i$ with the normal. For an observer moving with the glass, because of aberration – regardless whether the light source is terrestrial or celestial – the light ray strikes the surface at O perpendicularly. If Snell's law holds from this observer's perspective, the light thus goes straight through ($r' = i' = 0^\circ$), which from the perspective from which Fig. 1 is drawn means that the refracted ray follows the solid line segment OR . As the light is travelling through the glass, it must therefore be dragged from OQ to OR . Suppose it takes the light an amount of time Δt to get from O to R . In that case,

$$OQ = (c/n) \Delta t, \quad PR = v \Delta t, \quad QR = f v \Delta t, \quad (1)$$

where f at this point is some unknown fraction of v . Since the angles i and r are very small, their tangents and sines can be used interchangeably. Moreover, the angle PQO is almost a right angle. Hence, $\tan r$ can be set equal to PQ/OQ . Substituting this value into Snell's law in the form $\tan i \approx n \tan r$ and using that the aberration angle i satisfies $\tan i = v/c$, one finds:

$$\frac{v}{c} \approx n \frac{PQ}{OQ} = n \frac{PR - QR}{OQ}. \quad (2)$$

Substituting the expressions in Eq. (1) in Eq. (2), one finds:

$$\frac{v}{c} \approx \frac{v}{c} n^2 (1 - f). \quad (3)$$

It follows that, to order v/c , f must be equal to $1 - 1/n^2$, which is just the Fresnel drag coefficient.

Direct confirmation of the 'drag' effect, or so it seemed, was provided by Fizeau with an interference experiment that convincingly showed that flowing water drags along light waves with about half its velocity, which is roughly the value of the Fresnel drag coefficient for water. As a prelude to their famous ether drift experiment, Michelson and Morley (1886) repeated Fizeau's experiment and

found the same result. In the period 1914-1927, Zeeman measured the velocity of light in various moving liquids and solids and confirmed the Fresnel drag coefficient – with a small correction term due to Lorentz – with much greater accuracy than either Fizeau or Michelson and Morley.⁴

Lorentz' two derivations of the Fresnel drag coefficient in the 1890s

Although the formula for the Fresnel drag effect was widely accepted in the 19th century, the proposals for the physical mechanism behind it – be it Fresnel's picture of full drag of some ether or Stokes's picture of partial drag of all ether – were not. Stachel (2005, pp. 6-8) quotes statements by Fizeau in 1851 and by Ketteler, Mascart, and Velthmann in the early 1870s to this effect. As one historian put it, Fresnel 'succeeded in accounting for the phenomena in terms of a few simple principles, but was not able to specify an aether which would in turn account for these principles.'⁵

The main objection to the literal interpretation of the Fresnel drag coefficient in terms of ether drag was connected to a more general problem facing theoretical accounts of the phenomenon of optical dispersion, the differential refraction of light of different colours familiar from rainbows and prisms.⁶ Dispersion theory ought to furnish a formula showing how the index of refraction depends on the frequency of the refracted light. In the early part of the 19th century, as mentioned above, the index of refraction was assumed to be proportional to the square root of the ether density. This means that substances must carry different amounts of ether for different colours of light, which, in turn implies that, if the Fresnel drag coefficient is interpreted literally, substances must drag along ether with different fractions of their velocity for different colours!

What eventually led to the abandonment of these simple theories of refraction and dispersion in terms of variable ether density was that they could not account for the phenomenon of *anomalous* dispersion, in which the index of refraction for part(s) of the spectrum decreases rather than increases with frequency. The phenomenon had been noticed by early pioneers in photography but did not receive serious attention from physicists until the 1870s. At that point, Sellmeier, Helmholtz and others began to develop a new type of dispersion theory in which the behaviour of light in transparent media is explained in terms of the interaction of the light waves with small harmonically-bound particles with resonance frequencies at the absorption frequencies of the material. It is in the vicinity of these frequencies that dispersion becomes anomalous. Originally, these theories were purely mechanical, but in the early 1890s they were reworked in terms of electromagnetic waves interacting with electrically charged particles, later to be identified as electrons. The most sophisticated theory along these lines was the one proposed by Lorentz (1892) in a monograph-length paper on Maxwell's electromagnetic theory and its application to moving bodies. The ether is completely

immobile in this theory and has the same density everywhere. The index of refraction is related not to ether density but to the concentration of charged oscillators.

Lorentz' 190-page treatise is divided into seven chapters and an appendix. The behaviour of light in dielectric media is the topic of the final two chapters. In Ch. VI, which takes up 24 pages, Lorentz derives the equations governing the propagation of light in a medium at rest in the ether and shows that they have solutions describing waves travelling with velocity c/n through the ether, where n can be expressed in terms of properties of Lorentz' microscopic model of the medium. In Ch. VII, which takes up 30 pages, he derives the analogous equations for a medium moving through the ether with some velocity v , using a co-moving frame of reference – related to a frame at rest in the ether through a Galilean transformation. Lorentz (1892, (pp. 524-527)) shows that these equations allow waves with velocity $(c/n) - (v/n^2)$ in the direction of motion of the medium. The velocity of these waves with respect to the ether is $(c/n) + (1 - 1/n^2)v$, in accordance with Fresnel's formula.

Physicists had been struggling with dispersion since the days of Newton, so it was a tremendous success for Lorentz' theory that it gave a reasonably satisfactory account not just of normal but also of anomalous dispersion.⁷ What especially inspired confidence in Lorentz' theory was that it gave the Fresnel drag coefficient without introducing any actual ether drag. This was a triumph for the theory on a par with the explanation of the normal Zeeman effect half a decade later.⁸ Einstein still rehearsed the final steps of Lorentz' 1892 derivation of the Fresnel drag coefficient in an unpublished review article on special relativity twenty years later as well as in courses on special relativity in 1914-15 (see Fig. 2) and 1918-19 in Berlin, as can be gleaned from his lecture notes (Janssen et al. (2007), Vol. 7, p. 279, note 7). What makes this all the more remarkable is that Einstein did not cover – neither in these three documents nor in any other document that I am aware of – a far simpler derivation of the Fresnel drag coefficient that Lorentz gave in 1895 and that is much closer in spirit to special relativity.⁹

$$1 - \frac{v^2}{c^2} = \frac{\epsilon-1}{\epsilon^2} (V-v)^2$$

$$c^2 - v^2 = (\epsilon-1) (V^2 - 2Vv)$$

$$c^2 = \epsilon V^2 - 2(\epsilon-1)V_0 v$$

$$c^2 = \epsilon V_0^2 + 2 \epsilon V_0 \Delta - 2(\epsilon-1)V_0 v$$

So ist die Eigenschaft Δ , $v = 0$

$$c^2 = \epsilon V_0^2 \quad \frac{c^2}{\epsilon} = V_0^2 \quad V_0 = \frac{c}{n} = \frac{c}{\epsilon^2}$$

$$\boxed{\Delta = \frac{\epsilon-1}{\epsilon} v = \left(1 - \frac{1}{n^2}\right) v} \quad \text{Dies ist Erfahrungsergebnis}$$

Fig. 2 – Einstein covering Lorentz' 1892 derivation of the Fresnel drag coefficient in a lecture in Berlin during the winter semester 1914-15 (Kox et al. (1996), Doc. 7)

John Norton (2004, pp. 87-92) has conjectured that this 1895 derivation was one of the stepping stones on Einstein's path to special relativity and is thus forced to explain away that Einstein repeatedly covered the 1892 derivation without so much as a hint at the 1895 one.

The 1895 derivation is given in two short sections of the *Versuch*,¹⁰ Lorentz' famous book on the electrodynamics of moving bodies, a text we know Einstein read before 1905. The new derivation is an application of the so-called theorem of corresponding states that Lorentz first introduced in this book. In modern terms, this theorem expresses, though initially only partially and approximately, the Lorentz invariance of Maxwell's equations.

Lorentz first subjected Maxwell's equations to a Galilean transformation from a frame at rest in the ether with Cartesian coordinates (x_0, y_0, z_0) to a frame moving through the ether at velocity $\mathbf{v}$ with coordinates (x, y, z) . It will be convenient to assume that this velocity is in the x -direction. Lorentz now replaced the electric and magnetic fields and the time coordinate with auxiliary quantities such that, as long as quantities v^2/c^2 and smaller are neglected, the equations in the moving frame have the same form as Maxwell's equations in a frame at rest in the ether. To first order in v/c , the quantities replacing the fields and the time t in the moving frame are just what would now be called the Lorentz transforms of the fields and the time $t_0 = t$ in the frame at rest. The auxiliary time variable thus depends on position and Lorentz gave it the suggestive name 'local time.'¹¹ For the moving frame under consideration here, it is given by:

$$t' \equiv t - (v/c^2)x. \quad (4)$$

Lorentz used the embryonic Lorentz invariance of Maxwell's equations to show that one could never detect the earth's motion through the ether with a first-order experiment in optics that ultimately boils down to the observation of a pattern of brightness and darkness. Any such experiment performed on earth, in near-uniform motion through the ether, would give the same result that one would find if one could somehow perform the experiment at rest in the ether.

Given how broad this class of experiments is, the argument for this claim is surprisingly simple.¹² The auxiliary fields at a point with coordinates $\mathbf{x}$ and at local time t' in the experiment on earth will have the same values as the real fields in the experiment at rest in the ether for the same values of the coordinates $\mathbf{x}_0$ and the real time t_0 . To describe a pattern of brightness and darkness it suffices to specify where the fields are large averaged over times that are long compared to the periods of the light waves used and where these averages vanish. The components of the auxiliary fields are linear combinations of components of the real fields. They vanish or are large wherever and whenever the real fields are. Since patterns of brightness and darkness can only be defined on time scales that are large compared to the periods of the light waves producing them, local time and

real time can be used interchangeably. Combining these observations, one arrives at the conclusion that if there is a bright (dark) spot at point $\mathbf{x}_0$ in the experiment at rest in the ether, then there will likewise be a bright (dark) spot at the corresponding point $\mathbf{x}$ in the experiment on earth. The experiment will not reveal the earth's motion through the ether.

The class of optical experiments covered by Lorentz' argument clearly includes refraction experiments. Fresnel had shown that according to the immobile-ether theory refraction experiments will reveal motion through the ether unless the Fresnel drag coefficient is added to the theory. Lorentz' theory thus must imply the Fresnel drag coefficient. In fact, it is a consequence of the embryonic Lorentz invariance of Maxwell's equations that Lorentz established with his theorem of corresponding states. As he showed explicitly, it follows directly from the expression for local time.¹³ In Ch. VI of his 1892 treatise, Lorentz had shown that Maxwell's equations can serve as the basis for a theory explaining why light travels at velocity c/n through a transparent medium with refractive index n at rest in the ether. The components of the electric and magnetic fields of a light wave travelling in the x -direction all depend in the same way on $\mathbf{x}_0$ and t_0 via the combination

$$t_0 - \frac{x_0}{c/n}. \quad (5)$$

Now consider the same transparent medium moving through the ether with velocity v in the x -direction. Replacing the real fields, the coordinates $\mathbf{x}_0$, and the real time t_0 in the description of a light wave in the medium at rest in the ether by the auxiliary fields, the coordinates $\mathbf{x}$, and the local time t' of the moving frame, one arrives at a description of a light wave in the same medium in motion through the ether. For a wave in the x -direction, the components of the auxiliary fields all depend on t' and x via

$$t' - \frac{x}{c/n}. \quad (6)$$

The same is true for the components of the real fields, which are just linear combinations of the components of the auxiliary fields. Using expression (4) for t' , one finds that they all depend on t and x via

$$t - \left(\frac{v}{c^2} + \frac{n}{c} \right) x. \quad (7)$$

Taking the reciprocal of the expression in parentheses, one finds that the light wave in the moving medium has velocity

$$\left(\frac{v}{c^2} + \frac{n}{c}\right)^{-1} = \frac{c/n}{1 + (v/cn)} \approx \frac{c}{n} - \frac{v}{n^2} \quad (8)$$

in the x -direction with respect to the medium. The medium itself is moving through the ether with velocity v in the x -direction. So, to order v/c , the light wave in the moving medium has velocity

$$\frac{c}{n} + \left(1 - \frac{1}{n^2}\right)v \quad (9)$$

with respect to the ether, in accordance with Fresnel's formula.

Lorentz' exceedingly simple derivation of the Fresnel drag coefficient of 1895 rendered the lengthy calculations in Ch. VII of his 1892 treatise superfluous. The new derivation made it clear that it suffices to derive from Maxwell's equations that light has velocity c/n in a medium at rest in the ether with refractive index n , as he had done in Ch. VI of the 1892 treatise, and to show that Maxwell's equations are invariant under Lorentz transformations, at least to first order in v/c and for the kind of charge distributions involved. Although Lorentz himself saw it merely as a convenient shortcut for his derivation of 1892, he had thus achieved a good deal more with his new derivation of 1895. The 1895 derivation shows that the Fresnel drag coefficient is kinematical in the broad sense of being independent of the details of the dynamics.

Laue's derivation of the Fresnel drag coefficient from the relativistic addition theorem for velocities

It was left to Laue to show that the Fresnel drag coefficient is also kinematical in the narrow sense of having to do with standard spatiotemporal behaviour in special relativity. Laue (1907) showed that the drag coefficient is a direct consequence of the relativistic addition theorem of velocities. Einstein (1905) derived the theorem in his first paper on special relativity, but missed this important application of it. This is another omission that is hard to square with Norton's (2004) conjecture about the importance of Lorentz' derivation of the Fresnel drag coefficient from the expression for local time for Einstein's path to special relativity.

As both Einstein and Poincaré recognised, the x -dependent term in Lorentz' expression for local time reflects the relativity of simultaneity. This is the only effect that matters in Laue's derivation of the Fresnel drag coefficient. To derive the addition theorem of velocities in full generality, one also needs to take into account the effects of time dilation and length contraction, but those are effects of second order in v/c while the validity of the Fresnel drag coefficient is restricted to first order.

Consider light moving through a medium moving at velocity v , both in the (positive) x -direction. For an observer moving with this medium, the light has velocity $u' = c/n$. Let $\Delta x'$ be the distance covered by the light in the time $\Delta t'$ from the point of view of the co-moving observer. In other words,

$$u' \equiv \frac{\Delta x'}{\Delta t'} = \frac{c}{n}. \quad (10)$$

What is the velocity u of the light with respect to the medium for an observer with respect to whom the medium is moving at velocity v in the x -direction? To order v/c , the two observers agree on the distance covered: $\Delta x = \Delta x'$. However, they do not agree on the time it takes to cover this distance. This is because they disagree about the synchronisation of the clocks at the end points of the interval $\Delta x = \Delta x'$. $\Delta t'$ in Eq. (10) is determined on the assumption that these two clocks are properly synchronised according to the co-moving observer. For the other observer, as follows from Eq. (4), the clock on the left is fast compared to the clock on the right by an amount of $(v/c^2)\Delta x$. This amount needs to be added to the time $\Delta t'$ reported by the co-moving observer. According to the observer with respect to whom the medium is moving, the velocity u of the light with respect to the medium is thus given by:

$$u \equiv \frac{\Delta x}{\Delta t} \approx \frac{\Delta x'}{\Delta t' + (v/c^2)\Delta x'} = \frac{u'}{1 + (v/c^2)u'}. \quad (11)$$

If c/n is substituted for u' , this reduces to (cf. Eq. (8))

$$u \approx \frac{c/n}{1 + (v/nc)} \approx \frac{c}{n} - \frac{v}{n^2}. \quad (12)$$

It follows that, to order v/c , the light has velocity (cf. Eq. (9))

$$u + v = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right)v \quad (13)$$

with respect to the observer for which the medium is moving at velocity v in the x -direction. This concludes the proof that the Fresnel drag coefficient is a direct consequence of the relativity of simultaneity.

Laue's 1907 derivation of the Fresnel drag coefficient is mathematically equivalent to Lorentz' 1895 derivation (compare Eqs. (10)-(13) to Eqs. (5)-(9)). Laue's derivation, however, clearly brings out the meaning of the x -dependent term in Lorentz' local time in terms of the relativity of simultaneity. It also shows, in the unkind glare of hindsight, that it was a mistake to look for a dynamical explana-

tion of the extra velocity component that Fresnel showed was needed for a satisfactory account of refraction in moving media (cf. Eqs. (1)-(3)). Ketteler, Veltmann, and Mascart were right in the 1870s to use Fresnel's formula but to ignore its dynamical explanation in terms of ether drag. And physicists in the 1890s were wrong to count Lorentz' dynamical explanation of 1892 as further evidence for his impressive electro-dynamical theory of refraction and dispersion. The Fresnel drag coefficient did not call for a new dynamics but for a new space-time kinematics.

The kinematical nature of the Fresnel drag coefficient (both in the broad and in the narrow sense) was emphasised by Einstein in his popular book on relativity. After presenting Laue's derivation of the drag coefficient from the relativistic addition theorem of velocities, he wrote:

a theory of this phenomenon was given by H.A. Lorentz [1892] long before the statement of the theory of relativity. This theory was of a purely electro-dynamical nature, and was obtained by the use of particular hypotheses about the electromagnetic structure of matter.¹⁴

In another passage in the book, Einstein explicitly stated that special relativity gives the Fresnel drag coefficient 'without the necessity of drawing on hypotheses as to the physical nature of the liquid' (ibid., p. 51).

Norton suggests that Einstein may have had an ulterior motive in mentioning Lorentz' derivation of 1892 on several occasions but not his derivation of 1895: 'Einstein may have wanted to contrast Lorentz' dynamical derivation of 1892 with the kinematical derivation in special relativity, conveniently passing over Lorentz' 1895 result' (Norton (2004), p. 91). Norton disparages Lorentz' 1892 derivation as 'quite unilluminating, demonstrating only that a rather cumbersome and opaque application of Maxwell's equations to the propagation of electromagnetic waves in moving media yields the Fresnel drag', while praising the 1895 one as 'a much simpler, essentially kinematical derivation' (ibid.). When the two derivations are put side-by-side, it is hard to disagree with Norton's assessment. I do, however, want to register some reservations. First, Lorentz' by Norton's lights equally 'cumbersome and opaque' application of Maxwell's equations to the propagation of electromagnetic waves in media at rest in the ether in Ch. VI of his 1892 treatise was a milestone in the checkered history of dispersion theory. Moreover, even Ch. VII on moving media was of considerable value. In this chapter Lorentz showed for the first time in nearly three quarters of a century that a coherent account of the physics behind the Fresnel drag coefficient was possible. That he did not recognise right away that his was only one possible account hardly diminishes this achievement. Finally, it is hard to believe that Einstein would pass over Lorentz' 1895 derivation in silence (cf. note 9) if that derivation really was as important as Norton conjectures it was for Einstein's path to special relativity.

With Laue's derivation of the Fresnel drag coefficient its status was finally fully clarified. Contrary to what its origin in the analysis of refraction and aberration suggests, the drag coefficient carries no information whatsoever about the physics of light in transparent media other than that it is in accordance with the general rules for the spatiotemporal behaviour of systems in Minkowski space-time. The Fresnel drag coefficient just reflects that the velocities involved when light propagates through a moving medium add the way all velocities add in special relativity.

Acknowledgments

This essay is meant to be a small token of my esteem for Anne J. Kox, who, as my advisor at the University of Amsterdam in the second half of the 1980s, introduced me to the intricacies of the history of special relativity and especially to the role the man we affectionately refer to as 'HAL' played in the development of this theory. In fact, many of the points made in this essay come directly out of the many lengthy discussions Anne and I had about Lorentz and special relativity back then (see, e.g., note 9). I am grateful to the Einstein Papers Project and the Hebrew University of Jerusalem for permission to reproduce in facsimile part of a set of lecture notes of Albert Einstein (see Fig. 2).

Notes

1. This essay is an expanded version of one of three case studies that make up my paper 'Drawing the line between kinematics and dynamics in special relativity' in *Studies in history and philosophy of modern physics* (Janssen (2009)). I want to thank Dennis Dieks and Jos Uffink, the editors of the journal, for giving me permission to use this material for this volume.
2. See Janssen & Stachel (2004) for a concise version of the history of optics in moving bodies in the 19th century.
3. Stachel (2005).
4. Zeeman (1927). See Kox (1993) for discussion of this work by Zeeman.
5. Whittaker (1951-53), p. 125.
6. For a brief discussion of 19th-century dispersion theory and references to further literature on this topic, see Duncan & Janssen (2007), sec. 3.1.
7. Only two decades later, the old quantum theory would pull the rug out from under Lorentz' account of dispersion (Duncan & Janssen (2007), sec. 3).
8. See Kox (1997) for an account of the discovery of the Zeeman effect based on Zeeman's laboratory notebooks.
9. Anne Kox first drew my attention to this remarkable blind spot on Einstein's part when we discussed these matters in the 1980s.
10. Lorentz (1895), secs. 68-69, pp. 95-97.
11. Lorentz (1895), p. 81.

12. But I suppress one key assumption that Lorentz tacitly made, viz. that a material system producing a particular field configuration at rest in the ether automatically turns into the system producing the corresponding state of that field configuration in a frame moving through the ether if it were carefully and slowly accelerated to the velocity of that frame. Lorentz only made that assumption explicit a few years later in the context of the first version of his exact theorem of corresponding states, in which case the differences between the two corresponding states are much more pronounced, including for instance the Lorentz-FitzGerald contraction (Lorentz (1892)). For this reason, I have dubbed this extra assumption the ‘generalised contraction hypothesis’. (Janssen (2002), p. 425; (2009), pp. 32-33).
13. Lorentz (1895), secs. 56-58.
14. Einstein (1917), p. 41.

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